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Finding a new test method for Inlay carpets instead of taxi tests

Master's thesis in Product Development

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In collaboration with Volvo Cars Corporation

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Abstract

This thesis focuses on developing a new and faster test method to evaluate wear in automotive inlay carpets, as an alternative to long taxi tests. Currently, the industry uses taxi based testing, where carpets are used in real taxis for about 1.5 years. However, this method has many limitations. The results depend on how different drivers use the car, as well as environmental conditions such as dirt, water, salt and stones. Because of this, the results are not consistent. In addition, standard laboratory tests like Taber and Martindale do not properly represent real foot movement of driving conditions.

To solve this problem, a structured product development approach was used. This included reviewing research papers, studying existing patents and conducting user studies. A detailed user study was carried out with drivers of different percentile and driving habits. This helped to identify key types of foot movements, such as pivoting, sliding forward and backward, side movements and pedal pressing. These findings were then used to define requirements and develop different design concepts.

Based on this, a proof-of-concept (POC) test rig was developed. The setup was designed to simulate real life foot movements, applied loads and environmental conditions like dirt and stones. Tests were carried out on different carpet materials, including Polyamide (PA) and Polyester (PES).

The results show that the new method is able to reproduce some wear patterns, but they are not exactly the same as the taxi tested carpets. Overall, this study shows that including realistic human foot movement in testing improves the accuracy compared to existing test methods, but more modification and testing are required before it can be used as an industry standard.

Keywords: Inlay carpets, Taxi tests, Proof of concept (POC), Environmental conditions, Wear patterns

Acknowledgements

This journey of developing a new test method for inlay carpets instead of taxi tests has been an amazing and rewarding experience for us. Through this project, we gained valuable insights about how product development concepts and methodologies are applied in real industry settings. It also provided us with a deep understanding of how companies actually work with complex projects, manage the cross-functional collaboration and translate theoretical concepts into actual solutions.

Firstly, we would like to express our gratitude to our company supervisor Christina Blomberg and our manager Erik Rydberg at Volvo cars for continuous guidance and support throughout this thesis. We thank our academic supervisor Lars Lindkvist, at Chalmers University for his support and feedback throughout this period. Our appreciation also goes to John Carden and Fredik Karlsson from the rig department for their collaboration and providing us with technical assistance. Lastly we would like to thank the Floor systems and interior trims department at Volvo cars for necessary resources and welcoming environment throughout the project.

Finally, we thank everyone who contributed to this project in various ways - whether through discussions, brainstorming sessions and interviews which helped us to make this thesis possible.

Aniket Kulkarni & Tejas Budke, Gothenburg, 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

DOE	Design of Experiments
PA	Polyamide
PES	Polyester
POC	Proof of concept
SAE	Society of Automotive Engineers
VCDC	Volvo Cars Demo Center

Nomenclature

Below is the list of Nomenclature that have been used throughout this thesis:

Variables

$N - Cycles$	Number of test cycles
F	Applied normal force (N)
P	Contact pressure between heel and carpet

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1
Introduction

1.1 Background

At present Volvo Cars are evaluating the longevity of inlay carpets using the the taxi tests. In this method they install the inlay carpets in taxi and allow them to use it for 1.5 years, after 1.5 years the carpets are returned to Volvo for evaluation. These taxi tests are inaccessible as we cannot monitor how carpets are been used by the taxi driver and under what conditions. Moreover, these tests are time consuming and the results of these tests depends upon the person using the carpet under different conditions such as different driving patterns like jumping from acceleration pedal to brake pedal, pivoting the foot by keeping heel at one place, sliding of the foot sideways and front and back. It also depends upon the shoes type and also environmental conditions like dirt, water, stones and salt.

Other method for abrasion testing done such as taber test, differ notably from those of taxi tests. Therefore, there is a need of test method which would mimic the human foot movements and give abrasion results close to the taxi test results. Developing a new test method which closely relates with taxi tests would enable Volvo Cars to evaluate a wider range of carpet designs and materials more efficiently. This would allow for better prediction of carpet lifetime and support optimization of carpet structure, surface patterns, material and pile direction.

1.2 Aim & Objective

This thesis project explores the development of a new test method for inlay carpets, which intend to reflect the real world conditions such as different foot movement, foot positions and environmental conditions. The primary aim of this thesis is to conceptually develop a test method that can replace long-duration taxi tests.
During this master's thesis, a proof-of-concept was developed using a structured product development approach. The work focused on identifying wear parameters based on user studies and translating these findings into conceptual design supported by CAD modeling.

1.3 Project scope

The scope of the project is to develop a Proof-of-concept of the new test method by applying product development methods that correlate to wear results in taxi tests. The project focuses on translating the driver foot movements observed in user study into a controlled setup.

The scope also includes the identification of key wear parameters derived from the user study, as well as the conceptual development and CAD modeling of the proposed test method. The scope is limited to proof-of-concept development and does not include a final industrial product.

1.4 Research Questions

1. What limitations exist in current abrasion testing methods, and why is there a need for an improved test method to evaluate carpet wear more accurately?

2. How factors such as foot pivoting, sideways motion (jump in jump out), back and forth movement, pressing motion on gas and brake pedal can be incorporated into the design of POC?

3. How closely do the results of the new test method match those observed in taxi tests?

1.5 Limitations

The main limitation of this thesis is the restricted project duration of 20 weeks, which limits the number of experiments, iterations, and validation steps that can be performed. Although all needed data and carpet samples are available, the time constraint prevents a broader evaluation of more carpet types, extended long-term wear tests, and larger statistical repeatability studies. Therefore, the work focuses on developing and assessing a feasible test method rather than conducting an exhaustive validation of all possible wear conditions.

2

Data Collection / Data Gathering

2.1 Literature Study

The aim of the literature study is to obtain more knowledge and insight into existing carpet wear testing methodologies and to understand their applications and limitations in the context of automotive interior carpets. By conducting a thorough literature review, it becomes possible to identify knowledge gaps, evaluate current industry standards and determine the shortcomings of present abrasion test methods. This understanding supports the development of the new test method that more accurately simulates real world wear patterns that observed in taxi tests while improving repeatability and efficiency in controlled environments.

Many industrial research work are dedicated to abrasion and wear tests for automotive interior and carpets, mainly to assess their durability. Standard laboratory instruments, like Taber abrasion[3], Martindale abrasion tester[4], ABREX shoe sole tester[5] etc. these are commonly used to determine the resistance of the material against surface wear under well controlled motion, force and cycle parameters. These methods recreate very simple abrasion patterns to check the visible wear loss of mass or deterioration of the coating. However, they mainly rely on fixed, repetitive rubbing motions and therefore cannot fully capture the complexity of real life foot interactions inside the vehicle.

Carpet manufacturers in the automotive sector always welcome testing standards like SAE J1530 that not only help them test and assess the abrasion resistance but also fiber loss and bearding behaviour of auto carpets. These norms spell out the method of specimen preparation, wheel conditioning, load application and consecutive abrasion sequences under controlled environment that enhance the repeatability of tests. However, they still measure the wear on a very limited motion pattern that changes little and is quite different from the natural variability of human foot behavior[6].

Apart from the standard test devices, many car manufacturers use their own abrasion standards, which are usually derived from the taber rotary method. Even though these procedures are the most common ones, they generally lack the capability of imitating real driving conditions, as different foot angles, multidirectional sliding or changing pressure distributions that take place during normal pedal operation are not considered.

To better understand the real sources of carpet wear, several studies focusing on driver foot biomechanics, pedal operation behavior, and musculoskeletal loading are highly relevant [7]. Research analyzing foot angles, postures, leg muscle activity and foot gesture dynamics during accelerator pedal usage provides essential insight into typical movement patterns that contact the carpet surface. These works examine natural sliding motions, heel pivots, and repeated micro-adjustments that contribute significantly to carpet wear. Similarly, studies on driver pedal ergonomics [8], pedal error prediction and lower limb biomechanics further reveal how footwear, foot rotation and interaction forces vary between drivers and across driving conditions.

These literature findings also include investigations on automatic or variable loading carpet testing devices, which highlight the need for mechanical systems capable of reproducing realistic loading conditions rather than static or single axis abrasion. Existing literature repeatedly emphasizes this mismatch, confirming the need for a new test method that combines the repeatability of lab tests with the real of human like foot movements.

Previous studies have shown that ingress and egress are repetitive movements which involve significant interaction between driver and vehicle interior. Drivers frequently use interior components such as steering wheel and door panel as a support to maintain balance while entering and exiting the car [28]. Moreover, kinematic analysis done identified that different movement strategies during egress such as one foot and two foot strategies involve pivoting, stepping and long contact of feet with the floor [29]. Another investigation demonstrates that ingress and egress motions generates vertical and shear forces at foot-floor interface which results in repeating mechanical loading on floor surface [27]. Therefore, these studies indicate that frequent ingress and egress motions combined with foot sliding, load transfer and stabalisation using vehicle support can contribute to the abrasion and wear of inlay carpets over time. Experimental analysis of this behavior indicate that these motions vary depending on vehicle architecture, roof height, seat position and driver anthropometry leading to different contact forces and movement patterns on the carpeted areas [14].

Research focuses on driver foot biomechanics and pedal operation further demonstrates that foot movements inside the vehicle are not static but involve continuous small adjustments. Studies analyzing foot angles, heel rotation and lower limb muscle activity during pedal use report repeated pivoting and sliding of the foot, particularly around the heel area [17]. These findings suggest that carpet wear is influenced not only by vertical loading but also by lateral and rotational motions. Additionally, literature on taxi driver's behavior highlights variability in driver movement patterns, which influenced by habitual and learned behaviors over time such as multi day cruising patterns. Such variability supports the assumption that different drivers interact with interior carpets in different ways.

Studies related to ergonomics and anthropometry differences involve that foot size and leg geometry affect driver movements. Older drivers with larger foot sizes tend to maintain more stable foot positions during driving, while drivers with smaller foot sizes often perform more frequent adjustments including back and forth motion, lateral shifts, pivoting and rapid ingress egress transitions [16]. These differences lead to uneven carpet wear, which is not properly represented by conventional abrasion test method.

In conclusion, this overall study about ingress, egress and driver foot movements strongly affect carpet wear. And this highlights the need for a test method that can simulate realistic foot movements instead of simple one direction abrasion test.

2.2 Patent Analysis

The purpose of the patent analysis is to investigate existing patented solutions related to carpet wear testing, static and dynamic loading and human foot interaction mechanisms. These patents focuses on practical and commercially viable implementations, how industry approaches durability testing challenges. This analysis of patent documents helps to identify existing solutions, understand their working principle and evaluate technical limitations which supports the development of improved test method.

Relevant patent documents were collected using the Espacenet [18] patent database with focus on development related to carpet testing devices such as automated load application systems, abrasion measurement mechanisms and human foot interaction simulation. The reviewed patents ranges from early abrasion testing concepts which is automated and heel based test devices those are primarily in Japan, China and through international patent filings.

Most of the patents focuses on testing carpets wear using controlled and simplified test conditions. Many of the proposed devices apply fixed loads or repetitive motions to evaluate abrasion resistance or heel wear at specific contact points. Some patents introduce automated systems to improve test repeatability and reduce manual work. However, these solutions usually simulate only a limited type of movement and do not represent the complex foot motions that occur during real driving.

Several patents also focuses on monitoring foot position or reducing wear by using protective components rather than directly evaluating carpet degradation. While these approaches are useful for specific purposes, they do not provide a complete representation of carpet wear caused by natural driver behaviour over time. Important factors such as foot rotation, sliding motion, changing pressure distribution and environmental influences are generally not included.

This patent review shows that existing patented solutions address carpet wear in a controlled and simplified manner but do not fully capture realistic driver foot movements. No patent was found that offers a test method capable of replacing long-duration taxi tests while still providing realistic and repeatable results. This demonstrates a clear need for developing an improved test method.

Below table shows the key patents identified during the Espacenet patent search that were considered relevant to carpet abrasion, heel wear and test device development[18].

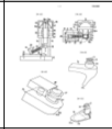
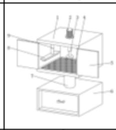
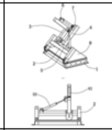
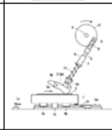
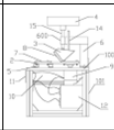
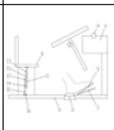
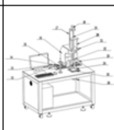
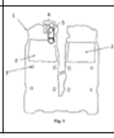
Sr. No.	Group	Patent Number	Year	Patent name	Company name	Drawing	Country	Focus
1	Abrasion and Wear Testing Devices	JP_2831459_B2	1992	Abrasion Tester	Toyota chemical Co., Ltd.		Japan	1. Mechanical Abrasion 2. Controlled loading 3. Simplified motion
2		CN_209764632_U	2019	Deivce for Abrasion resistance of automotive interior	Shenzhen Tonggui Technology Testing Co., Ltd.		China	
3		CN_222561482_U	2024	Device for the abrasion resistance of car carpets, foot pads and heels	Changchun Fusheng automotive technology R&D Co. Ltd.		China	
4		JP_2016070715_A	2016	Testing method and testing machine for flooring materials	Takiron Co. Ltd.		Japan	
5	Heel / Foot Position & Wear Interaction	CN_214150272_U	2020	Floor mat heel wear testing device	Taifu (Wuhan) automotive acoustics products Co. Ltd.		China	1. Heel wear 2. foot location 3. Monitoring rather than wear simulation
6		CN_219202494_U	2022	Driver's right heel position monitoring device	Zhengzhou university of light industry		China	
7		CN_221280864_U	2023	Flexible heel wear testing device	Foshan shilihe automotive technology Co. Ltd.		China	
8	System-Level Flooring Protection	WO_2024041914_A1	2024	Abrastion resistant pad for an automotive flooring system	Autoneum management AG		World Intellectual Property Organisation (WIPO)	1. Abrasion resistant pads 2. Protection instead of evaluation

Figure 2.1: List of Patent Analysis

2.3 User Study

User study played an important role in the development of new test method. For generating a new test method it was important to understand the variation in driving behaviour across different users, including factors such as vehicle type, footwear, physical characteristic such as height and weight, and individual driving patterns.

2.3.1 Method

For user study, diverse group of participants were selected representing different percentiles range between 170 to 210 cm. This group included Volvo car employees, Master's students and a former Volvo employee. This study included multiple vehicle models such as Volvo XC90, Volvo V60, Volvo EC40 and Polestar2. The reason behind selection of these car models is because volvo has done their previous study with taxi drivers on these car models.

Participants from Floor systems and luggage compartment were instructed to drive XC90 and V60 car in the city for approximately 1-2 hours. The reason behind choosing city driving instead of highway driving is because city area involve more breaking and acceleration than highways. This is relavant because taxi drivers predominantly drive more in cities. Frequent braking and acceleration will help us better understand foot movement patterns and areas where abrasion occurs. In addition, a separate user study was also conducted with a former Volvo employee using a Polestar 2 under similar conditions. Another study was carried out at Volvo Cars Demo Center, where participants drove along a short route, although the driving duration in these case were limited but still a wide range of foot movement patterns were observed.

Foot movement data were captured using GoPro cameras positioned near driver's footwell, along with the external light source to ensure sufficient visibility (see figure 2.2).

Figure 2.2: User Study Setup

In addition, pressure mats were installed under the inlay carpets to measure the force and pressure distribution in acceleration and braking area. To validate these measurements grid lines of 5cm x 5cm were drawn on the inlay carpets using chalk (See figure 2.3). The grid was drawn based on fixing point of the carpet, as main focus was to examine abrasion patterns in braking and acceleration area. As participants moved their feet during driving, the chalk marks will gradually worn off making it easy to identify areas with high foot movement.

