THE TAILORED TRAVELLER

Exploring digital vehicle data and large-scale FDM 3D printing to produce a luxury sleeping space

The Tailored Traveller

By
William Calder Rykers

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School of Design
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ABSTRACT:

This research is focused towards the use of large-scale FDM 3D printing within the automotive industry, specifically to design a bespoke habitable sleeping environment attached to a Range Rover Sport. 3D printing has risen as a viable form of manufacturing in comparison with conventional methods. Allowing the designer to capitalise on digital data, enabling specific tailored designs to any vehicle model. This thesis asks the question “Can design use the properties of digital vehicle data in conjunction with large-scale FDM 3D printing to sustainably produce bespoke habitable sleeping environments for an automotive context?” Further to this, FDM 3D printing at a large-scale has so far not been explored extensively within the automotive industry.

FDM 3D printing is an emerging technology that possesses the ability to revolutionise the automotive industry, through expansion of functionality, customisation and aesthetic that is currently limited by traditional manufacturing methods. Presently, vehicle models are digitally mapped, creating an opportunity for customisation and automatic adaption through computer aided drawing (CAD). This thesis takes advantage of the digitisation of the automotive industry through 3D modelling and renders as a design and development tool.

This project explored a variety of methods to demonstrate a vision of a 3D printed habitable sleeping environment. The primary methodologies employed in this research project are Research for Design (RfD) and Research through Design (RtD). These methodologies work in conjunction to combine design theory and practice as a genuine method of inquiry. The combination of theory and design practice has ensued in the concepts being analysed, reflected and discussed according to a reflective analysis design approach. The design solution resulted in an innovative and luxury bespoke habitable sleeping space to be FDM 3D printed. Through the use of digitisation, the sleeping capsule was cohesivly tailored to the unique design language of the Range Rover Sport. This thesis resulted in various final outputs including a 1:1 digital model, high quality renders, accompanied by small scale prototypes, photographs and sketch models.

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KEY TERMS: AUTOMOTIVE DESIGN GLOSSARY

A-line: The line running over the car, from headlight to tail light, tracing the car's silhouette.

Backlight: The rear window glass.

Belt Line: A demarcation or crease between a vehicle's body panels and the side windows.

Bonnet: The hood of the vehicle.

Cab: Short for cabin. The enclosed compartment of a vehicle which contains the driver and passengers.

Cant Rail: The structural member which usually sits squarely on top of the B-pillar forming the top edge of the door frame aperture, and which may run seamlessly into the A and C pillars.

Character Line: An important feature line which may be sculpted, or more pleasingly, created by the meeting of two planes on a car's surface, and which gives or adds both definition and 'personality' to the form.

Crease Line: A crease is the pressed or folded line created by the meeting of two different planes or surfaces. Unlike feature lines, a crease is integral to a design, and cannot simply be applied to a surface.

Feature Line: A simple line in a car's body surface. The best feature lines will be sympathetic to the design of a car.

Greenhouse: The upper, glazed, part of the passenger compartment which 'sits' on the bodywork.

Gill: A vent on the side of the wing panel, it can be used for hot air ventilation but it is often decorative.

Haunch: Where the shoulderline of the car gently swells out to accentuate the muscularity of the rear wheel. Haunch is the name given to the sculpting of the wing panel above the rear wheelarches.

Lightline: Lightlines are effectively 'paths' of reflected light which 'run' along a surface and make it possible to understand its sculptural form without reference to its outline shape.

Monocoque: A type of vehicle construction in which the body is integral with the chassis.

Pillars: Pillars fulfill a number of primary functions: they are important structural members, doors are hinged off and/or close on to them, they support the roof, 'cage' and protect the occupants, and visually frame the windows.

A-Pillar: The upright structural supports either side of the windshield which is usually bonded to them. A-pillars invariably flow visually seamlessly into the cant rail.

B-Pillar: Strictly speaking, the B-pillars of most four and five-door (and some two and three-door) cars are not visible until their door or doors are opened. What we refer to as B-pillars are actually the adjacent uprights of the front and rear side window frames which sit over, and hide, the actual B-pillar.

C-Pillar: The third pillar is the rear door pillar, above the rear wheels.

D-Pillar: The rear most pillar, only evident in four and five door vehicles.

Plan Shape: Plan view is simply the elevational view of a car as seen from directly above.

Screen Angle: This is the angle the windshield of a car slopes back from the vertical.

Shoulderline: The shoulderline basically runs the length of a car's upper body side where it folds over to meet the side windows and its nature will reflect the essential character of the car.

Shutline: A shut line - or 'cut line' - is the necessary clearance gap between two adjacent exterior body panels or interior trim panels, either of which may be openable.

Stance: Stance suggests both attitude, intent and ability, confers presence, and is equally identifiable whether a car is stationary or on the move.

Surface Language: The basic form language of the car that defines the design.

Tumblehome: A car with more tumblehome suggests a faster, sportier car. Tumblehome describes the convex inward curvature of the side of a car above the belt line.

Tailgate: The rear door of a vehicle.

Wheel Arch: These are essentially circular apertures in the body sides which admit the road wheels, and importantly, frame them.

Wing: The local panels which are legally required to wrap or cover road wheels, protecting the bodywork.

