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Original scientific paper

DESIGN, ANALYSIS, AND OPTIMIZATION OF THE STEERING COLUMN SYSTEM FOR AN ELECTRIC STREET SWEEPER

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A b s t r a c t: This study explores the challenges and solutions related to improving the interior ergonomics of a small street sweeper, with a specific focus on redesigning the steering column and brake pedal system. The initial design faces issues such as obstructed field of view and limited space in the operator's knee area. The primary objective is to enhance comfort and safety for the operator within the constraints of the existing design. The proposed solution involves a new steering column structure that integrates the brake pedal system. Siemens Jack software was employed for ergonomic analysis, revealing improved operator comfort and larger field of view with the modified design. Dynamic analysis using ADAMS View confirmed that the new brake pedal system met the requirements outlined in the ECE R13 regulation. This solution improves ergonomics, offers larger field of view, and ensures optimal brake performance.

Key words: steering column; brake pedal; vehicle ergonomics; street sweeper

ДИЗАЈН, АНАЛИЗА И ОПТИМИЗАЦИЈА НА УПРАВУВАЧКИОТ СТОЛБ НА ЕЛЕКТРИЧНА МАШИНА ЗА ЧИСТЕЊЕ УЛИЦИ

А п с т р а к т: Ова истражување ги истражува предизвиците и решенијата поврзани со подобрување на ергономијата на машина за чистење на улици, со фокус на редизајнирање на управувачкиот столб и педалот на сопирачката. Почетниот дизајн се соочува со ограничувања како што се намаленото видно поле и ограничениот простор во пределот на колената на операторот. Примарната цел е да се подобри удобноста и безбедноста на операторот во рамките на ограничувањата на постојниот дизајн. Предложеното решение вклучува модифициран модел на управувачкиот столб во кој е интегриран педалот од системот за стопирање. Програмскиот пакет Siemens Jack е користен за ергономска анализа, потврдувајќи дека новиот дизајн има подобра удобност и поголемо видно поле. Динамичката анализа со помош на ADAMS View потврдува дека педалот и преносниот механизам на сопирачките ги исполнуваат барањата наведени во регулативата ECE R13. Новото решение ја подобрува ергономијата, нуди зголемување на видното поле и обезбедува оптимални перформанси на сопирачките.

Клучни зборови: управувачки столб; педал од системот за стопирање; ергономија на возила; машина за чистење улици

1. INTRODUCTION

Ergonomic methods are applied in the earliest stages of the vehicle design process since they include considering crucial points which determine the comfort and safety of both the driver and occupants, such as: the driver's body position, intuitive interactions at workstations, unobstructed field of view, easily reachable and useable controls, etc. [1]. The goal is to achieve an optimal "fit" between the drivers and the vehicle in a manner that eliminates, or greatly reduces, the risk of mistake and misuse that might lead to system failures and injuries [2]. Ergonomics is what makes the design safe, comfortable and convenient. However, the ergonomic tasks can be quite challenging when designing the vehicle interior subsystems – seats, controls, pedal systems, dashboards, and other elements, within the very limited space. Moreover, the vehicle interior design encompasses various aspects and standards [3]. In that sense, a systems approach is commonly used which includes analyzing the driver, the vehicle and the environment as interconnected systems with specific characteristics [2]. The input information required to help these systems function and exchange information successfully is a combination of multi-disciplinary data – ergonomic guidelines, anthropometric measurements, vehicle regulations, recommended practices for car interior design, etc. [2, 4]. The input information directly influences the interior design process.

The design and placement of the pedal systems is among the top priority vehicle ergonomic tasks since the accelerator, clutch and brake are the most frequently used controls in a vehicle. Authors Garg, Bhide and Gupta [5], emphasize that ensuring their proper positioning in alignment with human anthropology is of paramount importance, particularly concerning driver comfort. In their research, the authors highlight that the particular SAE standards (J1100, J1516, J1517) which provide the ideal pedal point position do not fully consider the differences in drivers of various percentiles. Therefore, they provide a model for optimizing the pedal points according to several inputs and packaging constraints: effective H30 value, pedal plate angle, pedal lever angle and length, anthropometric data, and also seat travel and torso angle [5].