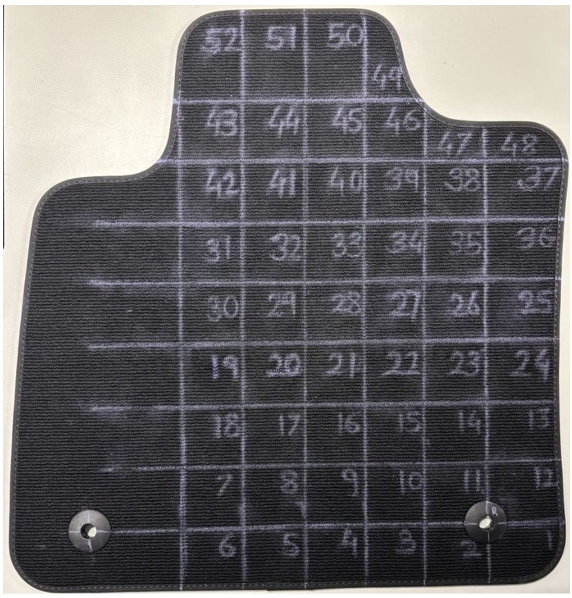


Figure 2.3: Grid Lines on Carpets

2.3.2 Observations

For user 1 whose height was 205 cm, the foot movements covered on XC90 carpet was approximately 5-6 blocks (see figure 2.4). There was no lifting of the foot when switching between accelerator and brake pedal, nor there was any front - back or sideways motion due to his tall height. Throughout the journey pivoting of the foot was performed. Moreover, the maximum force that was measured on the pressure mat was around 43N and small stones were observed under the formal shoes (see figure in appendix 1). This factors could potentially influence the carpet wear for long term, especially when the user rotated the heel slightly while braking which might twist the carpet surface. When the same user drove V60 car, the foot movement range on the carpets were reduced to 2 -3 blocks (see figure 2.5), although the force applied remained similar along with the shoes type.

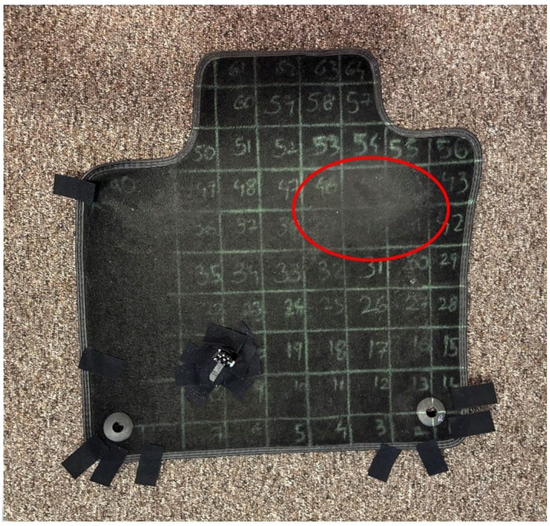


Figure 2.4: User 1 XC90

Figure 2.5: User 1 V60

User 2 with a height of 172cm showed very different foot behaviour. On XC90 user foot movement was limited to 2 blocks (see figure 2.6). The maximum force measured on pressure mat was around 19N and user frequently shifted between pivoting, slight lifting of foot and moving it left, right, forward and backward. When the same user drove V60 wearing sport shoes the foot movement area was increased to around 6 blocks (see figure 2.7) and randomness in foot motion was clearly visible. These results aligned well with the findings of the research paper where the taller drivers usually perform the pivoting motion, on the other hand shorter drivers often exhibit more varied and less predictable foot movements [15]. Moreover, seat height, vehicle type, and individual driving habits also contribute to the differences that are observed.

Figure 2.6: User 2 XC90

Figure 2.7: User 2 V60

Further tests with User 3 with a height of 186cm, revealed more controlled pattern similar to the tall drivers. The maximum force measured on the pressure mat was 21N and foot movement on XC90 car was observed around 3 - 4 blocks (see figure 2.8). Throughout the test his heel remained anchored in one spot and the movement observed was pivoting between the pedals and not any random movements. For User 4 a former Volvo employee with a height of 187cm, the same pivot pattern was observed. However, when examining the carpet from his Polestar 2, some irregular abrasion patches were observed (see figure 2.9). This suggests that not just the pivot patterns but real world factors such as driving durations, varying footwear, Ingress, Egress and environmental conditions may still affect the abrasion on the carpet.

Figure 2.8: User 3 XC90

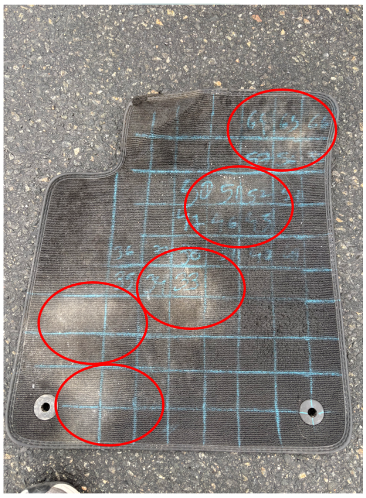


Figure 2.9: User 4 Polestar 2

An additional user study was conducted at Volvo Cars Demo Center (VCDC) on EC40 car, where data was collected from 10 users that included supervisors and master's students from Volvo (see figure 2.10 & Appendix A.19). While analyzing the data, height related trend was observed, drivers below 180 cm performed random foot movements such as jump-in and jump-out along with forward and backward motion. In contrast, users above 180 cm generally performed pivoting motion or a combination of pivoting with slight front and back motion. These findings strongly reinforced the earlier observations and provided a better understanding of how foot behavior varies across user groups.

Overall, the user study was essential to understand the motion patterns that need to be replicated in the proof-of-concept abrasion machine. The test demonstrated that the realistic simulation must include pivoting motion, along with slight front-back motion of approximately 0.5cm to 1cm and minor sideway motion. Moreover, environmental factors such as dirt, stones, water and salt must be incorporated to produce the abrasion effects seen in real world taxi tests.

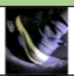
Date	User	Percentile/Height (cm)	Weight (Kg)	Image	Shoe Type	Foot/Shoe size (ft/inch)	Max_Force (N)	Seating Positior	Vehicle	Time duration (min)	Kms covered	Foot Pattern
2026-03-12	U1	182	65		Sports	NA	18,8		EC40	10	4,2	All four Movements
	U2	181	90,6		Sports	NA	26,05			8		Pivot + FNB
	U3	176	55		Sports	EU42	10,08			7		Jump
	U4	194	94		Sports	EU44	23,8			7		Pivot + FNB
	U5	173	73		Sports	EU42	19,9			6		FNB + J_IN_J_OUT
	U6	182	88		Sports	NA	26,4			7		Pivot + FNB
	U7	171	84		Sports	NA	20,75			7		Pivot + J_IN_J_OUT + FNB

Figure 2.10: User study on EC40 at VCDC

2.4 Carpet Nomenclature

Automotive inlay carpets are single or multilayer textile components used in car interiors to provide comfort, better hold on your feet and durability while protecting the base carpet structure. A clear understanding of carpet nomenclature and structure is required to relate carpet construction to wear behavior while driving.

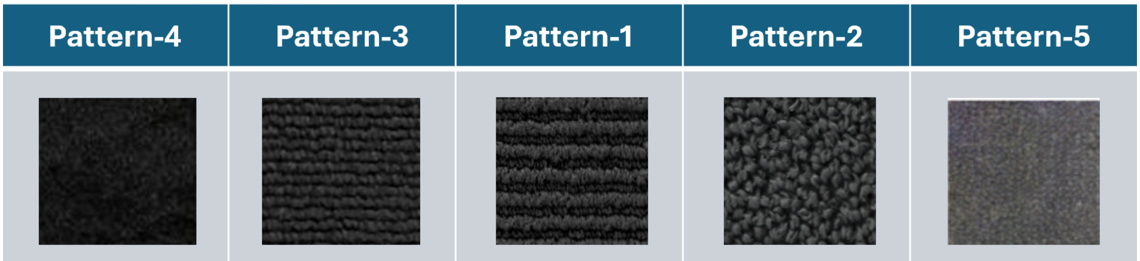


Figure 2.11: Types of Carpet Structures (Source: Volvo Cars internal documentation)

Above table shows five different automotive inlay carpet types considered in this study along with their respective names. These carpet types depends on their yarn configuration, pile direction, material composition and backing arrangement which controls abrasion behavior and durability.

Inlay carpets typically consist of a pile layer, which forms the visible surface and is directly exposed to foot contact during driving, ingress and egress. Beneath the pile layer, a primary backing secures the yarn and provides structural stability. This layer makes the carpet stiffer and helps to keep its shape. It also changes how the carpet feels when pressed, how well it bounces back and how long it lasts. The yarn structure shows how the fibers are arranged in the carpet. Most automotive carpets use tufted yarns and these yarns create loop pile or cut pile surfaces. Pile height is the length of the yarn above the backing and pile density shows how close they are to each other. And this affects how the carpet feels and how much abrasion it has.

The material of the yarn such as polyamide (PA) and polyester (PES) plays an important role in determining wear resistance and recovery after repeated cycles. Additionally, the pile orientation of yarn structure that is in the longitudinal and transverse directions relative to movements of how sliding, pivoting and back and forth interaction with the carpet surface.

2.5 Sustainability Aspects

The choice of polymer-based textile carpets instead of rubber mats in automotive interiors is generally driven by a combination of sustainability, functionality, design and lifecycle considerations. Textile carpets made from polymers such as recycled polyamide (such as Econyl®), recycled polyester (rPET), and polyester-based structures incorporating a middle or backing layer which allow manufacturers to reduce the use of virgin raw materials and support more sustainable ones which provided by integrating post consumer or post-industrial recycled content. [9]

Polymer carpets can be made from a single material or from materials that work well together, which makes them easier to recycle at the end of a vehicle's life. Rubber mats, on the other hand, are usually made from vulcanized rubber mixed with fillers and additives, so separating the materials and recycling them in a closed loop is much harder. Using fewer material types in interior parts improves recyclability and supports circular-economy goals in the automotive industry. [10],[11],[12]

Although, rubber mats are very durable and resist moisture and wear, but these advantages can be outweighed by their poor recyclability and complex material makeup when looking at the full life cycle. Because of this, textile carpets are usually chosen as the main interior flooring, while rubber mats are mostly used as removable protective accessories. Overall, choosing polymer-based textile carpets supports better recyclability, circular material use, and long-term environmental performance not just durability. [13]

2.6 Wear Patterns Study

The wear pattern study was carried out using carpets taken from vehicles that had been used as taxis and therefore driven for long distances/kilometers. Taxi usage represents intensive real world conditions because the vehicles experience frequent entry and exit and continuous daily use. This makes the carpets suitable for studying wear behavior under operating conditions.

The observations show that wear on automotive carpets is not evenly distributed across the surface. Most of the wear is concentrated in the driver's footwell, especially in the heel area and near the pedals. The shape of the worn areas clearly follows typical foot movements such as pivoting, forward and backward motion, and entry and exit movements. This indicates that wear development is mainly influenced by driver behavior rather than by continuous material degradation.

Material type, pile structure and loop pattern were found to affect how wear appears on the carpet surface. Carpets made from polyamide based materials, including recycled polyamide, generally showed smaller worn areas under similar usage conditions. Polyester based carpets showed earlier visible wear, mainly in the form of pile flattening and changes in surface appearance. However, in most cases the carpets remained functionally intact. Differences in pile pattern and loop direction also influenced how clearly wear zones could be seen. In many samples, first wear appeared as surface flattening rather than complete fiber damage.This outcome suggests that visible wear does not necessarily mean the carpet has reached the end of its functional life.

3
Methodology

This chapter outlines the systematic methodology adopted to achieve the objectives of the project. Since the aim of the project was to develop a new accelerated test method for evaluating wear in inlay carpets, the problem was approached as product development task rather than an experimental trial and error process. To ensure a structured, transparent and systematic development process, product development methodologies were applied. The framework described in Product Design and Development by Ulrich and Eppinger [1] was selected, as it provides well defined tools for translating customer and stakeholder needs into feasible and well justified concepts. The methodology begins with requirement specifications which ensure that the developed test method addresses the internal requirements. Based on the defined requirements, a function-means tree was developed to systematically decompose overall function into sub-functions and identify possible solution principles. Idea generation and brainstorming techniques were used to explore wide solutions for each sub functions. The generated solution alternatives were evaluated and refined using elimination matrix, allowing infeasible or less promising solutions to be filtered out at an early stage. Morphological matrix was then used to combine different solutions alternatives into concepts. Finally, a pugh matrix was used to compare these concepts against the requirements, leading to the selection of most suitable concept for further development.

3.1 Product Synthesis

3.1.1 Requirement Specification

Ensuring that the New test method would effectively address the objective a structured approach to requirement specification is essential. The requirement were developed by combining requirements provided by Volvo cars and additional requirements derived from user studies and departmental discussions. The requirement specifications was divided into different categories and then sub-divided into Requirements. Each requirement was marked as Desire (D), meaning it must be fulfilled, or Wish (W), meaning it is beneficial but not essential. The requirements were then rated on the scale from 1-5 with 5 as most important. In addition, for each requirement justification and verification method was defined to explain why each requirement was necessary and how it can be tested or confirmed during the development process.

Need No.	Req/Desirable	Need	Important	Unit	Remarks
A. Functional requirement of the machine					
1	D	Pivoting motion of foot	5	Degree	Angle
				rpm	Rotating speed
2	D	Lateral motion between pedals	5	Distance (mm)	Left to right
				Distance (mm)	Forward and backward
3	D	Applied force on the carpeted area near the pedal at the heel location	5	Newton(N)	Force
				(Kg)	Weight/Mass
4	W	Jump in Jump out of Foot	3	Height/Distance (mm)	
5	W	Sufficient pressing the Pedal	3	Newton(N)	Force
				Degree	Angle
6	W	Seating Position of Taxi driver	3	Distance (mm)	
B. Environmental condition					
7	D	Dirt	4	gms	Quantity/weight
		Soil			
		Wet			
		Stones			
C. Heel type					
8	D	Taxi drivers may wear formal, Chelsea, sports, or block style shoes while driving.	4	Size (inch/feet/mm)	
				HRC	Hardness
D. Other Foot movement behaviour of Taxi driver					
9	W	Ingress and Egress motion of drivers foot	4	Counts	No. of cycles (How frquently)
				Newton(N)	Force on carpet

Figure 3.1: List of Requirement Specification

3.1.2 Function means tree

A function means tree was created to better understand the purpose of the project, it was performed in the early stages of the project as a foundational step. Instead of beginning with the proper machine or technical solutions, following this approach focuses on what the product should achieve. The function means tree began by identifying the main function of the product, which was to simulate the taxi wear (see figure 3.2). Focusing on this main function it was further broken down into technical solutions (Means) each representing a specific task or behavior required for the system to fulfill its overall purpose. The function-means model helped to visualize what the product must do but also helped to visualize how problems can be solved in different ways. Moreover, the function-means diagram also played an important role in the concept generation phase as it became the foundation for the morphological matrix by linking each function to multiple alternate solutions. The inherent structure of the function-means analysis proved beneficial for initial concept creation phase where system boundaries and use cases were still evolving throughout the design process.

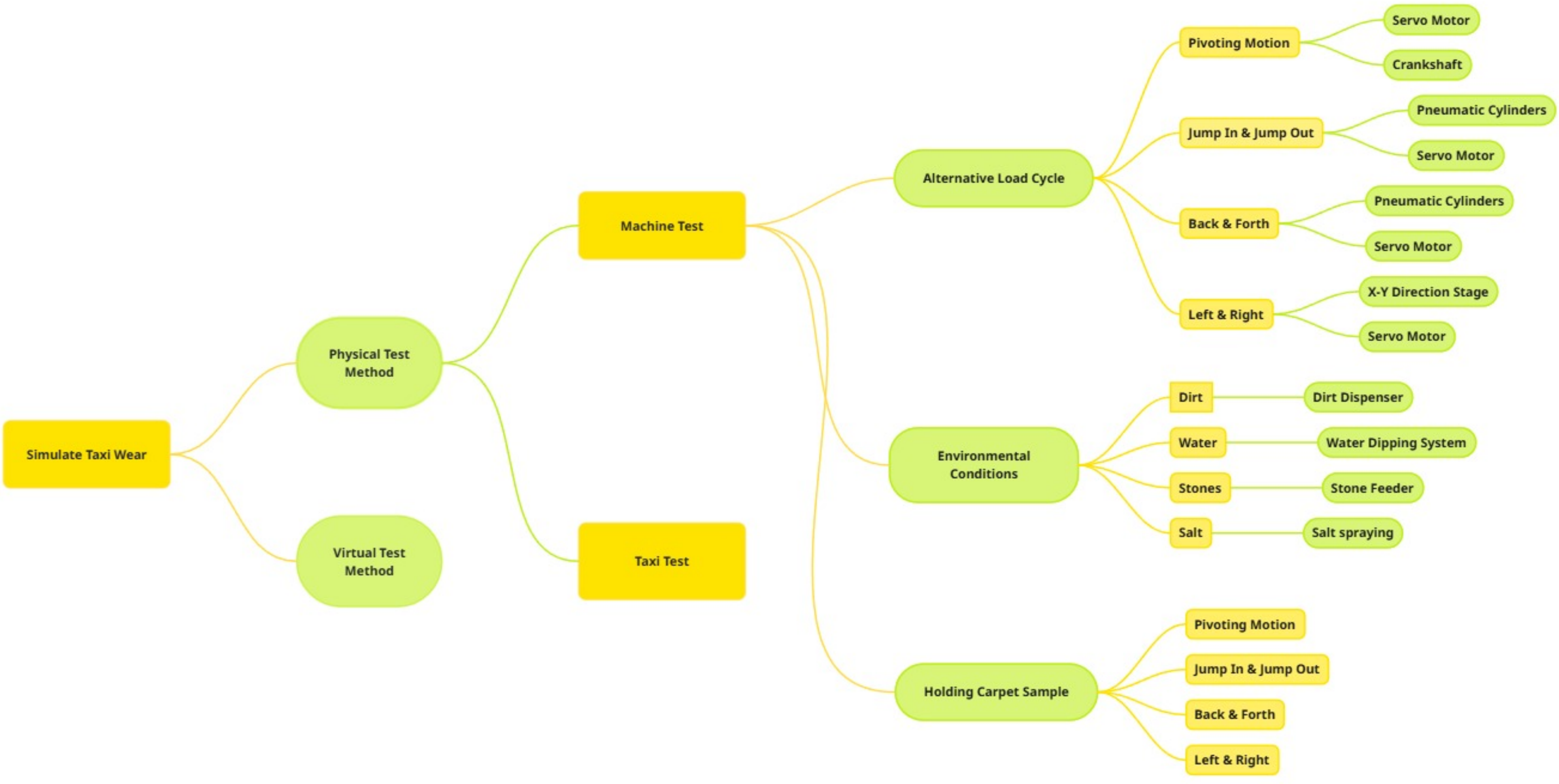
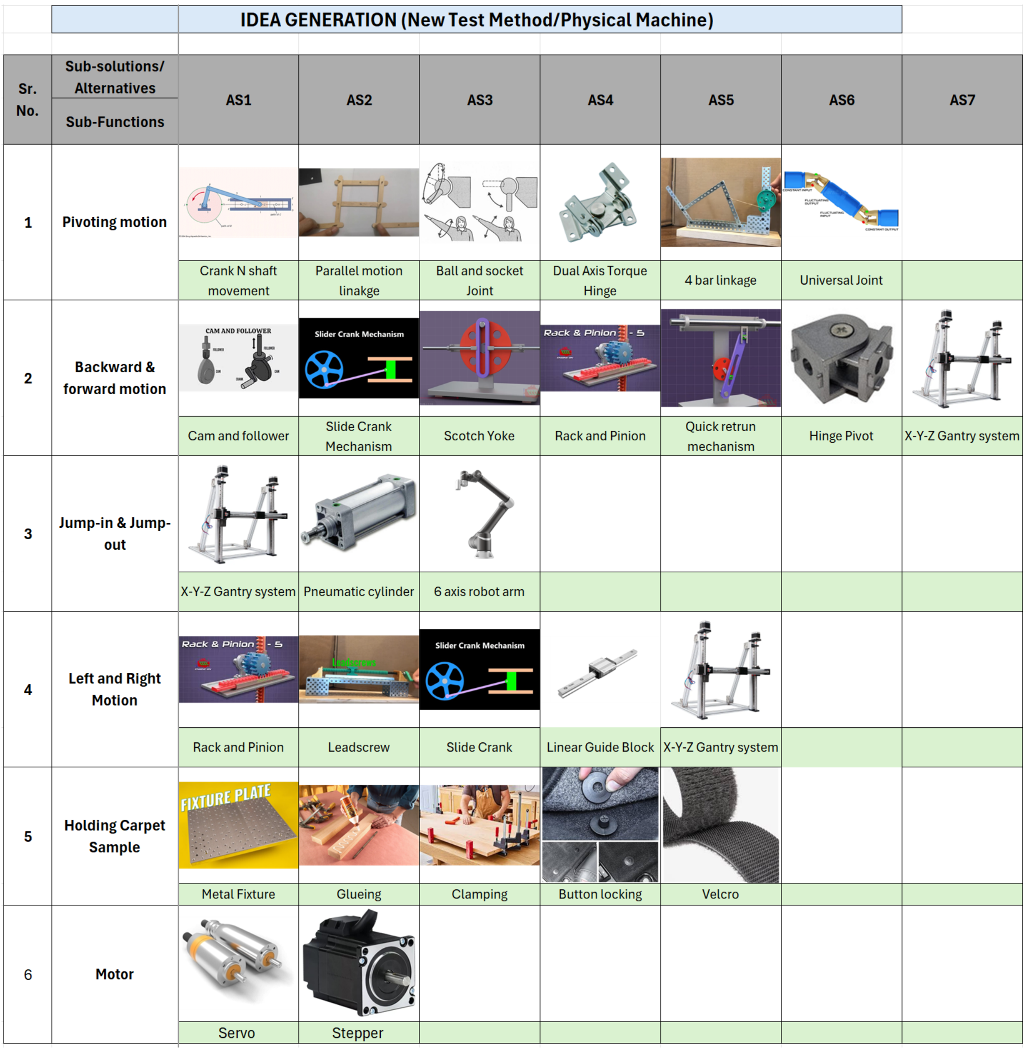


Figure 3.2: Functional Means Tree

3.2 Brainstorming & Idea Generation

Brainstorming is one the most common techniques used for idea generation during the product development process. Brainstorming was carried out at various stages throughout this project. In this process diverse and innovative ideas are generated. In this project, Idea generation was carried out according to the second and third step of five-step method proposed by Ulrich [1]. After defining the problem and identifying the functional requirements, the next task was to explore the possible solutions.This process started by breaking down overall problem into smaller sub-functions. For each sub-function, multiple solution alternatives were created. Brainstorming was carried out both individually and collaboratively. Initially, open-ended sessions were conducted without restrictions, wide range of ideas and solutions were welcomed, even those ideas that seemed unconventional. The focus at this stage was not to evaluate the feasibility of the solutions but rather was to generate as many possibilities as possible. Images, rough sketches and discussions were used to document these thoughts.



	IDEA GENERATION (New Test Method/Physical Machine)							
Sr. No.	Sub-solutions/ Alternatives Sub-Functions	AS1	AS2	AS3	AS4	AS5	AS6	AS7
1	Pivoting motion	Crank N shaft movement	Parallel motion linakge	Ball and socket Joint	Dual Axis Torque Hinge	4 bar linkage	Universal Joint	
2	Backward & forward motion	Cam and follower	Slide Crank Mechanism	Scotch Yoke	Rack and Pinion	Quick retrun mechanism	Hinge Pivot	X-Y-Z Gantry system
3	Jump-in & Jump-out	X-Y-Z Gantry system	Pneumatic cylinder	6 axis robot arm				
4	Left and Right Motion	Rack and Pinion	Leadscrew	Slide Crank	Linear Guide Block	X-Y-Z Gantry system		
5	Holding Carpet Sample	Metal Fixture	Glueing	Clamping	Button locking	Velcro		
6	Motor	Servo	Stepper					

Figure 3.3: Idea Generation

3.2.1 Elimination Matrix

Following the formulation of requirement specification and idea generation, elimination matrix was constructed to assess the proposed sub-solutions in relation to different criteria. Each sub-solution were assessed on three points: continue (+), remove (-) and more info needed (?). Each sub-solutions were evaluated on criteria such as Solve main problem, Fulfills all demand, Compatible /reliazable, reasonable cost, fits portfolio and enough information. Solution alternatives for each sub-function were then discussed with the rig team to evaluate their technical feasibility. These discussion helped us to determine whether a particular sub-solution could achieve the required motion or task and whether it could function in coordination with other movements such as pivoting, front-and-back movement and sideways motion. Ideas that were not suitable or were difficult to implement were eliminated . Out of 28 solution alternatives 11 were eliminated and 17 were continued. Eliminating such ideas early prevented unnecessary development of the concepts. Once the unsuitable alternatives were filtered out, the remaining ideas formed a set of building blocks for the next stage of design process. These surviving alternatives were then used to construct the concepts through morphological matrix. Overall, elimination matrix served as an effective tool for transitioning from broad idea exploration to structured concept development.

ELIMINATION MATRIX									
Sub-Functions	Alternative Solution	Solves Main Problem	Fulfils all demands	Compatibl e/Realizab	Reasonab le cost	Fits Portfolio	Enough Informatio	Comments	Decision
Pivoting Motion	AS1	(+)	(+)	(+)	(+)	(+)	(+)	Simple Mechanism	(+)
	AS2	(+)	(+)	(+)	(+)	(?)	(?)	Controlled motion, evaluation needed,need to think will it work with rest of mot	(+)
	AS3	(-)	(-)	(+)	(+)	(-)	(+)	Too many DOF, not controlled pivot	(-)
	AS4	(-)	(-)	(+)	(+)	(-)	(?)	Can't be integrated properly	(-)
	AS5	(+)	(+)	(?)	(+)	(+)	(+)	Suitable for controlled pivot	(+)
	AS6	(-)	(-)	(-)	(+)	(-)	(-)	Not suitable for pivoting at certain range	(-)
Back and forth	AS7	(+)	(-)	(-)	(+)	(-)	(-)	Can't be integrated properly with the other motions	(-)
	AS8	(+)	(-)	(-)	(+)	(-)	(-)		(-)
	AS9	(+)	(+)	(+)	(+)	(+)	(+)		(+)
	AS10	(+)	(?)	(-)	(+)	(?)	(?)	Not feasible to set up in machine	(-)
	AS11	(+)	(-)	(+)	(+)	(+)	(?)		(+)
	AS12	(-)	(-)	(+)	(+)	(+)	(+)		(+)
	AS13	(+)	(+)	(-)	(-)	(+)	(+)	Complex, expensive but motion can be achieved	(+)
Jump in & Jump out	AS14	(+)	(+)	(-)	(-)	(+)	(+)	Complex, expensive but motion can be achieved	(+)
	AS15	(+)	(+)	(+)	(-)	(+)	(+)	Costly, but if available inhouse then it's useful	(+)
	AS16	(+)	(?)	(-)	(-)	(+)	(+)	Motion possible, but too expensive.	(-)
Left and Right Motion	AS17	(+)	(-)	(-)	(+)	(-)	(-)	Complex,not optimal solution	(-)
	AS18	(+)	(+)	(+)	(+)	(+)	(+)		(+)
	AS19	(-)	(-)	(+)	(+)	(-)	(-)	Wrong motion	(-)
	AS20	(+)	(+)	(+)	(+)	(+)	(+)	Easy to implement and applicable	(+)
	AS21	(+)	(+)	(+)	(-)	(+)	(+)	Costly, but if available inhouse then it's useful	(+)
Holding carpet sample	AS22	(+)	(+)	(+)	(+)	(+)	(+)	Stable, strong ideal for machine testing	(+)
	AS23	(-)	(-)	(+)	(+)	(-)	(+)	Not reusable	(-)
	AS24	(+)	(+)	(+)	(+)	(+)	(+)	Flexible, easy and strong	(+)
	AS25	(+)	(+)	(+)	(+)	(+)	(+)	Stable, strong ideal for machine testing	(+)
	AS26	(-)	(-)	(+)	(+)	(-)	(+)	Unstable, not strong	(-)
Motor	AS27	(+)	(+)	(+)	(-)	(+)	(+)	Precise control, little epensive but okay	(+)
	AS28	(+)	(+)	(+)	(+)	(+)	(+)	Cheaper, less smooth	(+)

Criteria fulfilment:	
(+)	Yes
(-)	No
(?)	More info needed

Decision:	
(+)	Continue
(-)	Remove
(?)	More info needed

Figure 3.4: Elimination Matrix

3.2.2 Morphological Matrix

After generation of sub-solutions for respective sub-functions, the next step was to create the concepts with the help of morphological matrix which would be evaluated with pugh matrix. The purpose of morphological matrix is to explore all possible combinations of the sub-solutions in systematic way. The potential concepts that could generate from morphological matrix after eliminating solution alternatives were around 650 and it was not feasible to explore every single combination. Thus in order to reduce the number of concept it was decided to that each of us would generate 3 to 4 concepts.

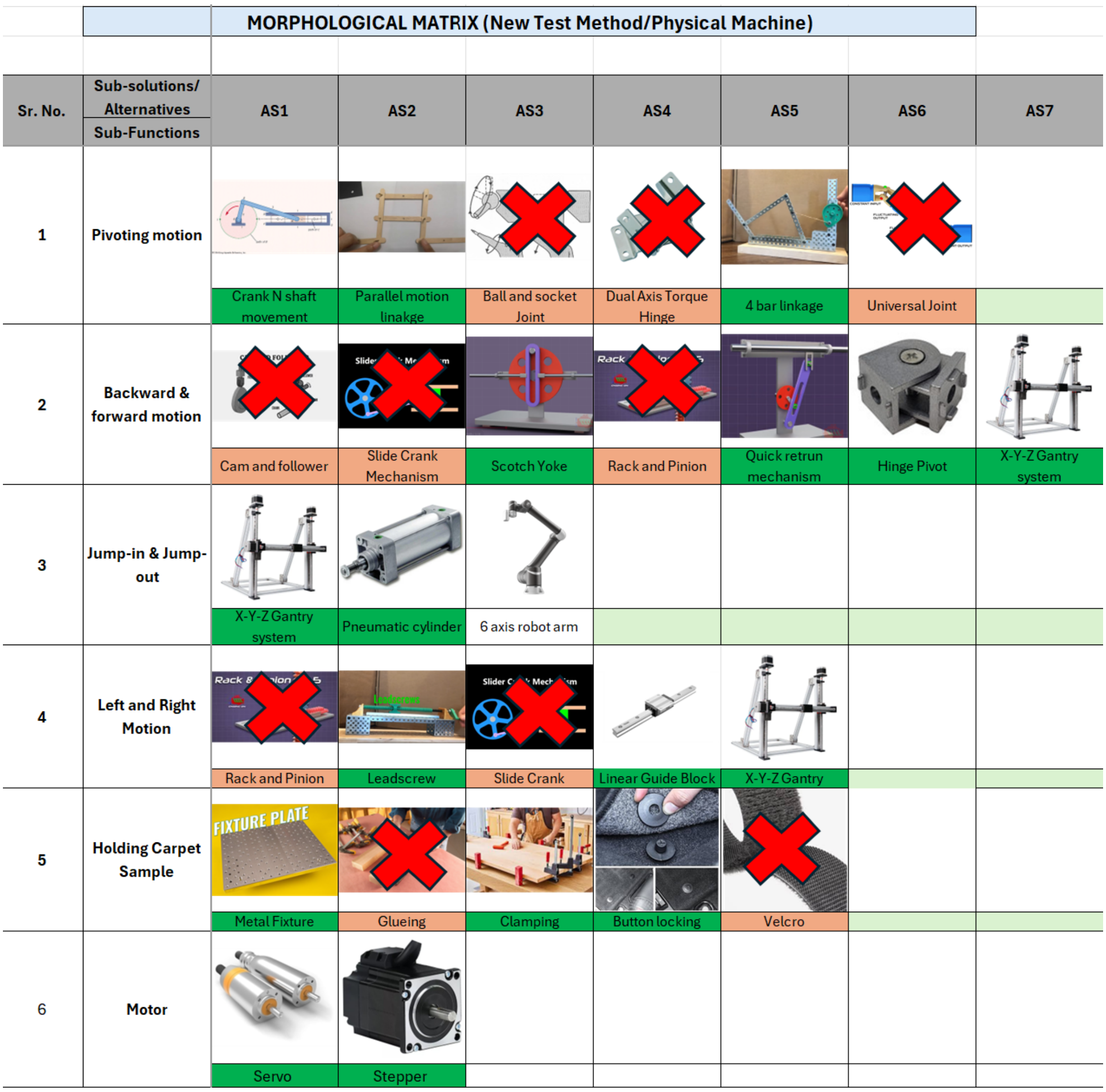


Figure 3.5: Morphological Matrix

3.3 Concept Generation & Concept Evaluation

Concept generation is a important phase in product development, in this process wide range of possible solutions are explored before narrowing it down to feasible concepts. This chapter includes the process of generating concepts and sketching them, evaluating the concepts and screening them using traditional product development methods. The concept generation phase was performed according to the five step method proposed by Ulrich et al., 2021 [1].