In the study of Zarizambri bin Ahmad [6], an analysis was conducted to enhance and further optimize the pedal box system for a small race car (Formula SAE Third Race Car). The author takes into consideration the ergonomic recommendations for accessibility of controls, the dimension constraints of the specific vehicle type, seat and safety features, the requirements for the pedal systems and relevant regulations. Based on all considered parameters, the author designs a new pedal box and evaluates it through virtual ergonomic tools, FEM analysis and kinematic and dynamic simulation tools [6]. Similarly, in the project of Evan Beery the pedal box assembly for the electric formula SAE racecar team's 2016 racecar was designed and produced [7]. The design is based on interior measurement standards, as well as durability, manufacturability, and cost requirements [7].

The work of Ravan et al. [8], on the other hand, is the design and ergonomic considerations precisely for a clutch pedal assembly. The research assesses the subjective comfort levels experienced by various drivers of different stature percentiles when using the clutch pedal. Additionally, the study aims to analyze the pedal lever and its mounting arrangement using software tools. Conclusions include that the H-point (hip-point) to AHP (accelerator-heel-point) distance should be 650 mm so that the pedals can be optimally used by different stature drivers by adjusting the seat placement. In addition, preferences regarding all pedal clearance and dimensions are given – clearance of 30 mm between clutch and steering column, 47.5 mm between steering column and brake, and 60 mm between brake and accelerator [8].

Slightly differently, the paper of Zhang et al. [9] proposes a kind of pure mechanical lifting pedal applied to rail transit vehicles. This pedal is engineered to accommodate various vehicle structures and operators, significantly enhancing its versatility and reliability across applications.

The review of existing scientific literature on the ergonomics of vehicle pedals has furnished valuable insights. This research includes several of the previously stated methodological approaches with the goal to design, analyze and optimize a brake pedal system according to ergonomic requirements and packaging constraints given by a street sweepers' manufacturer. This paper elaborates a case study and an evaluative research involving comparisons of performance in using different vehicle brake pedal system designs and determining the most convenient to use, with a focus on a user – centered approach. Input data is used from several sources (vehicle characteristics; specific production requirements; required performance according to the ECE R13 regulation; anthropometric data; ergonomic recommendations; ISO standards for physical dimensions of operators, minimum operator space envelope, zones of comfort and reach of controls; etc.) to design a brake pedal system assembly incorporated in the steering column construction. Furthermore, this research utilizes a combination of ergonomic and dynamic assessment tools.

The main objectives of this research, the used methodology, as well as the multi-body and ergonomic simulation, optimization results, and discussions, are elaborated in the following sections.

2. PROBLEM STATEMENT

The research elaborated in this paper is the outcome of the work on a specific engineering task where the main requirement was to improve the interior ergonomics of a small street sweeper. Due to very limited cabin interior space there was insufficient clearance around the vehicle operator, uncomfortable use of the brake pedal and obstructed field of view. The issue with the field of view was due to the size of the new steering column which was positioned higher in order to incorporate (beside the steering wheel components) the given brake pedal cylinder and two control screen holders. Therefore, there was a need to redesign the brake pedal system while keeping the same type of master brake cylinder and achieving the required brake performances and brake pedal force according to the ECE R13 regulation, but incorporating all components in a reduced steering column construction that does not invade the operator space envelope and the view of the road while the sweeper is working. In addition, the rules for an ergonomic brake pedal, in terms of pedal size, angle and placement needed to be followed.

Table 1 displays all the general input data required for the steering column and brake system design.

Table 1

Input data

Vehicle characteristics	
Vehicle type	Street sweeper
Brake cylinder	Single master cylinder
Max pedal force	700 N
Cabin interior size (height × width × depth)	1365 × 990 × 1160 mm
Vertical distance between the accelerator heel point (AHP) and the seating reference point (SgRP) – H30	440 mm
Horizontal distance between accelerator heel point (AHP) and seating reference point (SgRP) – L53	720 mm
Vertical distance between accelerator heel point (AHP) and steering wheel midpoint – H17	710 mm
Horizontal distance between accelerator hell point (AHP) and steering wheel midpoint – L11	125 mm
Ergonomics parameters [2, 10, 11]	
Foot angle	6.5°
Ankle angle	96.5°
Knee angle (for comfort and reaching the brake pedal with a force of 338 – 507 N)	110°
Spine angle from the thigh bone	100°
Comfortable head tilt	30° up and down
Brake resistance	44.5–222.4 N
Pedal travel	13–64 mm
Height above accelerator (for unassisted foot operation)	91 mm
Pedal dimensions – minimal (height × width)	25.4 × 76.2 mm
Pedal spacing	About 50 mm
ISO 3411:2007 Physical dimensions of operators and minimum operator space envelope	
Horizontal sitting surface height	400–495 mm
Eye height sitting	690–858 mm
Buttock–knee length	530–670 mm
Knee height, sitting (with shoes)	500–627 mm
Hip breadth, sitting	320–456 mm
Width within space for legs	>560 mm
Clearance between enclosure and operator’s shoe working pedal	>30
ISO 6682:1986 Zones of comfort and reach for controls	
Foot control location comfort zones, forward from the SgRP (side view)	600–900 mm
Foot control location comfort zones, from the SgRP to the floor (side view)	150–500 mm
Foot control location comfort zones, left and right from the SgRP (top view)	300 mm

This research is based on the application of the given input data in the design of a new solution that will have an improved steering column and brake pedal system of the street sweeper, from both ergonomic and brake performance perspectives.

The main research questions that were addressed are:

1) What do the results of the ergonomic analysis reveal about the comfort assessment and field of view of the initial steering column design?
2) Does the modified model of the steering column and brake pedal offer improved cabin ergonomics?
3) Does the modified brake pedal system achieve satisfactory brake performance while adhering to the given requirements?

Addressing these questions was essential to understand the limitations of the initial brake pedal design and to establish guidelines for improved solutions. Furthermore, a new modified model was introduced, in which the shortcomings of the initial design were addressed. Additionally, in this research a verification process is conducted to confirm that the ergonomic and dynamic parameters of the modified model adhere to acceptable values.

3. METHODOLOGY

The diagram in Figure 1 outlines the steps taken to address the main research questions. Firstly, data was extracted primary from academic literature and publication, as well as SAE recommended occupant packaging, ISO standards and other ergonomic recommendations. Next, the problem was thoroughly defined with all the critical parameters that need to be optimized. In this stage, the objecttives were listed and all the input data regarding the vehicle characteristics, required brake pedal features, as well as the extracted ergonomic information were systematized (Table 1). The following step was the development of the new design. The initial model served as a base, and according to the input data modifications were made and a new brake system and steering column were modeled using SolidWorks. To validate the modified model, two types of analysis were made. For generating a simulated workspace to evaluate the driver's comfort and the field of view and compare the ergonomics of initial design and the proposed solution, Siemens Jack software was chosen as a virtual ergonomics tool. The ergonomic tests were followed by a dynamic simulation of the brake pedal model in ADAMS in order to test the brake pedal and master cylinder performances and to conduct an optimization. Finally, the results were analyzed and conclusions were drawn.

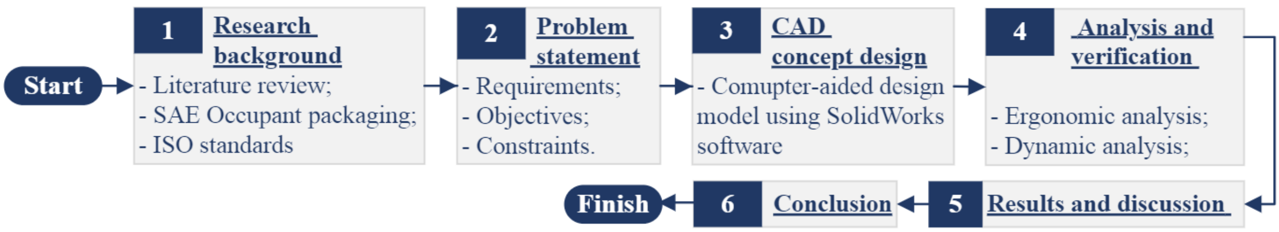
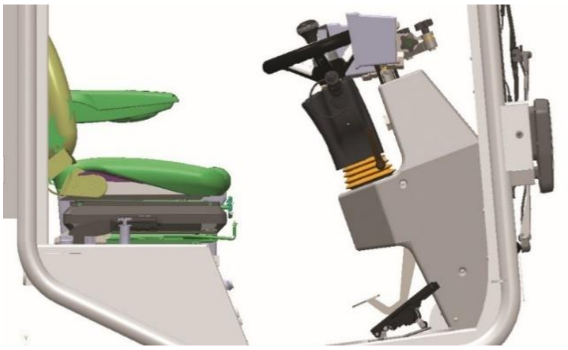