3.3.1 Concept Sketching

These 7 concepts generated using morphological matrix were sketched for better visualization and understand each solution. These sketches helped in assessing how machine might look in it's initial form. Moreover, sketching helped us to identify which components could be difficult to fit or install and assess whether they would work in coordination with rest of the machine.

Concept 1
The inspiration for Concept 1 is derived from human leg and foot movements while driving a vehicle, combined with basic mechanical linkage systems. This concept is designed to replicate the motions of a driver's lower foot during vehicle operation. As illustrated in the Concept 1, numbered annotations indicate different components and their respective functions. The mechanism incorporates four primary motions such as

1. Pivoting motion, achieved using a four bar linkage mechanism.
2. Left and right lateral motion, enabled by a linear guide block to which the central arm (aluminium extrusion) is attached.
3. Forward and backward motion, generated through a Scotch yoke mechanism.
4. Jump-in and jump-out (vertical) motion, accomplished using a hydraulic or pneumatic cylinder.

All motions are intended to be controlled via software input, allowing adjustment of parameters such as motion matrices, number of iterations and operational cycles.

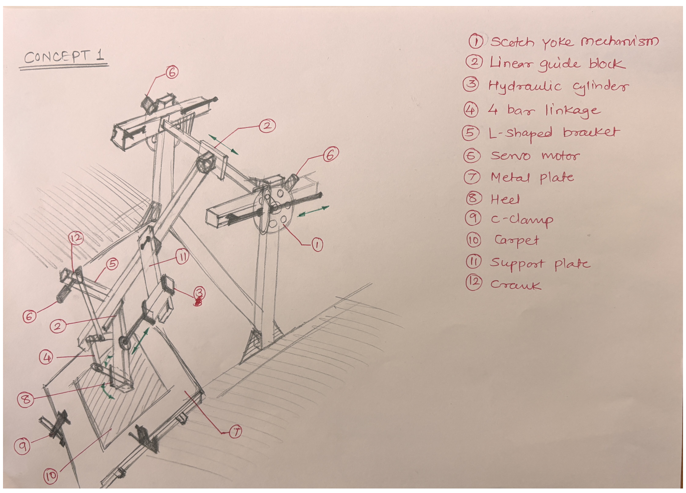


Figure 3.6: Concept-1

Concept 2

Concept 2 is based on a gantry-style mechanical system intended to replicate multiple human foot motions at a single location. The primary intention behind adopting a gantry configuration is to achieve left–right, front–back and vertical foot motions using a single, structured platform, while excluding pivoting motion. The system employs linear guides, timing belts and a motor-driven transmission mounted on an aluminium extrusion frame to ensure controlled and repeatable movement. This concept represents a preliminary, conceptual approach and its ability to accurately replicate realistic human foot kinematics, along with its economic feasibility, would require further analysis, simulation and cost evaluation.

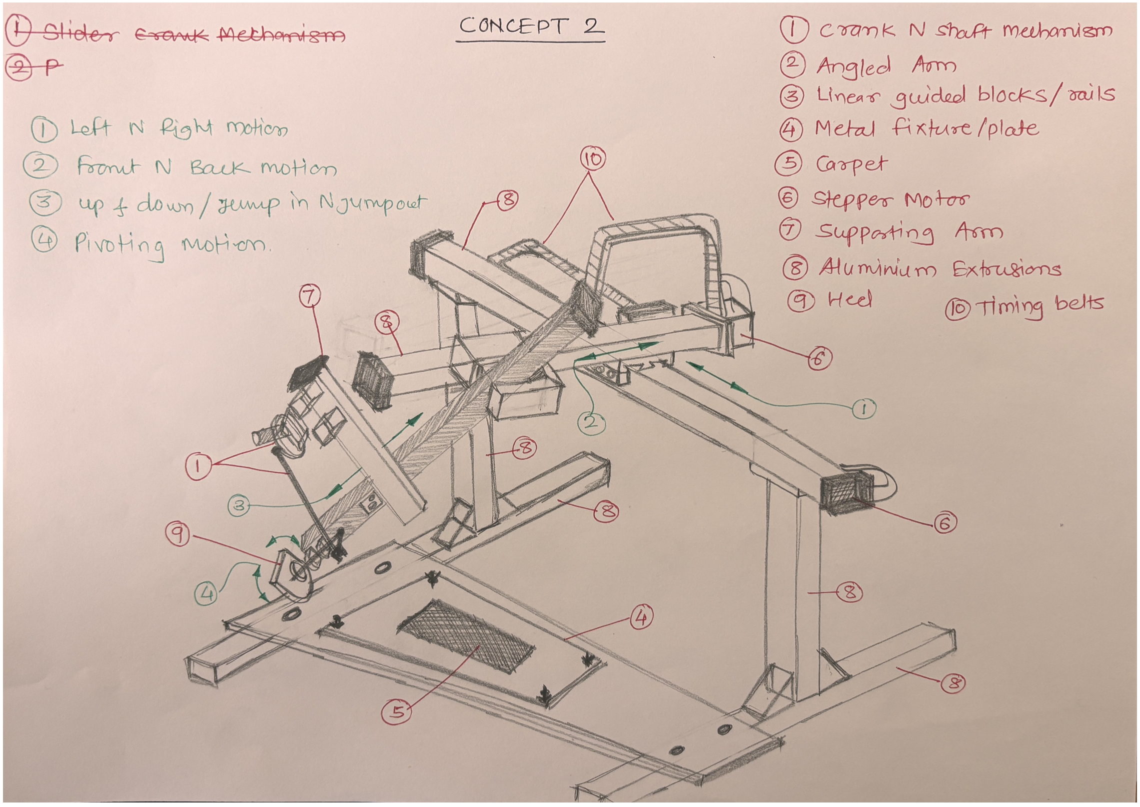


Figure 3.7: Concept-2

Concept 3

This concept takes on the mechanical attempt to have multi-degree-of-freedom foot motion through a series of linkage and guide-based mechanisms. Parallel linkage produces the pivoting motion, and a Scotch yoke mechanism produces front–back heel motion, while left–right motion is developed using a linear guide block. The vertical jump-in and jump-out motion is left out from the base concept but can be implemented with the addition of a pneumatic cylinder. Parallel linkage arrangement presents an advantage of accommodating two different types of foot fixtures simultaneously. This includes assembly, alignment, and integration considerations for mechanical complexity in the concept.

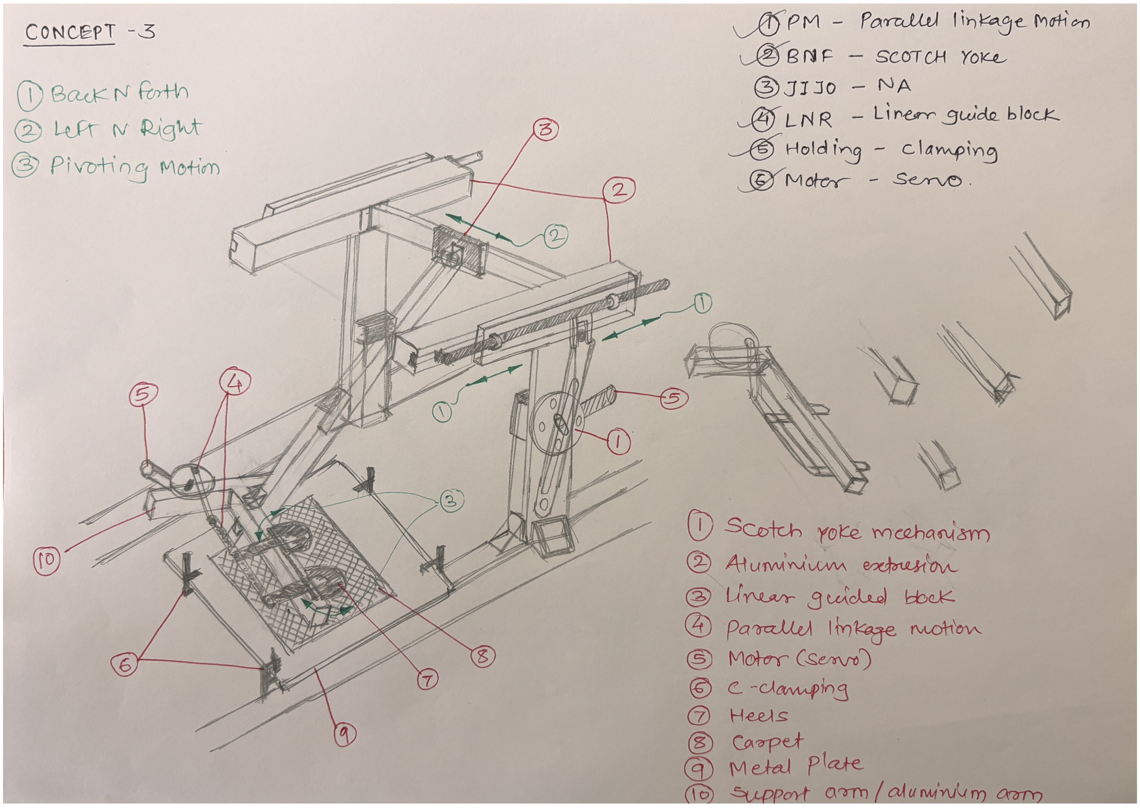


Figure 3.8: Concept-3

Concept 4

This conceptual design aims to streamline the mechanical architecture. This approach generates all required foot motions through a minimal set of mechanisms, each specifically tailored to its function. For instance, pivotal movement is achieved via a slider-crank mechanism, while a linear guide block restricts lateral motion. The forward and backward displacement of the heel is facilitated by a hinged arm, which is driven by a pneumatic actuator. Vertical movements, such as jump-in and jump-out, utilize either a pneumatic or hydraulic cylinder. This particular configuration offers reduced structural and assembly complexity compared to multi-axis or gantry-based systems. Nevertheless, a comprehensive evaluation remains necessary to assess motion accuracy, control precision and the impact of dynamic loading effects. This assessment will determine whether the generated motions sufficiently replicate real human foot behavior and get expected abrasion on carpet.

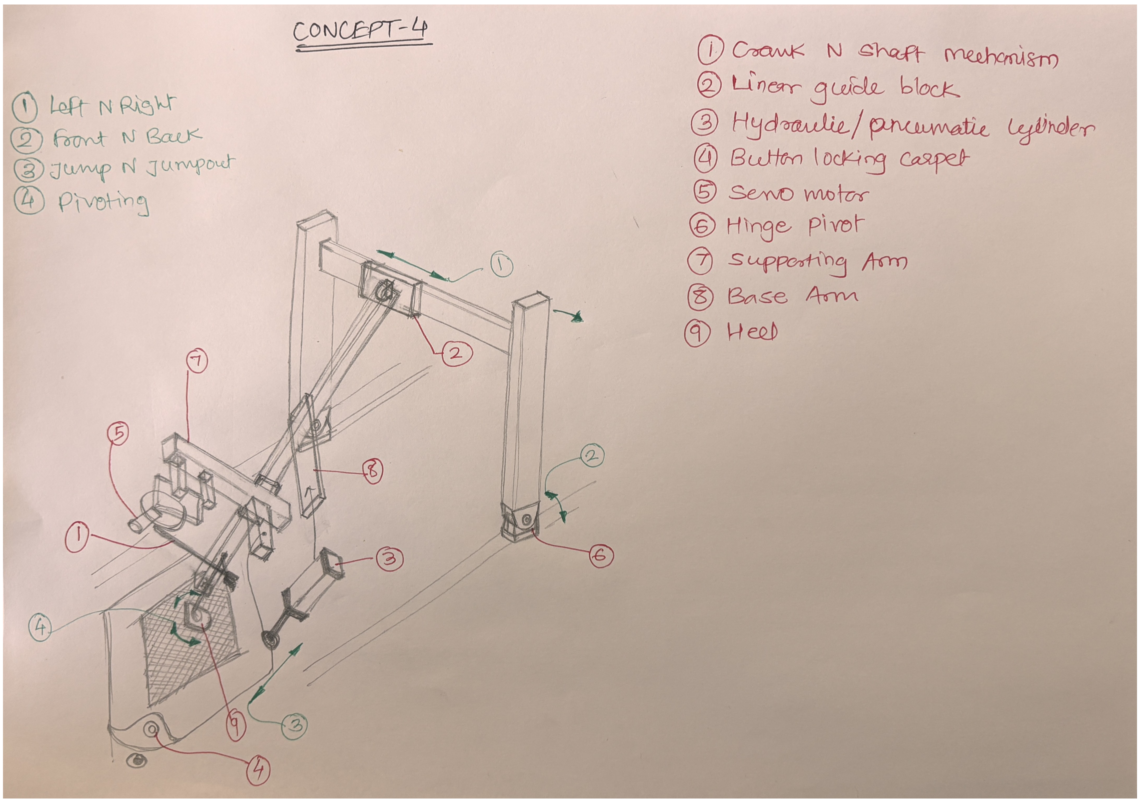


Figure 3.9: Concept-4

Concept 5

Concept 5 uses a gantry system combined with a four-bar linkage to create all the necessary foot movements. The gantry allows movements from side to side, front to back, and up and down (jumping in and out), while the four-bar linkage handles the pivoting motion separately. An angled aluminium arm links the pivot mechanism to the gantry carriage, helping coordinate their movements. A metal plate is added to hold and support the carpet evenly, keeping it stable during use. Although this setup allows flexible and controlled motion, attaching and fitting the angled arm is a tricky mechanical issue that needs careful design attention.