Fig. 1. Research methodology flowchart

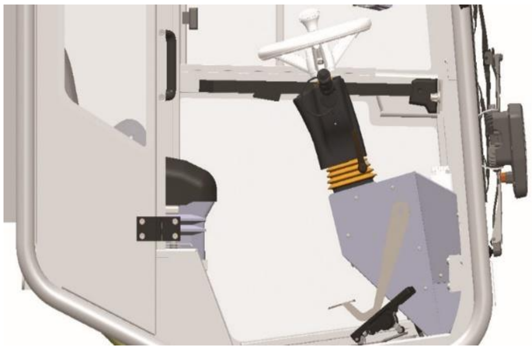
4. CAD CONCEPTS

The CAD model of the initial design is given in Figure 2 (a and c). The height of the steering wheel column construction is 651 mm, or 800 mm including the steering wheel and screens. The distance between the steering column and the seat in this case is 300 mm. This increased height of the column construction is due to the design of the brake pedal system which has a cylinder positioned in an upward direction. In addition, two screens are incorporated, with their holders connected to the column, positioned to the left and right side of the operator.

In the modified design, given in Figure 2 (b and d), a new orientation of the brake cylinder is chosen to create a more compact design and as a result the column is significantly reduced in height. The new height of the column is 400 mm. The screen holders are also removed from the column construction and added to the left and right main profile of the cabin. This results in additional field-of-view-obstruction clearing. The steering column is also shortened in the front for more clearance around the operator's knees, and the new distance achieved between the column and seat is 330 mm.



a) Initial design – steering column



b) New design – steering column

c) Initial design – brake pedal system within the column construction

d) New design – brake pedal system within the column design

Fig. 2. SolidWorks model of the initial and new design of the steering column and brake pedal system

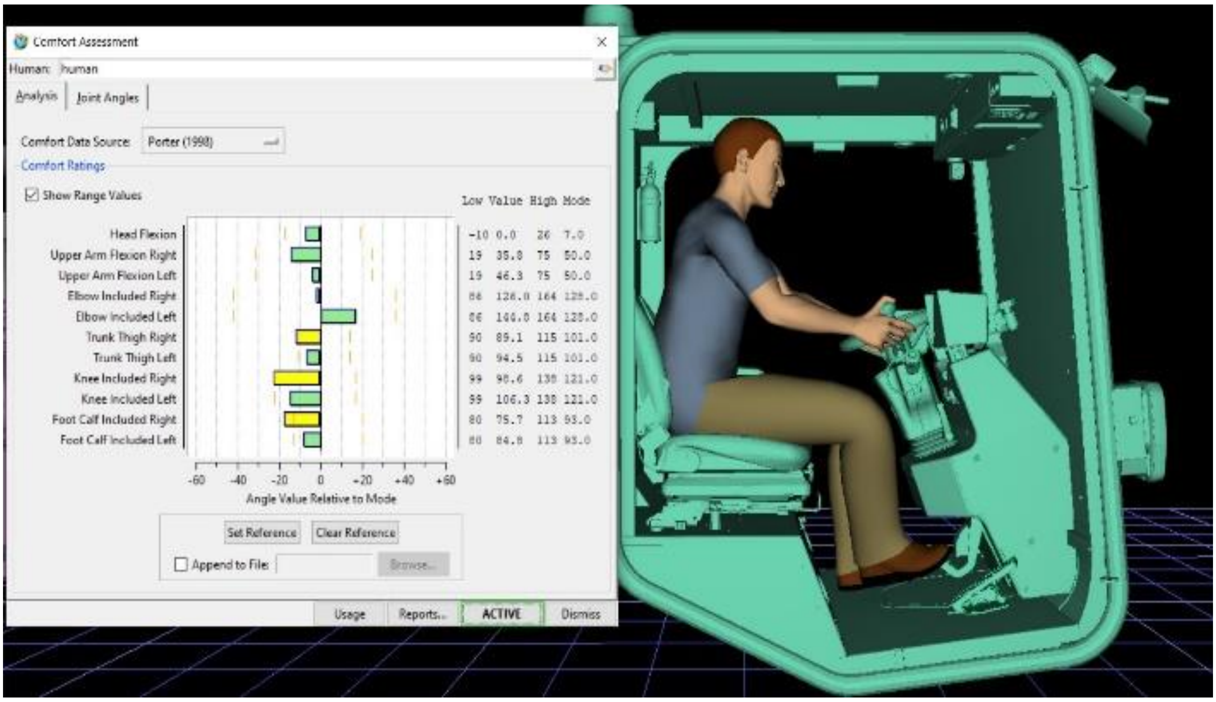
5. ANALYSIS AND RESULTS

As previously explained, this research includes two types of validation analysis – ergonomic and dynamic. The obtained results and comparisons between the two models are elaborated in this section.

5.1. *Ergonomic analysis*

A total of four simulations were conducted using Siemens Jack, by using two different tools for both the initial and modified model. The street sweeper cabin together with the steering column and the brake pedal were imported in Jack's software. The default male mannequin, with a height of 175 cm, belonging in the 50th height percentile, was used and adjusted in a static position that helped to conduct ergonomic analysis for comfort assessment and field of view of the initial and modified design. In the first case, the mannequin was positioned in the vehicle cabin with the initial steering column design, in a seated position. The right leg was placed on the brake pedal, while the left leg remained free, and both hands were firmly placed on the steering wheel. After that, from the Occupant Packaging Toolkit, the Comfort Assessment tool and Obstruction Zones tool were applied. The Comfort Assessment tool helps to check whether a given Jack model is in a comfortable seated posture based on individual joint angles and overall body posture. It generates bar graphs which indicate if the body parts and joints are within the comfort range (green bars – comfort values; yellow bars – outside of the recommended range; red bars – extreme positions). The Obstruction Zones tool, on the other hand, requires the selection of the mannequin's eye point sight, and the obstruction segment (in this case the whole steering column) to generate planes which illustrate the obstructed part of the field of view. In the second case, the same procedure (same mannequin placement and same tools) was conducted using the new design as well.

The results of the Comfort Assessment analysis are given in Figure 3 (a – initial design; b – new design). The comparison of these results shows that the initial model exhibits worse outcomes and discomfort in the right thigh muscle, right knee, as well as the right calf muscle of the leg (shown with yellow bars). These less favorable values are a consequence of limited space and minimal room for accommodating a steering column. In contrast to that, the results from the comfort assessments for the modified model show better outcomes, falling within the range of allowable values.