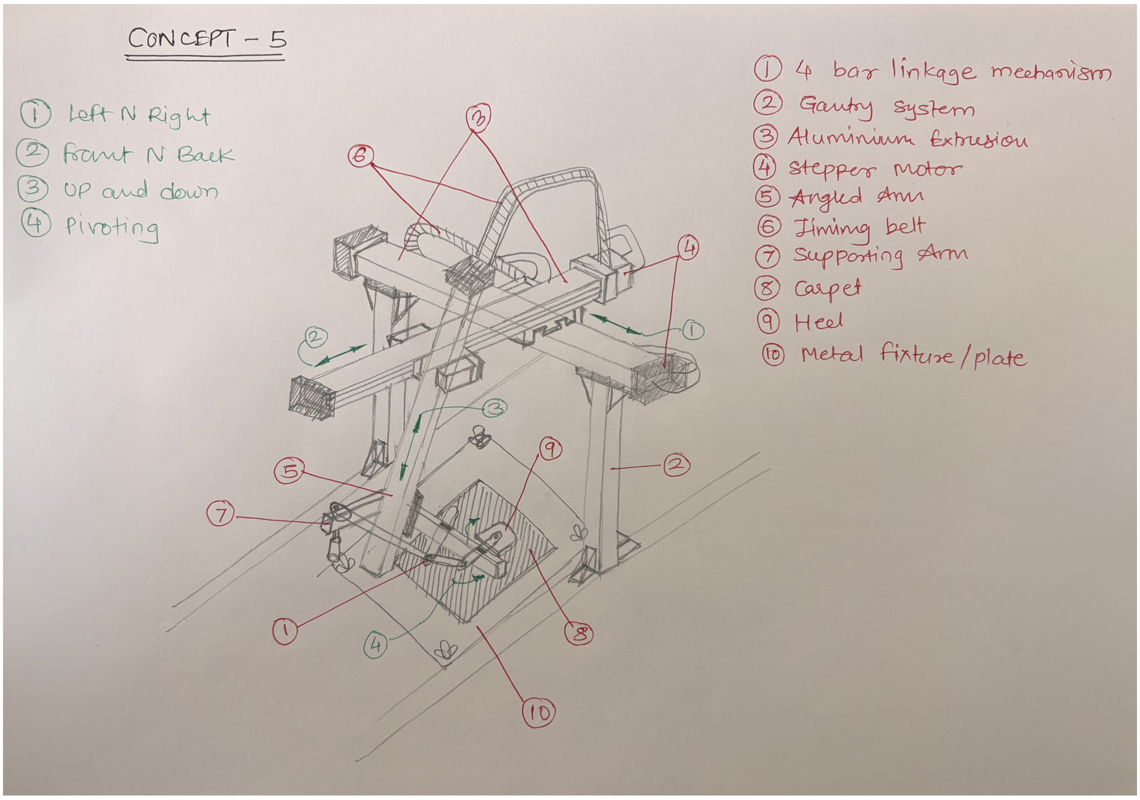


Figure 3.10: Concept-5

Concept 6
This concept uses a lead-screw mechanism driven by a servo motor to move an angled aluminium arm precisely from side to side. The pivoting action comes from a parallel linkage system, which makes it possible to install two different types of heels at the same time for comparison testing. Vertical movement, like jumping in and out, is handled by pneumatic cylinders. Front-to-back motion is provided by hinged pivot arms, which are supported by tension springs to help spread the load and keep things stable. To keep the carpet fixed in place during testing, button-type fasteners similar to those in car carpets are used for consistent positioning. This concept tries to strike a balance between accurate movement, realistic testing, and practical setup, but it's still at an early stage and needs further checks.

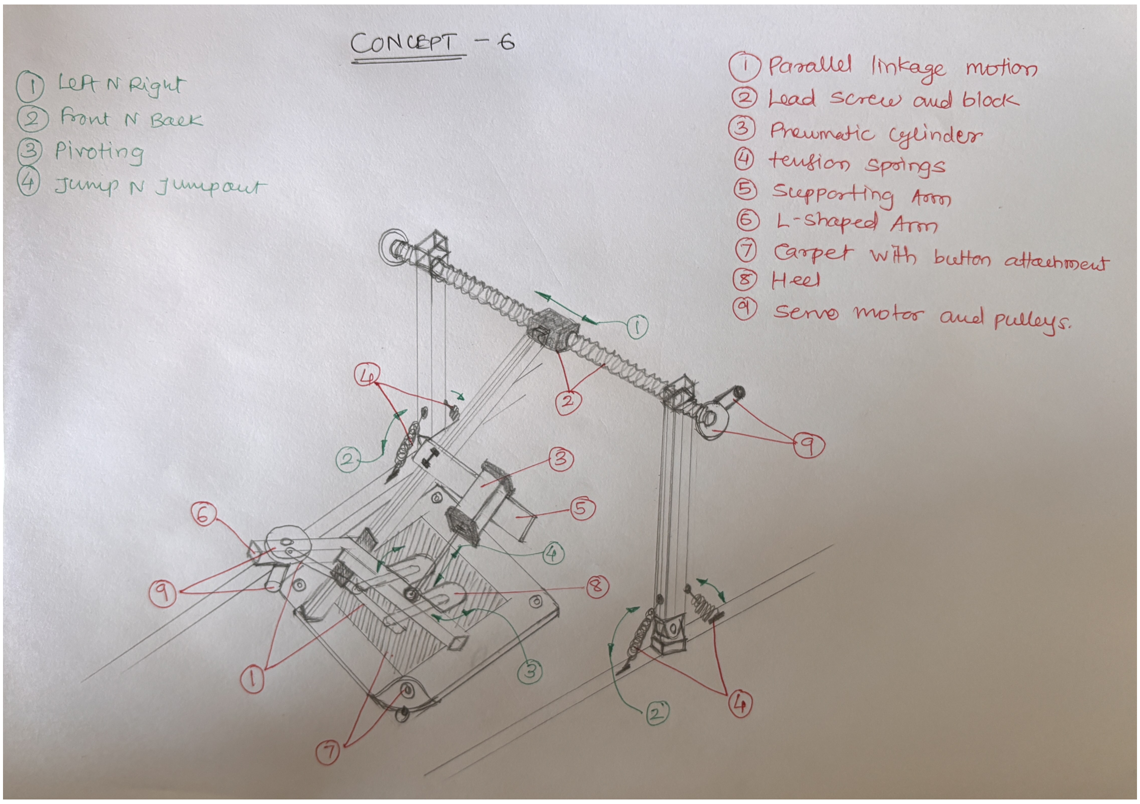


Figure 3.11: Concept-6

Concept 7

This concept combines several mechanical parts to create all four foot movements in one system. The front and back movement comes from a quick-return mechanism. Side to side motion is done with a lead-screw setup that uses a worm gear and servo motor. Pivoting is handled by a slider-crank mechanism and the up and down jumping motion relies on a pneumatic or hydraulic cylinder. A sturdy metal plate holds the carpet firmly, keeping its position steady and abrasion consistent during tests. While this concept covers all the needed motions, its mechanical design is quite complex, which makes synchronization and reliability difficult, so it stays only as an idea for now.

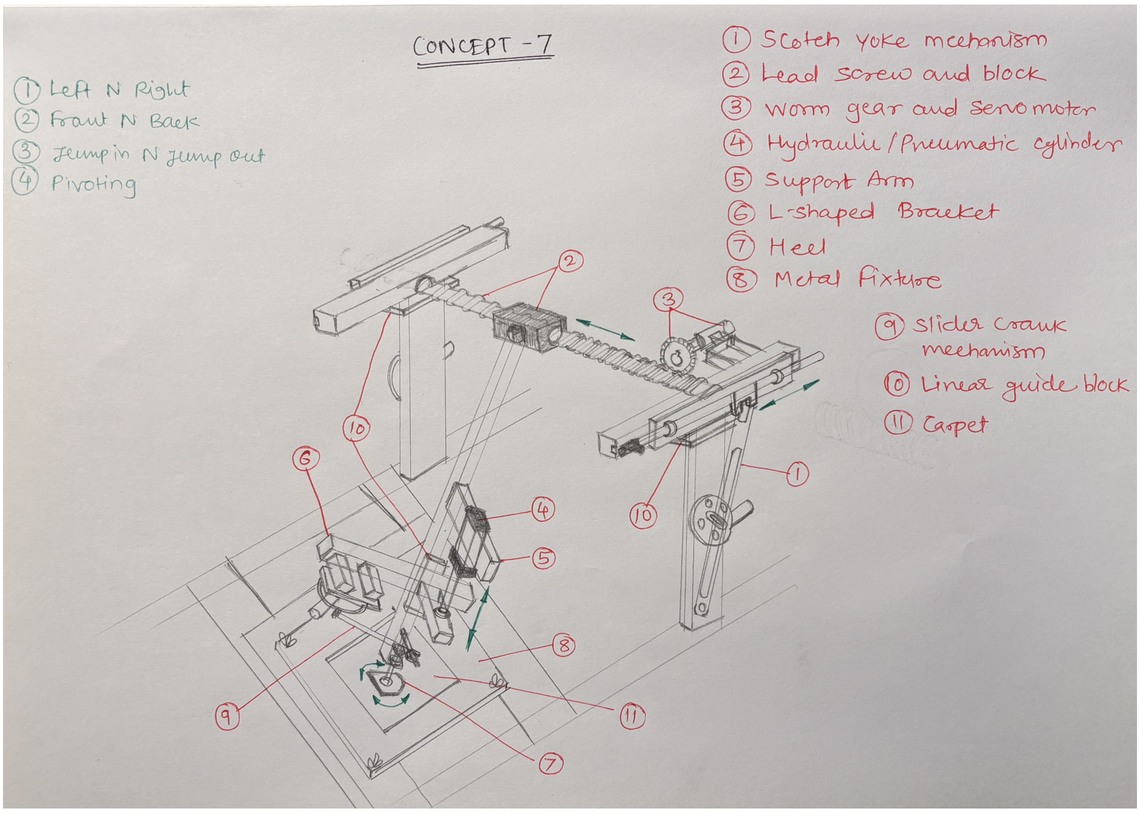


Figure 3.12: Concept-7

3.3.2 Pugh Matrix

After the morphological matrix was complete and concepts were generated, a systematic approach for evaluation of concepts was used. The method that we used for evaluating the concepts was pugh matrix as it allows the concepts to be weighted based on criteria relative to a reference product. Pugh matrix was constructed using criteria that were inspired by requirements. Moreover, one of the generated concept was used as a reference (datum). This reference concept served as a baseline for comparison and all other concepts were evaluated as being better, equal or even worse. The results of pugh matrix showed that Concept 2 and Concept 4 performed better from the rest of the concepts. These 2 concepts emerged as the strongest concepts for further development. The pugh matrix provided a clear and systematic way to narrow down the concepts and ensured that selection process was based on comparison rather than subjective judgement.

Sr. No.	Demands /Wish	Criterion	Concepts/Alternatives						
			C3(Ref)	C1	C2	C4	C5	C6	C7
1	D	Overall M/c Performance		+	+	+	+	-	0
2	D	Easy to operate	D	-	+	+	+	-	0
3	W	Cost efficient	A	-	-	-	-	+	+
4	W	Suitable for long run	T	0	+	+	+	-	0
5	W	Maintainability	U	-	+	+	-	-	-
6	D	Easy Assemble	M	-	+	+	-	-	-
7	W	Durability of parts		0	+	0	+	0	+
		Σ+		1	6	5	4	1	2
		Σ-		5	2	2	4	6	3
		Σ0		2	0	1	0	1	3
		Net value		-4	4	3	0	-5	-1
		Ranking		5	1	2	3	6	4
		Further Development		No	Yes	Yes	No	No	No

Overall M/c Performance	How well the concept mimics the foot motion?
Easy to operate	Carpet fitting > Heel change > Placing the foot > Adjusting the weight > Start n Stop > Easy to control?
Cost efficient	Simple mechanism, Less Expensive components
Suitable for long run	Continuous operation possible ?, Performance over time.
Maintainability	Easy to repair and service? Standard Components ? Easy to access ?
Easy Assemble	No of parts ? Ease of building system ?
Durability of parts	Are components robust ?

Figure 3.13: Pugh Matrix

3.4 Final Concept

After completing Pugh matrix, 2 concepts - Concept 2 and Concept 4 were selected for further consideration. These concepts were presented to the rig team and brainstorming session was held to discuss about their feasibility for developing proof-of-concept (POC). Based on the feedback from the rig team, Concept 4 was ultimately chosen as the most suitable option for proof-of-concept (POC) (see figure 3.9).

Reason behind selection of concept 4 is because of it's design characteristics and implementation feasibility. Compared to concept 2, concept 4 was easier to manufacture, less complex in structure and more cost-effective. An additional factor influencing the selection of concept 4 was the orientation of heel and lower leg. In real driving conditions, the driver's lower leg and heel are positioned at an inclined angle rather than acting perpendicular to the floor. Concept 4 allows the heel and lower leg to be implemented in slant orientation, replicating the natural posture of driver's leg.

In contrast, gantry system has vertical suspended actuators operating along x-y-z axes. Moreover, it is possible to install the inclined mechanism within gantry system but doing so would require additional structural components and control adjustments. This might increase the complexity of the system. For a proof-of-concept aiming at realistic motion, concept 4 provides a simpler and more effective method.

The proof-of-concept will be used to test the carpets made from mono-polymer material and the abrasion patterns will be compared with those obtained from taxi tests. If the outcome shows good alignment between the results the POC can be adopted as a standardized test method within Volvo cars for evaluating all carpets in their inventory. If discrete patterns are observed the machine will undergo further refinement to improve the accuracy of the test results.

4

Designing & Testing

The Design process started with the identifying and evaluating of multiple concepts using morphological matrix and pugh evaluation. From that, two feasible and practical concepts were selected for further development based on their less complexity, cost effectiveness and performance for POC.

The selected concepts were carried out into detailed design stages of the product development process, where virtual modeling and simulation were conducted before physical POC. Siemens NX was selected as the primary tool for CAD modelling due to its advanced capabilities and our prior hands-on knowledge with the software[30]. Having familiarity with the tool allowed for efficient modelling, reduced learning time, and better utilization of its features such as parametric design, assembly constraints and motion simulation. Additionally, Siemens NX provides an integrated environment for both modelling and analysis, making it suitable for the complete design workflow.

4.1 Concept Description

Based on the insights obtained from the user study, certain design decisions were refined to improve feasibility and practicality. Initially, the proof of concept (POC) was developed by focusing on two primary motion parameters such as pivoting and sideways motion. These motions were prioritized as they were more feasible to implement within the given constraints and allowed effective validation of the core functionality. The third and fourth motions, which involve forward and backward as well as jump-in, jump-out movement, was intentionally prolonged to a later stage due to its construction concerns. This phased approach helped in reducing initial design complexity while still achieving meaningful functional validation.

In parallel, the second selected concept was based on a gantry system, which offered greater motion accessibility and higher degrees of freedom with fewer operational constraints. However, upon further evaluation, it was observed that the construction of this concept was comparatively more complex and involved higher costs when compared to Concept 1.

Considering these factors, the development process proceeded with Concept 1 for the initial prototype due to its simplicity, feasibility and cost effectiveness. Nevertheless, Concept 2 remains a viable alternative and may be considered for future development and optimization by the company, if improved functionality is required.

4.2 Component construction and requirements

The modelling process started by developing the selected concept into a detailed design. To keep the process structured and manageable, the design was divided into three main stages: (1) base assembly and fixture placement, (2) angled extrusion arm assembly and (3) the fourth motion assembly. This staged approach was inspired by a modular, Lego-like method, allowing us to build and refine the system step by step. These stages included proper assembly of parts and their dimensional information for each individual component, which helped in accurately translating the conceptual ideas into 3D models. All parts of assembly were modeled using appropriate design parameters.

4.2.1 Base assembly and fixture placement

In the base assembly, there were two main aspects that needed to be prioritized: the base arms and the plates used for fixing the carpet along with their attachments. To begin with, aluminum extrusions of size 40 × 80 × 1150 mm were used and positioned with a spacing of around 320 mm between them.

Using the slots in these extrusions, a square metal plate referred to as the base plate was mounted with the help of bolts and nuts. Once this was secured, holes were drilled at the four corners of the metal plate to allow the aluminum fixture plate to be installed on top of it. A square pocket was then created at the center of the fixture plate to enable proper contact between the rubber heel and the carpet surface.

Following this, two aluminum arms measuring 40 × 80 × 587 mm were positioned vertically and fixed in place using a linear guide assembly. To complete the structure, another extrusion arm of length 400 mm was attached across the top ends of these vertical arms, forming the upper connection. This forms the complete base assembly along with its key supporting components.