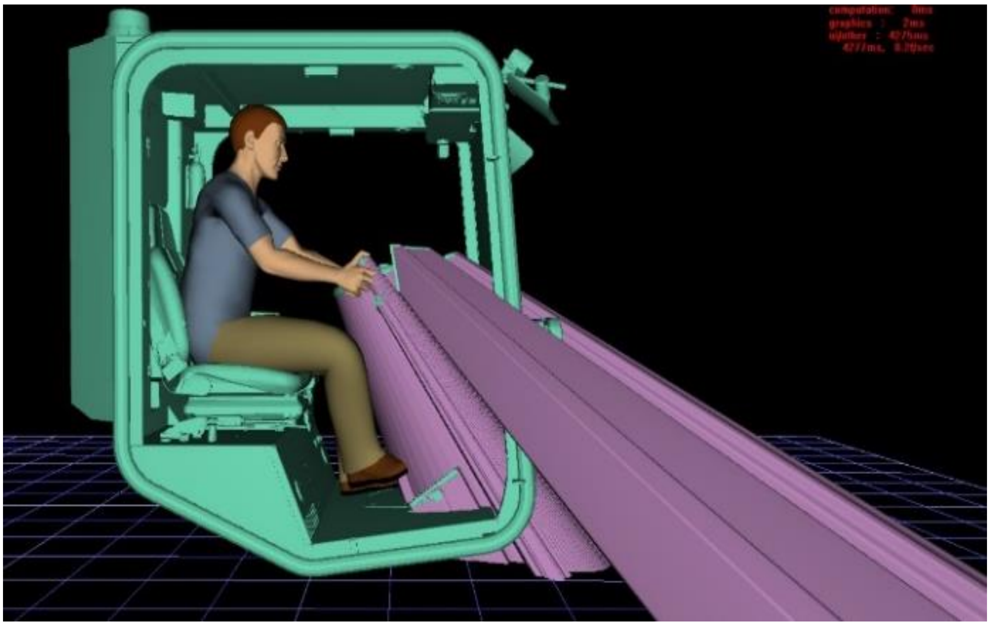


a) Comfort assesment results for the initial design

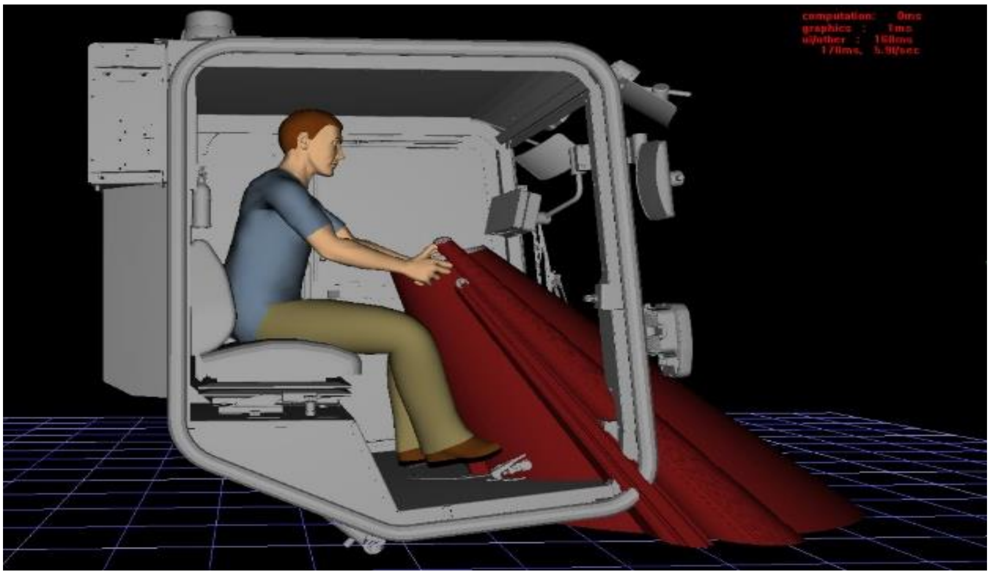
b) Comfort assesment results for the new design

Fig. 3. Comparison of results from the ergonomic analysis using the Comfort Assessment tool in the Occupant Packaging Toolkit in Siemens Jack software

The results of the Obstruction Zones analysis are given in Figure 4 (a – initial design; b – new design). Since for the street sweeper operator an important task is to constantly monitor the road ahead the field of view should be as clear as possible. From the field of view comparison of both models, it is clear that with the second variant, where the steering column is reduced mostly due to the new pedal system design, the operator has a better field of view. This is visible from reduced angle of the planes illustrating the obstructed part of the field of view.



a) Obstruction Zones results for the initial design



b) Obstruction Zones results for the new design

Fig. 4. Comparison of results from the ergonomic analysis using the Obstruction Zones tool in the Occupant Packaging Toolkit in Siemens Jack software

5.2. *Kinematic and dynamic analysis*

In order to ensure the effectiveness of the braking system, a multibody dynamic analysis was conducted using ADAMS View. To fulfil the ECE R13 regulation, a 60 bar hydraulic pressure is needed to be achieved and the minimum needed piston stroke was determined to be 16.5 mm. Therefore, the minimal required actuation force of the cylinder had to be 1710 N.

The ECE R13 regulative mandates that the pedal force should not exceed 700 N, thus the applied force of the virtual model is equal to the maximum one allowed, in order to test the braking performances in extreme conditions.

The results of the original design can be observed in Figures 6 and 7 where it can be obtained that the results are satisfactory and the required goals for minimal cylinder force and piston stroke are achieved. But, for the purpose of achieving improved braking performances and reducing the necessary pedal force, an optimization was conducted. Due to the design space limits, and defined required ergonomic parameters, limited number of changes were available to the design of the system. The pedal and master cylinder positions were not changed, while the attachment position of the pedal (Point 1 – P1) and the connecting point (Point 2 – P2) between the master cylinder rod and the connector plate were modified. These positions are presented in Figure 5. P1 was chosen to be the origin of the coordinate system.

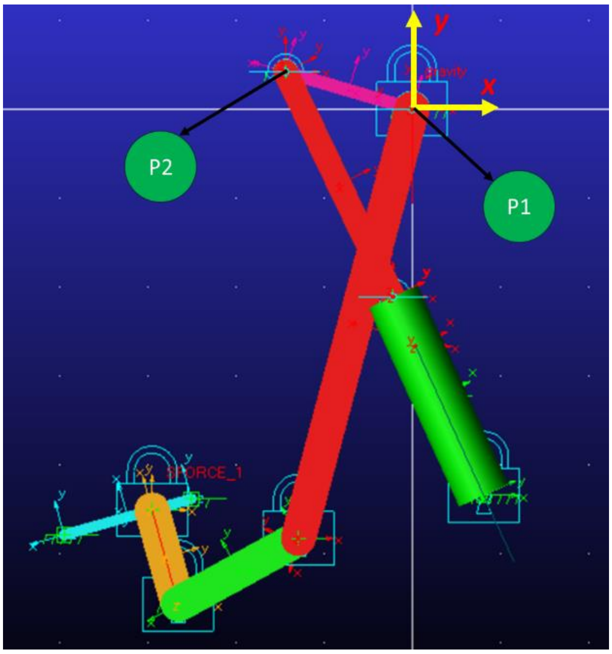


Fig. 5. Virtual multibody model

Table 2 presents the created design variables (DV) and their range. The range was determined based on the limits of the column construction.

During the optimization process, 3 iterations were made to determine more optimal position of the connecting points. The results of the optimization and the position of the connecting points is presented in Table 3.

T a b l e 2

Design variables parameters

Design variable	Initial position	Position change range
Point 1 – DV 1	0	(–25, 20) translation along *y* axis
Point 2 – DV 2	–71.84	(–130, –50) translation along *x* axis
Point 2 – DV 3	20.94	(–30, 40) translation along *y* axis

T a b l e 3

Optimization results

Iterations	Master cylinder force (N)	DV1	DV2	DV3
Original design	2129.7	0	–71.84	20.94
Iteration 1	2710.9	–8.2	–50	–40
Iteration 2	3282.2	18.493	–50	–30
Iteration 3	3369.3	17.895	–50.04	–30

The optimization results show increase in braking force by 58% (Figure 6). This shows that even the minor modifications in a tight space can improve the braking performance. Although this force is almost two times higher than the minimal required one, it must not be forgotten that the simulation is conducted with maximal pedal force of 700 N. Therefore, the required minimal force can be achieved by applying smaller brake pedal force, thus increasing driver's comfort and satisfaction.

The only negative side is the need for bigger piston stroke of the brake cylinder (Figure 7), but fortunately the current master cylinder can achieve that.