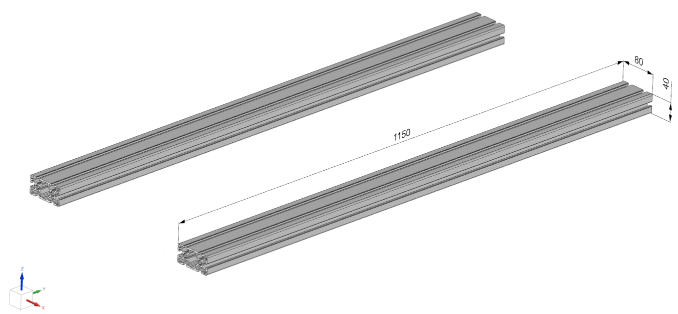


Figure 4.1: Aluminium Extrusion Arm

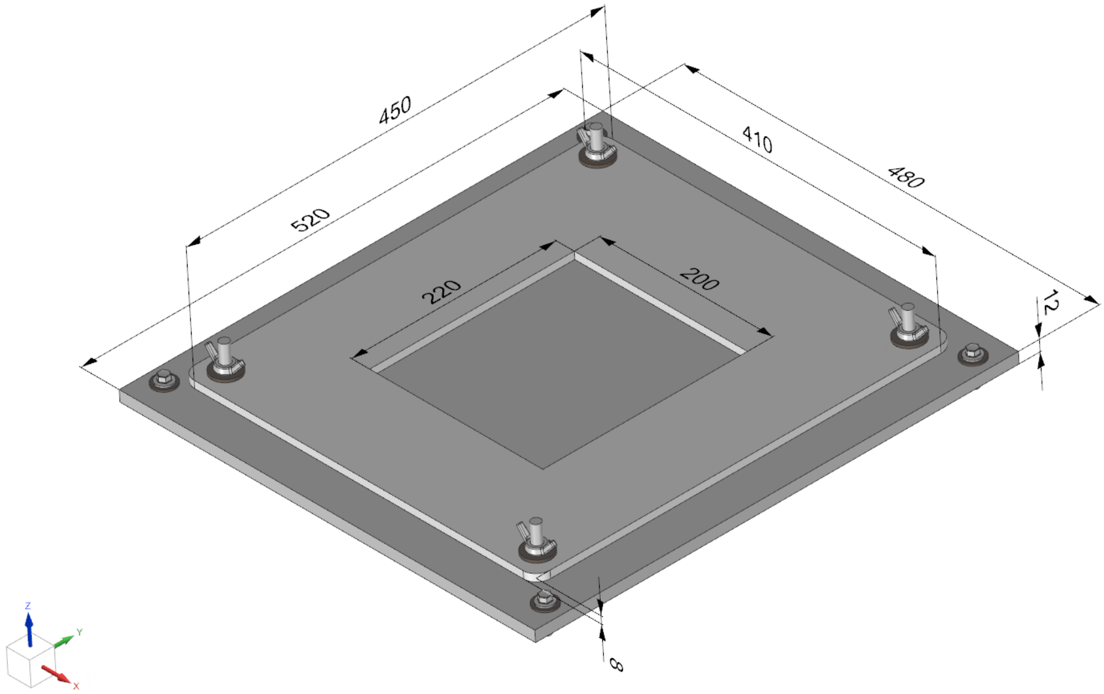


Figure 4.2: Base plate and Fixture plate assembly

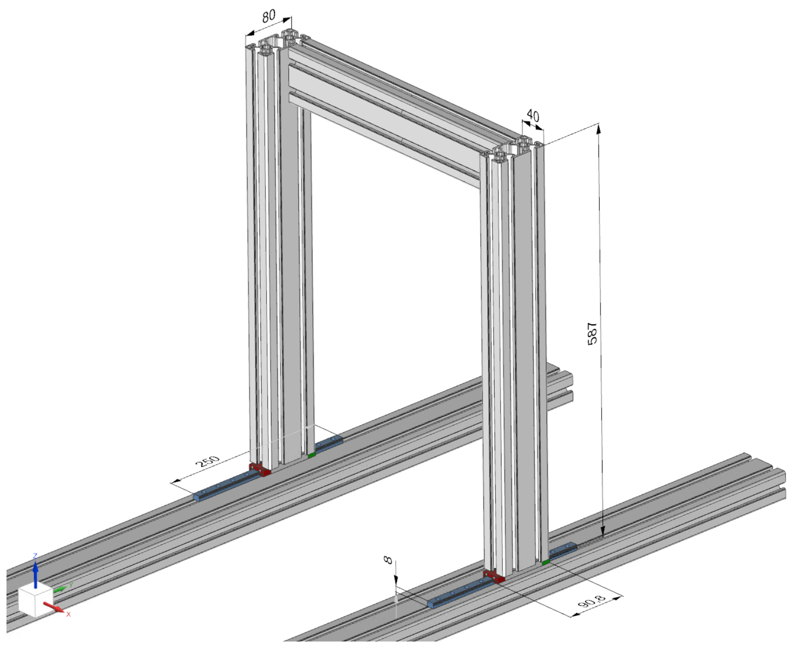


Figure 4.3: Vertical arms placement

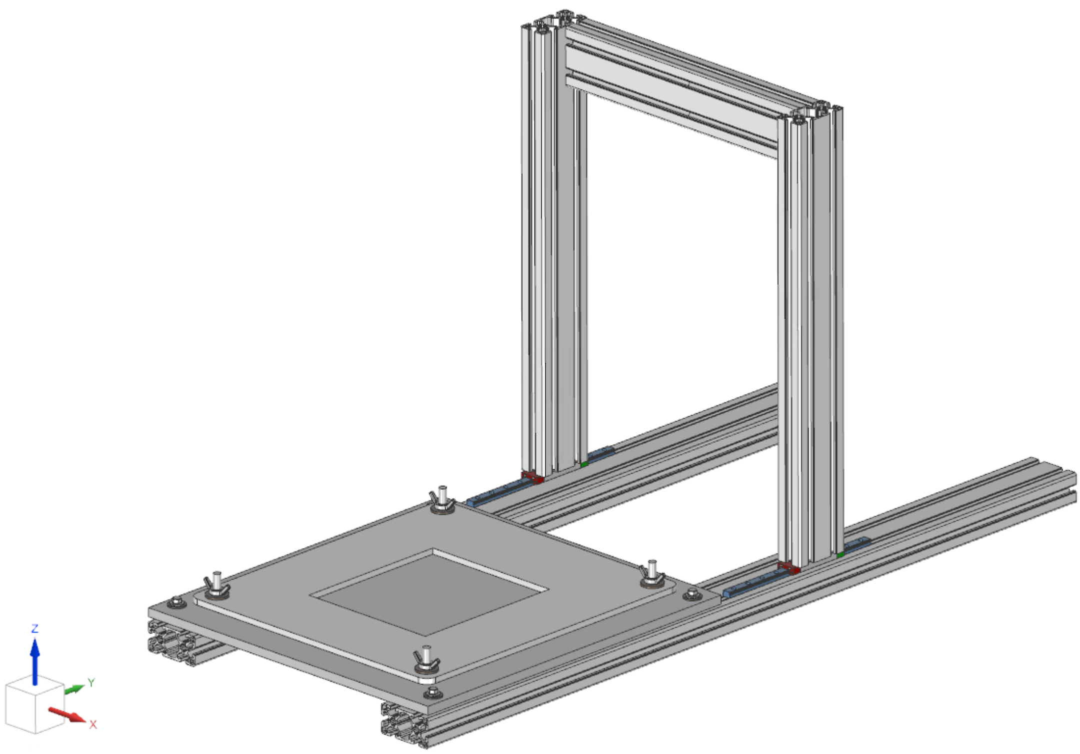


Figure 4.4: Base assembly

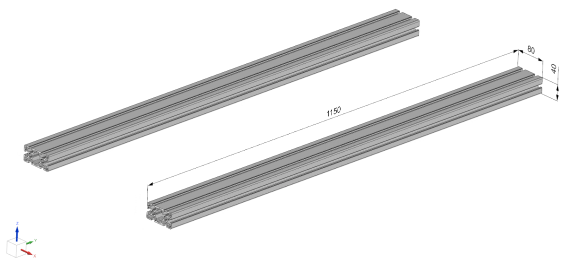


Figure 4.5: Caption

4.2.2 Angled extrusion arm assembly

After completing the base assembly, the next step was to develop the angled arm assembly, where three types of foot motions needed to be implemented: sideways motion, pivoting motion, and the jump-in jump-out motion.

To begin with, sideways motion was considered. In real driving conditions, a driver's right foot moves at an angle between the brake and accelerator pedals. To replicate this behavior, an aluminum arm measuring 40 × 40 × 655 mm was mounted at an angle of approximately 48 degrees from the base. A smaller support arm of size 40

$\times$ 40 $\times$ 180 mm was added to provide additional stability. A linear guide block was then attached to this setup, enabling smooth sideways movement.

For the pivoting motion of the heel, a slider crank mechanism was used. This mechanism was driven by a servo motor to achieve controlled movement. To support and position this mechanism, four aluminum extrusion blocks of different sizes were arranged in an F-shaped configuration. To hold the heel securely, two metal plates shaped according to the heel profile were fixed, allowing the heel to be properly positioned between them. Additionally, a U-bracket was installed to guide the motion of the slider crank mechanism in the desired manner.

Finally, the jump-in jump-out motion was implemented using a pneumatic cylinder combined with a linear guide block. This setup allowed the entire slider crank assembly to move forward and backward as required. With this configuration, all three motions sideways, pivoting, and jump-in jump-out were successfully integrated into the angled arm assembly. The corresponding components and assembly views are shown below.

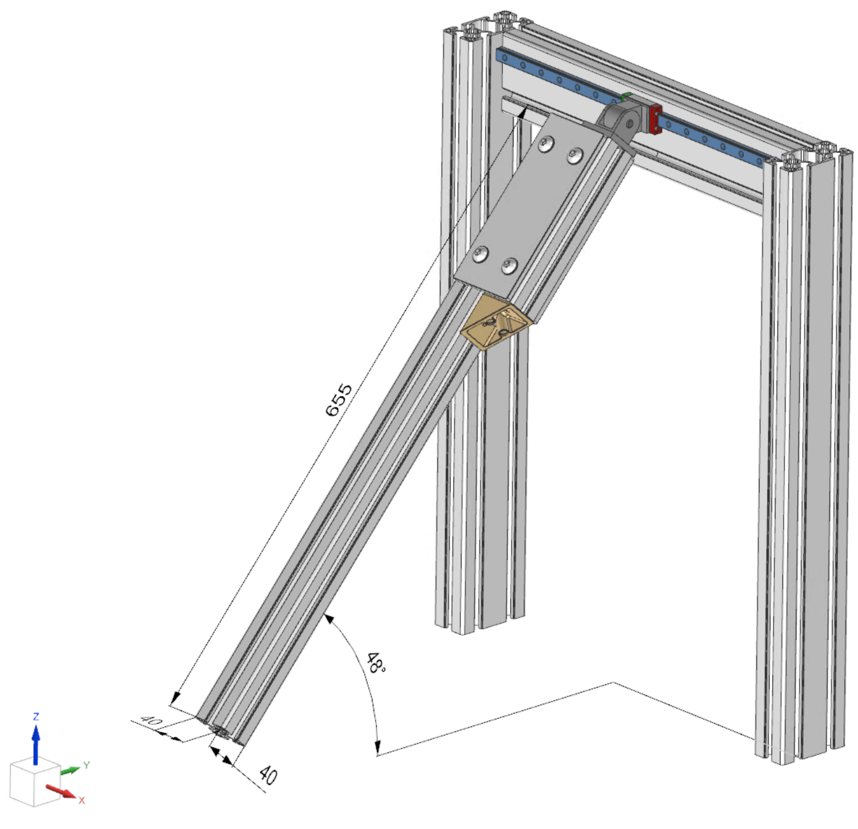


Figure 4.6: Angled aluminium extrusion arm

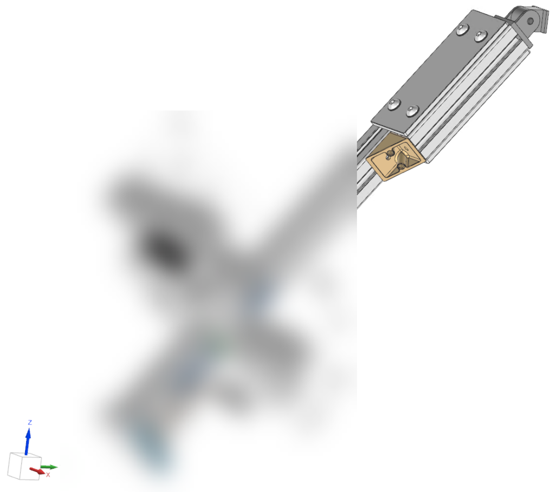


Figure 4.7: Angled arm with Pivoting motion mechanism

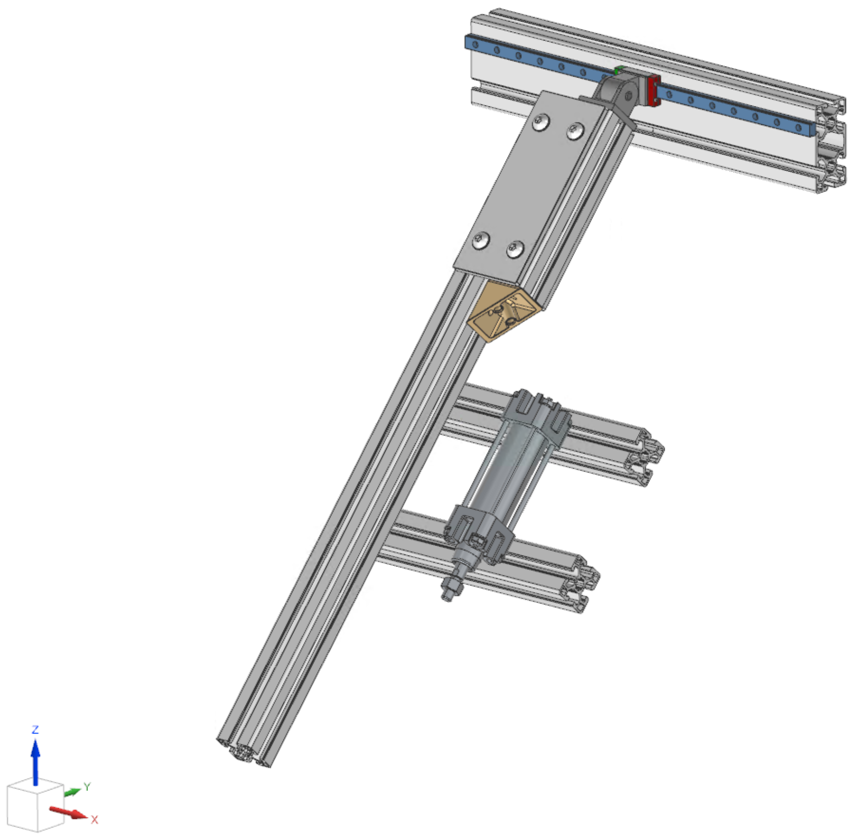


Figure 4.8: Jump-in, jump-out motion mechanism

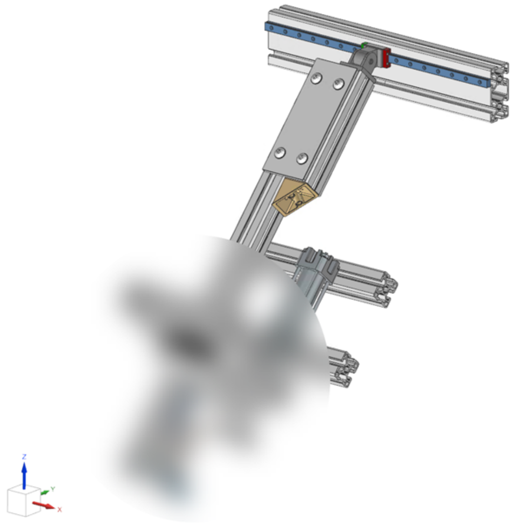


Figure 4.9: Angled Arm Assembly

4.2.3 Fourth motion assembly

After implementing the three primary motions, the system still needed one final movement to complete the full range of motion forward and backward. This was achieved by integrating pneumatic cylinders into the setup. Since linear guide blocks were already installed on the two vertical arms in the base assembly, the cylinders were used to drive these guides and enable controlled back and forth motion. With this addition, all four key foot motions of a driver responsible for carpet abrasion were successfully replicated using a combination of different mechanisms and attachments. The photos of the final motion are as follows.