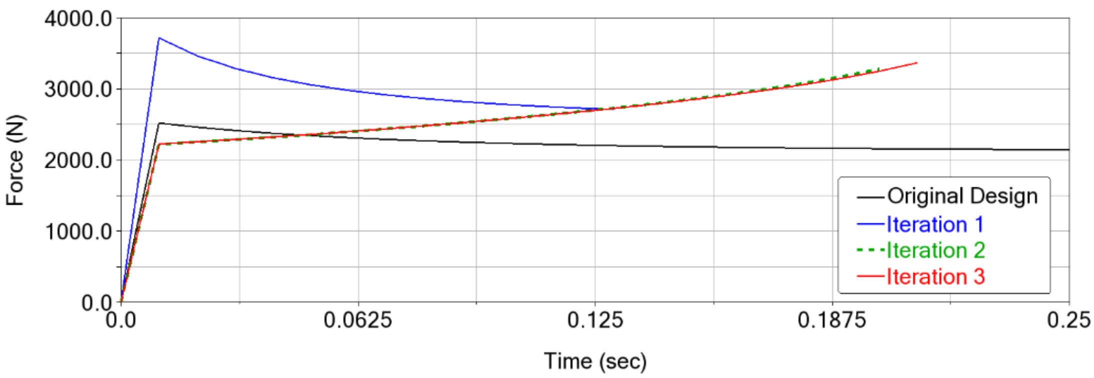


Fig. 6. Master cylinder braking force output

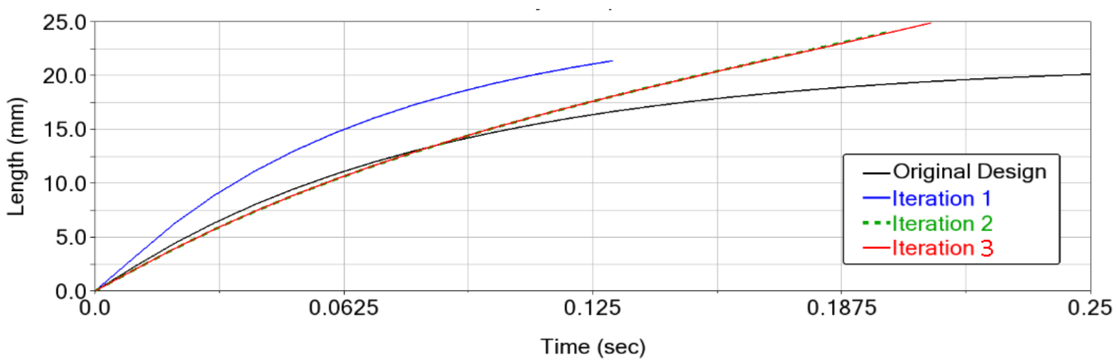


Fig. 7. Master cylinder piston stroke

6. CONCLUSIONS

This study is based on a specific methodological approach used in order to develop, assess, and enhance a brake pedal system that complies with specified ergonomic and packaging constraints. This paper presents a study and evaluation that compares the performance of two vehicle brake pedal system designs, aiming to identify the most user–friendly option. The main goal was to utilize the available input data (such as vehicle specifications, manufacturing requirements, ECE R13 regulation for necessary performance, anthropometric data, ergonomic guidelines, ISO standards, etc.) to create an alternative brake pedal system assembly integrated into a steering column structure which is designed in a manner that does not cause insufficient clearance around the operator, or uncomfortable use of the brake pedal, and does not obstruct the field of view.

There were two main challenges of the task: (1) solving the issue with obstructed field of view and limited space in the knee area of the operator due to the initial design of the steering column, and (2) redesigning the brake pedal system to fit in a smaller steering column while keeping the same type of master brake cylinder and achieving the required brake performances and brake pedal force according to the ECE R13 regulation.

To respond to the given requirements, a modified steering column structure was proposed with an integrated brake pedal system which featured a new orientation of the brake cylinder chosen to create a more compact design and reduce the size of the steering column. To verify the new design, ergonomic and dynamic analysis were made using Siemens Jack and ADAMS View.

Based on obtained results, it is evident that the ergonomic issues were successfully reduced. According to the Comfort Assessment analysis, more natural positions of the operator's body and joints while using the steering wheel and brake pedal were noted with the smaller steering column. Issues with discomfort of the thigh muscle, knee, and calf muscle of the right leg were overcome with the new design which is more compact and allows more space for leg movements. In addition, based on the Obstruction Zones analysis, we can see a reduced angle and height of the generated obstruction plane, meaning that a clearer view over the street and sweeper brushes will be possible with the new steering column.

The results from the multibody dynamic analysis of the new brake pedal arrangement were also satisfactory and the required goals for minimal cylinder force and piston stroke were achieved. Moreover, an optimization of the new brake pedal system was done to achieve improved braking performance which was conducted by varying the attachment position of the pedal and the position of the connecting point between the master cylinder rod and the connector plate. No other optimization modifications were made since the rotated orientation of the brake cylinder and limited interior space did not allow a possibility for more drastic variations. However, even with a small modification in the previously mentioned points, the optimization results showed an increase in the braking force and improved braking performance.

In the end, the new steering column with optimized braking system was implemented in the street sweeper and the solution was verified on the real model. The same brake cylinder was used, but with the new orientation the interior became more ergonomic. In addition, as previously elaborated, due to tested variations of the attachment position of the pedal and the connecting point between the master cylinder rod and the connector plate, optimum braking force output was achieved.

In conclusion, we can state that the initially given research questions were successfully addressed: (1) the ergonomic analysis revealed specific issues about the comfort assessment and field of view of the initial steering column design; (2) the modified model of the steering column and brake pedal did offer improved cabin ergonomics; and (3) the modified brake pedal system achieved satisfactory brake performance while adhering to the given requirements and reducing the needed brake pedal force applied by the driver.

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