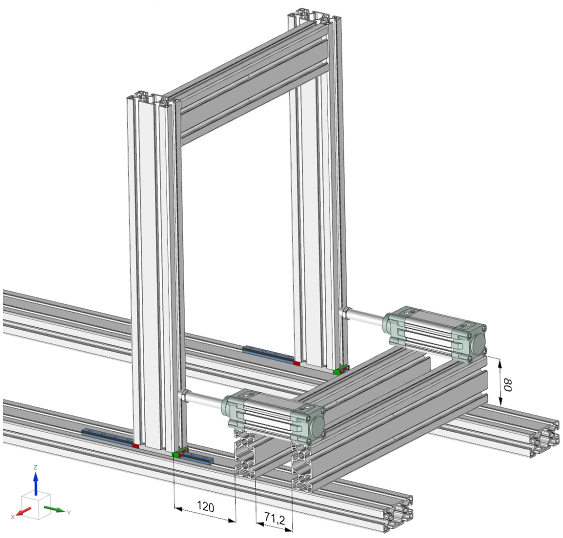


Figure 4.10: Front and back motion placement

4.2.4 Bill of Material (BOM)

A simplified Bill of Materials (BOM) was prepared to identify the key components required for POC development. Due to project confidentiality, detailed specifications such as exact dimensions and component details are not disclosed. Instead, a generalized representation of components is provided.

BILL OF MATERIAL

PRODUCT NAME	TEST RIG_POC	CONTACT INFO
APPROVED BY	RIG Department_VOLVO CARS	
DATE OF APPROVAL	NA	
PART COUNT	0	
TOTAL COST	NA	

PART NUMBER	PART NAME	DESCRIPTION	QUANTITY	UNITS
1	Aluminium Extrusion_1	40X80X1150	2	mm
2	Aluminium Extrusion_2	40X80X587	2	mm
3	Aluminium Extrusion_3	40X80X400	1	mm
4	Aluminium Extrusion_4	40X40X655	1	mm
5	Aluminium Extrusion_5	40X40X180	1	mm
6	Aluminium Extrusion_6	40X40X350	1	mm
7	Aluminium Extrusion_7	40X40X150	2	mm
8	Aluminium Extrusion_8	40X40X100	1	mm
9	Aluminium Extrusion_9	40X40X243	2	mm
10	Metal Square plate	Base plate attached with Al_Ex_1 520X480X12	1	mm
11	Metal aluminium fixture plate	Attached with metal square plate 450X410X8	1	mm
12	U-Bracket	Attached with Al_ex_4 40X40X47	1	mm
13	Linear guide assembly_1	Attached to two vertical Al_ex_2 12X8X250	2	mm
14	Linear guide assembly_2	Attached to horizontal and angled arm 12X8X400	1	mm
15	Linear guide assembly_3	Attached with Pivoting motion assembly 12X8X235	1	mm
16	Rotary Hinge	Attached with Al_ex_4 and horizontal Al_ex_3 (std.)	1	mm
17	Maxial track hoist	for fixing Metal aluminium fixture plate (std.)	4	mm
18	Pneumatic Cylinder_1	For Jump in Jump out motion (std.)	1	mm
19	Pneumatic Cylinder_2	For Front and Back motion (std.)	2	mm
20	L-shaped bracket	To intact complete assembly (std.)	14	mm
21	Aluminium rectangle plate	To fix Al_ex_arm_4 & 5 180X74X6	2	mm

Figure 4.11: Bill of Material

4.3 Design Evaluation and Final Approval

At the beginning of this stage the collaboration with the rig team played an important role throughout the design process. Initially, the two selected concepts were reviewed and approved by the rig team based on their feasibility and practical applicability. This early alignment ensured that the design direction was consistent with implementation requirements.

After completing the CAD modelling of both concepts, a cross-verification was carried out to evaluate whether the designs would function effectively in a real world setup. This included reviewing the assembly structure, motion behavior and overall practicality of the designs.

Following this internal validation, the designs were again presented to the rig team for further review. The purpose of this step was to confirm that the developed models met the necessary operational expectations and could be practically realized. Based on this joint validation, the rig team proceeded with the development of one of the selected concepts for the initial POC.

This process of interaction between the design and rig team ensured that the final design was not only working virtually but also practically feasible and ready for physical implementation.

4.4 Testing carpets on POC

Carpet testing was carried in Proof of Concept (POC) setup developed to simulate realistic foot movement and loading conditions. This section describes the carpet installation procedure, test parameters, motion characteristics, load applied, heel specifications, and environmental conditions used during testing.

4.4.1 Carpet Installation on POC Setup

The testing started with the installation of carpet samples onto the POC testing machine. Full-size carpets were not used, instead the carpets were cut into smaller parts suitable for mounting under the metal plate. A 10 x 10 cm block was defined on the metal plate for testing. The carpet samples were positioned below the metal plate to restrict any unwanted movements during the test. Initially, only inlay carpet sample was placed under the metal plate, which resulted in slippage during testing, as the contact between the metal plate and inlay carpet did not provide sufficient friction. To address this issue, a base carpet layer was placed below the inlay carpet sample. This additional layer improved frictional stability and ensured that the test carpet remained stationary throughout the testing.

4.4.2 Carpet Types

The following types of carpet were evaluated during the POC tests:

- Pattern 1 carpet made of Polyester (PES).
- Pattern 2 carpet made of Polyamide (PA).
- Pattern 3 carpet made of Polyester (PA).

Each type of carpet was tested until breakage of the yarn was observed. The total number of cycles completed and the corresponding time duration was recorded for comparative analysis.

4.4.3 Test Motion and Cycle definition

The motion applied on the carpet surface was designed to replicate repetitive foot movements. A front-back-front movement of the arm was defined as one complete cycle. Moreover, the duration of one cycle was approximately 10-12 seconds. The motion was maintained continuously until the failure criteria were met.

4.4.4 Load Application and Operating Parameters

The weight of the arm acted on the carpet was approximately 3kg and the angle of the arm was maintained at 55.5°. In addition, the front and back motion of the arm was executed using pneumatic cylinders while the sideways motion was achieved through pivoting mechanism. The combined motion was continuous throughout the testing process. The system was operated using a power source with an applied voltage of 7.58 V.

4.4.5 Heel Specifications

For testing the carpets two different Shore A type heels were used to simulate realistic footwear conditions.

- Heel 1 with Shore A hardness of 90.1.
- Heel 2 with Shore A hardness of 89.

Figure 4.12: Heel 1

Figure 4.13: Heel 2

4.4.6 Environmental Conditions

To better replicate driving conditions, environmental contaminants such as dirt, small stones were introduced during testing. These contaminants were manually sprinkled onto the carpet surface during operation. This approach enabled the evaluation of carpet performance under combined mechanical and environmental influences.

Figure 4.14: Carpet with Stones

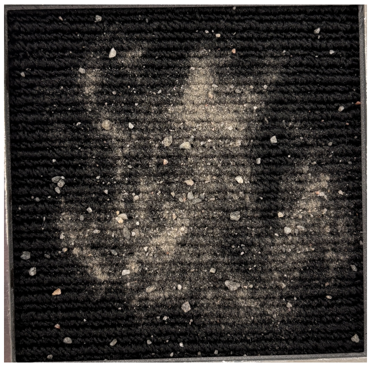


Figure 4.15: Carpet with Dirt, Stones & Water

4.5 Results

Abrasion tests were performed using the POC machine to evaluate the wear of inlay carpets. The test was conducted for a varying number of cycles until the yarn broke. The tests included 3 different types of carpet, two types of heel, and different environmental conditions. The tests were carried out perpendicular to the loop and parallel to the loop direction for all the carpets.

4.5.1 Influence of carpet structure on Abrasion

The results showed that the carpet structure plays an major role in abrasion resistance and wear performance. Carpets responded differently depending on their pattern and contaminants. The contaminants such as dirt, stones, and water accelerated wear in almost all cases due to the increased friction between the heel and the carpet. Furthermore, heel geometry and hardness contributed to the variation in contact pressure and wear distribution during testing.

4.5.2 PES Pattern 1 carpet results

The polyester (PES) pattern 1 exhibited the lowest abrasion resistance among all the carpets. The carpets failed at 3 different cycles - 167,75 and 50, according to their placement in the machine(see figure 4.16, 4.17, 4.18 below). Early yarn breakage was observed irrespective of the heel type or testing direction. Moreover, the presence of dirt, stone and water accelerated the wear process, leading to rapid degradation of loop structure and early yarn breakage.

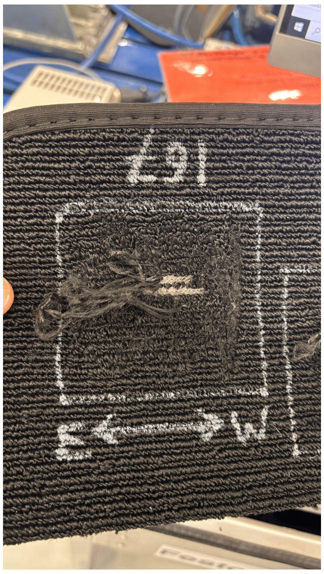


Figure 4.16: Heel 1, along loop direction

Figure 4.17: Heel 1, perpendicular to loop direction

Figure 4.18: Heel 1, perpendicular to loop direction with contaminants

The appearance of the generated wear was not matched with the wear observed in the taxi-tested samples. In taxi-test we observed that yarn breakage was not predominant, instead carpet fuzzing was observed. The findings suggest that the pattern 1 structure is highly sensitive to high load and pressure. Furthermore, the results indicated that the developed POC was unable to generate the wear patterns observed under actual conditions.

4.5.3 PA Pattern 2 carpet results

The polyamide pattern 2 carpet was evaluated under both normal and contaminated conditions using both heel types. Polyamide material has high strength and durability, but carpet were damaged at lower cycles because of high pressure and force exerted during front - back motion which accelerated the wear.

Under environmental conditions the wear behavior observed with both heel 1 and heel 2 was found different from the taxi test results. The carpet sustained approximately 100 cycles (see figure 4.19, 4.20). The wear pattern observed included flattening of yarns, color degradation, and slight loosening of fibers. These observations were consistent with patterns seen in taxi test samples, validating the relevance of the POC testing approach. Based on the cycle life and visual inspection, it can be concluded that PA pattern 2 exhibit moderate wear performance.

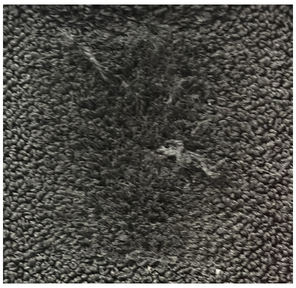


Figure 4.19: Pattern 2 carpet with heel 1

Figure 4.20: Pattern 2 carpet with heel 2

4.5.4 PA Pattern 3 carpet results

Polyamide is a high strength material and is generally expected to withstand higher load cycles without yarn breakage. However, differences were observed between POC and the taxi test. When tested with heel 2, yarn breakage was observed when the carpet was tested perpendicular to the pile direction (see figure 4.21),the carpet sustained for 217 cycles, in parallel to the loop direction no yarn breakage or loosening was observed (see figure 4.22), around 200 cycles color change was observed so it might sustain more. In contrast, when tested with heel 1 the carpet exhibited superior performance, no yarn breakage or loosening was observed in either direction, the carpet sustained approximately 900 cycles (see figure 4.23) when tested in perpendicular to loop direction and 1000 cycles (see figure 4.24) when tested parallel to pile direction.

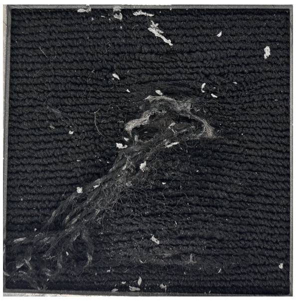


Figure 4.21: Perpendicular to pile direction with heel 2

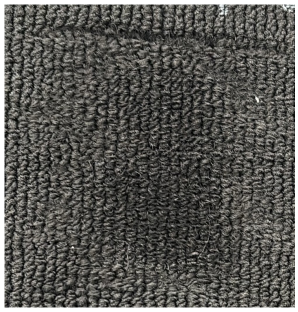


Figure 4.22: Parallel to pile direction with heel 2

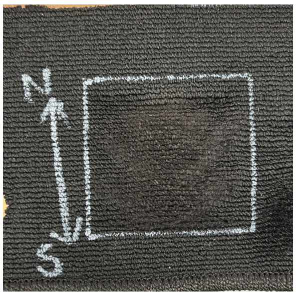


Figure 4.23: Perpendicular to pile direction with heel 1

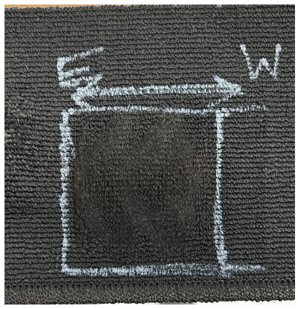


Figure 4.24: Parallel to pile direction with heel 1

Furthermore, when tested under environmental conditions the carpet (see figure 4.25) did not show yarn breakage even in perpendicular direction. Moreover, in parallel to loop direction the yarns were loosened but no breakage was observed (see figure 4.26). Although results did not exactly match those obtained from taxi tests. Based on the cycle life and visual inspection, the yarns remain intact with minimal breakage. The carpet was tested for less cycles but it might sustain more no of cycles in both directions. Therefore, it can be concluded that PA pattern 3 carpet has the best wear resistance among all 4 carpet types performing under both normal and environmental conditions.

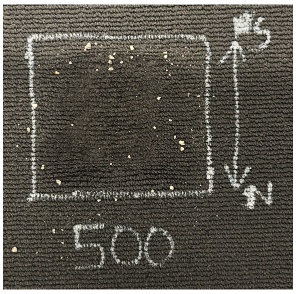


Figure 4.25: Perpendicular to pile direction with stones

Figure 4.26: Parallel to pile direction with stones

4.5.5 Key findings

- Carpet wear is strongly influenced by carpet material, carpet pattern, heel attachment, heel type and environmental conditions.
- The direction of testing relative to pile orientation significantly affects the durability and wear behavior.
- Environmental conditions such as dirt, water, and stones accelerate the wear and reduce carpet life.
- The test setup applies more force compared to actual usage conditions, leading to faster damage.
- The metal heel support used beneath the rubber heel increases the wear as it comes in contact with the carpet before the rubber heel during motion.
- Rougher and harder heel generates more abrasion which causes faster wear and reduces the carpet life.

5 Discussion

This chapter interprets the results of the new test method, compares them with real-world taxi test observations, and explains how effectively the research questions were achieved.

5.1 Research Approach

At the beginning of the project the new test method development was planned using structure and sequential approach where each phase such as literature study, user study, concept generation and testing would be completed before moving to next stage. So, the project adhered to a traditional Stage gate process due to dependency on user studies and departmental feedback. Since this is a new test method due to uncertainties in translating real world behavior into mechanical motion, iterative refinements are necessary during design and testing stages. Therefore, for this thesis a stage gate is better for overall structure but Agile practices is necessary during design and testing.

Only a few concepts were generated during this process. Some of these were discussed with the respective departments and after receiving approval, the design and development of the POC were initiated. Subsequently, the results obtained from the POC were evaluated. But they didn't match well with the taxi test results, For that necessary modifications were implemented to improve the performance and get the similar results from the POC. This entire procedure was conducted following a stage gate process, which provided a structured framework for the development of the new test method.

The observation from the POC testing indicate that although the concept is promising there are several aspects of mechanical design that replicate real driver behavior. The excessive pressure observed during forward and backward motion suggest that the applied load and motion are not yet optimized for realistic wear simulation. While the arm angle is appropriate, the current pneumatic actuation does not achieve the desired motion path, due to it's positioning and indirect force transmission. Relocating the pneumatic cylinders horizontally and directly connecting them to the arm can improve the motion accuracy. Furthermore, the pivoting action needs to be redesigned to match the natural rotation of driver's foot. Incorporating pedal like pressing actions for brake and accelerator movements is also essential. Instead of combining all motions simultaneously, a sequential execution of movements

- forward motion, pressing, pivoting, lateral movement followed by another pressing action and backward motion would better represent actual usage patterns.

The POC is not fully completed at this stage, as certain aspects require further fine-tuning. After implementing the necessary modifications, the project can progress toward the development of a final industrial machine. As the project is ongoing within the company, it is currently being handed over in its present state. Further modifications and improvements can be carried out in the future, depending on the needs and requirements of the Volvo CC.

5.2 Research Questions

5.2.1 RQ1

What limitations exist in current abrasion testing methods and why is there a need for an improved test method to evaluate carpet wear more accurately?

The current abrasion testing method used by Volvo, which are Taxi tests and Taber test, present several limitations that highlight the need for an improved test method. Taxi tests provide realistic information on carpet wear since they reflect actual driving conditions. However, they are time consuming, each test takes approximately 1.5 years and they lack repeatability because different drivers use same vehicle, each with their own driving style and footwear. Since the usage cannot be monitored it is difficult to determine how the carpet actually wears over time or whether it fails earlier than the expected lifetime.

On the other hand, the Taber test method offers controlled laboratory environment but is limited by simplified testing mechanism. It applies a single directional, rotary motion, which does not accurately represents the complex and multi-directional foot movements that occurs during real driving conditions.

Developing a new test method can address these limitations and will help Volvo reduce their dependence on long duration taxi tests. Furthermore, it would enable better understanding of carpet performance by identifying how different materials and patterns behave under realistic conditions. This would ultimately support optimization of carpet design, improve durability, reduce development time and cost.

5.2.2 RQ2

How can factors such as foot pivoting, sideways motion (jump in jump out),back and forth movement, Pressing motion on gas and brake pedal can be incorporated into the design of POC?

To identified human motion factors this can be incorporated into the design of POC by translating these physical movements into measurable and controllable mechanical inputs. Such as foot pivoting can be simulated by designing a rotating or hinged mechanism that replicates the natural angular movement of the foot. Sideways motion can be applied using linear guide movement systems such as sliding platform or guide rails to perform lateral motion. Backward and forward movement can be achieved through placing the pneumatic cylinder in horizontal direction and attached directly to the Angled arm that reproduce forward and backward shifts of the heel. Additionally, the pressing motion on the gas and brake pedals can be incorporated using pneumatic cylinder to accurately presses the heel and response behavior. By combining all these motions, this POC can effectively replicate real world driver actions, which allowed to produce more accurate testing and more precise results with taxi test conditions.

5.2.3 RQ3

How closely do the results of the new test method match those observed in taxi tests?

The results of POC test method showed a partial match with the wear observed in taxi tests. Similar wear characteristics such as pile flattening, fuzzing, color degradation and slight fiber loosening were seen in several cases, especially under environmental conditions including dirt, water, stones which were introduced during the testing. These similarities indicate that the developed method was capable of simulating certain real world wear conditions experienced in taxi applications.

However, not all carpet results matched taxi-tested results. For example, in PES pattern 1 carpet the test produced rapid yarn breakage at lower cycles whereas taxi tests mainly exhibited fuzzing and surface wear rather than severe yarn failure. This suggests that front and back motion in POC were more aggressive that those accuring in actual conditions. In contrast, other carpet constructions showed wear appearance that were visually closer to taxi test samples.

Overall, the developed POC method reasonably replicated real-life wear behavior, but accuracy of carpets depended on factors such as carpet structure, material type, pile orientation, heel properties and environmental conditions.

6
Future Work

There are several factors that must be considered in the development of a new test method for evaluating abrasion in inlay carpets. A lot of factors affect the abrasion on the carpets other than just standard leg movement. Actions such as ingress and egress contribute significantly to the carpet wear and should be incorporated into testing method. In addition, taxi drivers often exhibit nonuniform foot movements. Psychological factors may also influence their behavior, such as applying the brake and accelerator more aggressively due to fatigue or irritation from long working hours. Furthermore, variation in driving patterns, routes, and traffic conditions can also influence the nature of the carpet wear. Incorporating these variations into the test method is necessary to improve accuracy and realism. These conditions can be implemented into the simulator, enabling testing for different percentiles of drivers.

Currently, POC evaluates the abrasion using only the heel contact. However, using complete footwear rather than isolated contact could improve the accuracy of wear simulations, as shoes represent realistic load distribution, surface contact, and material interaction with the carpet. Moreover, it is necessary to evaluate all wide range of carpets that Volvo has through this test method because different materials and structures may provide different abrasion patterns. In addition, the current back and forward motion in the machine can be improved through design modifications because current motion exerts more force in the forward direction. This can be done by placing hydraulic, cylinders horizontally to drive the arm directly. In addition, the pivoting angle can be enhanced, and a pedal pressing movement can be integrated. At present all three movements are working simultaneously, however the machine's operation can be optimized by executing them sequentially - first moving forward, then pivoting, and finally returning back - forming a one complete cycle.

Quantitative evaluation of carpet wear is another important aspect of the test method. Measurement of percentage wear on carpets can be achieved by different methods for example gray scale analysis[2] (see figure 6.1), which would generate measurable and comparable data of wear. Such numerical data could be used to implement Design of Experiments (DOE), allowing the development of mathematical models to study and analyze the influence of different test parameters and predict wear behavior under varying conditions.

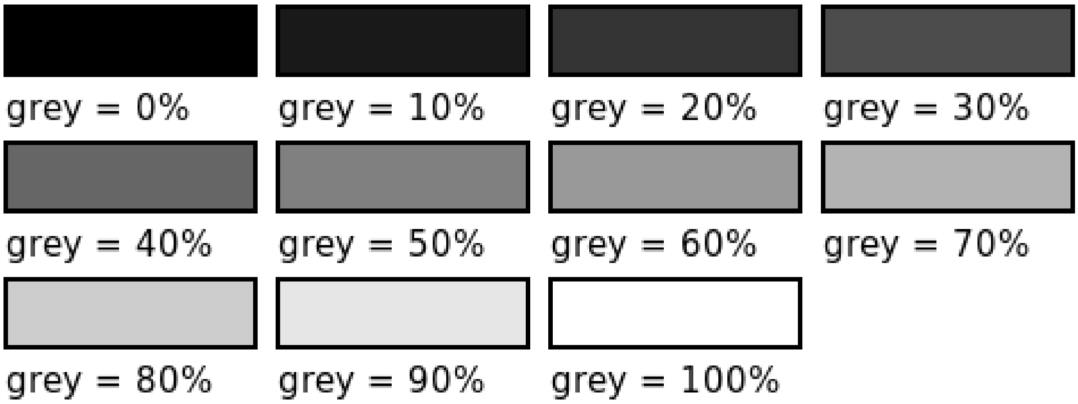


Figure 6.1: Grey Scale

Finally, the current Proof of concept (POC) was developed using a user study involving Volvo employees and students. A dedicated user study with taxi drivers can be conducted as they drive for longer durations. Due to time constraints in this thesis, this could not be conducted, but in the future this is possible.

7 Conclusion

This study focused on developing a new test method for inlay carpets. The team started by analysing the data provided by Volvo, understanding the carpet types and it's material, performing literature study and patent analysis. Conducting user study of different percentiles on different cars helped us in understanding various driving patterns of users. The design process started by identifying the requirements specifications from Volvo. Using function-means tree, teams generated some ideas for each sub-funcions. Ideas were generated through various brainstorming sessions. Concepts were created and evaluated focusing on various factors to reach the project goals. To verify concept feasibility and functionality CAD model and simulation was done for the selected concepts and a prototype was build for the selected concept as a proof-of-concept. While the project has meet the initial goals, resulting in a design proposal for the test method. However, future work should focus on implementing and validating proposed concepts, conducting user studies with respective groups, developing quantitative wear measurement techniques and establishing correlations between laboratory testing and real-world performance.

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A

Appendix 1

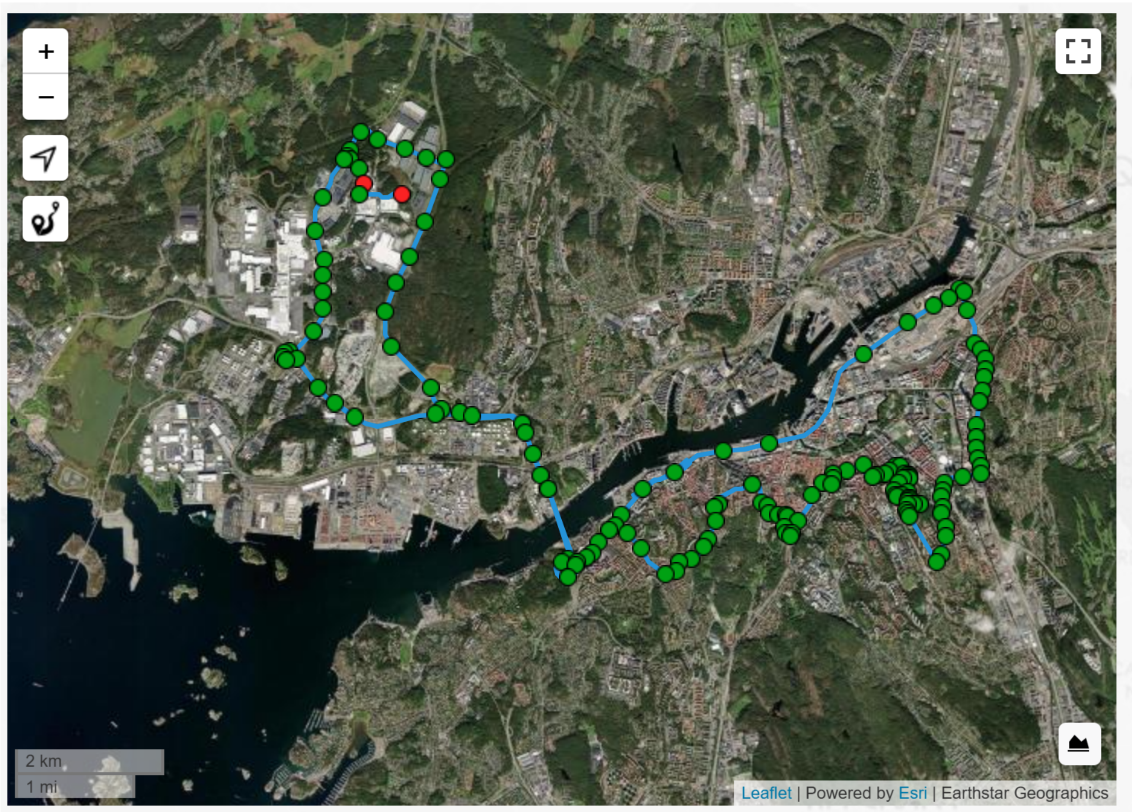


Figure A.1: City route for user study

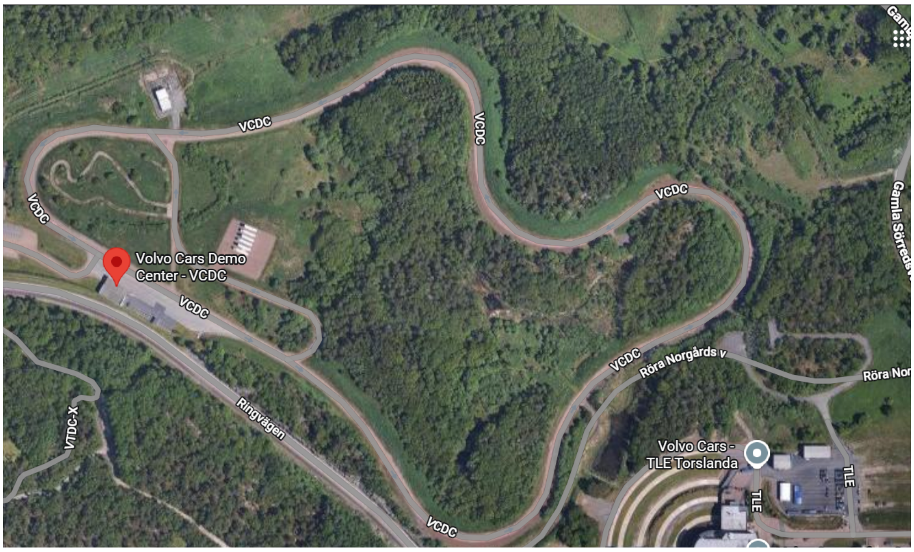


Figure A.2: VCDC Route for user study

VOLVO User study foot position

Figure A.3: User 1 foot position XC90

Figure A.4: User 2 foot position XC90

Figure A.5: User 3 foot position XC90

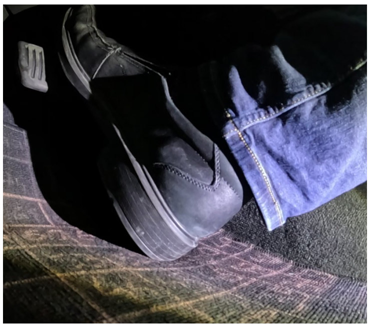


Figure A.6: User 1 foot position V60

Figure A.7: User 2 foot position V60

Figure A.8: User 4 foot position

VCDC User study foot position

Figure A.9: User 1 foot position EC40

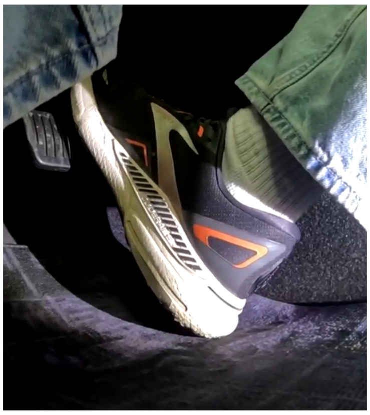


Figure A.10: User 2 foot position EC40

Figure A.11: User 3 foot position EC40

Figure A.12: User 4 foot position EC40

Figure A.13: User 5 foot position EC40

Figure A.14: User 6 foot position EC40

Figure A.15: User 7 foot position EC40

Figure A.16: User 8 foot position EC40

Figure A.17: User 9 foot position EC40

Figure A.18: User 10 foot position EC40

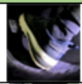
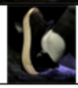
Test No	Date	User	Percentile/Height (cm)	Weight (Kg)	Image	Shoe Type	Foot/Shoe size (ft/inch)	Max_Force (N)	Seating Position	Vehicle	Time duration (min)	Kms covered	Foot Pattern	Carpet Image	Route (start from_To)
1		U1	182	65		Sports	NA	18,8			10		All four Movements		
2		U2	181	90,6		Sports	NA	26,05			8		Pivot + FNB		
3		U3	176	55		Sports	EU42	10,08			7		Jump		
4		U4	194	94		Sports	EU44	23,8			7		Pivot + FNB		
5		U5	173	73		Sports	EU42	19,9			6		FNB + J_IN_J_OUT		
6	2026-03-12	U6	182	88		Sports	NA	26,4		EC40	7	4,2	Pivot + FNB		Demo centre Track
7		U7	171	84		Sports	NA	20,75			7		Pivot + J_IN_J_OUT + FNB		
8		U8	186	95		Formal	NA	21			6		Pivot + FNB		
9		U9	185	88		Formal	NA	22,1			7		Pivot + FNB		
10		U10	182	73		Sports	NA	22,8			8		Pivoting		

Figure A.19: User study on EC40 at VCDC

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