Glossary terms retrieved from (Lewin & Borroff, 2010)

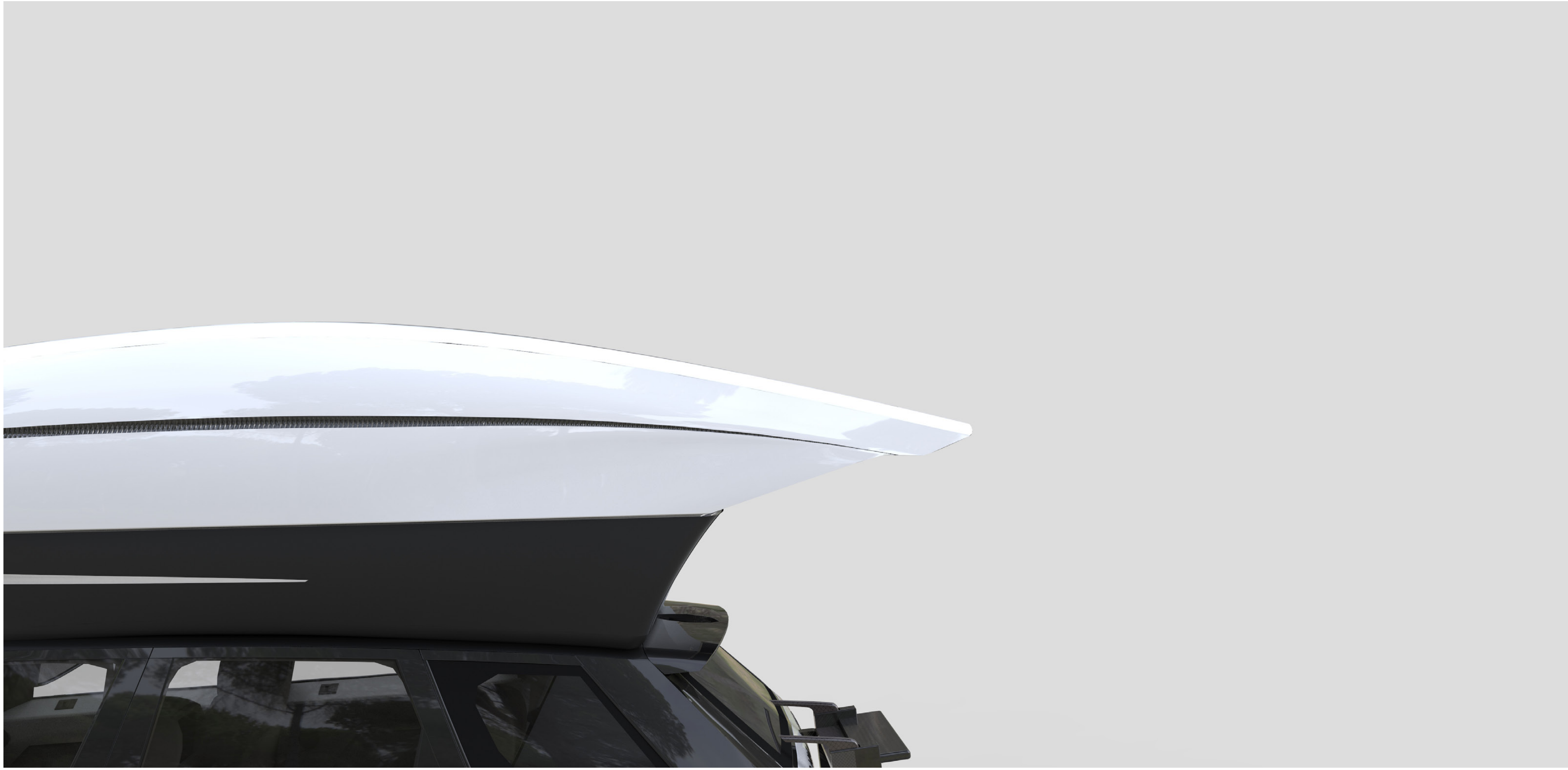

Figure 1. Range Rover Sport attached with a luxury sleeping capsule.

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INTRODUCTION

For decades the automotive industry has focused primarily on the driver and passenger, swaying away from complex customisation. Automotive manufacturers have continued to prefer traditional methods and processes in order to adhere to strategies that concentrate on providing enough variety for most customers to be satisfied.

With that being said, the rapid advancement of digital technologies within the automotive industry has resulted in every model having a 3D digital map of their unique surface language. This high precision and constantly updated database opens the door for emerging technologies, such as FDM 3D printing to utilise digital vehicle data to adapt and improve automotive manufacturing processes with the implication of sustaining complex customisation. Therefore, this thesis asks the question "Can design use the properties of digital vehicle data in conjunction with large-scale FDM 3D printing to sustainably produce bespoke habitable sleeping environments for an automotive context?"

This research uses design practice as a tool to create a bespoke habitable sleeping environment attached to a Range Rover Sport, which was selected due to;

- The brand being a design advocate for luxury SUVs.
- Symbolism through their vehicles strong visual language and resulting bloodline of models.
- Range Rover's history of exploring, whilst doing so in a luxury space.
- To prove FDM can excell within a high-end, extravagant environment.

FDM 3D printing was selected as the medium of production due to several significant characteristics;

- The ability to create lightweight and structurally sound parts.
- FDM 3D printing is cost effective and offers recyclable and biodegradable materials.
- FDM 3D printing is a single process, only requiring a digital CAD model for manufacturing.
- The use of a digital 3D model enables complete geometric freedom for the production of bespoke complex forms.
- Digital vehicle data is able to be utilised and embodied through CAD modelling, allowing the designer to tailor any design to the specific vehicle model and its defining style language.

Background research involving literature reviews, precedent concepts and case studies have been utilised to build the theoretical scope of this research and justify why FDM 3D printing is the chosen form of manufacturing. Literature is narrowed from additive manufacturing as a whole, down to key characteristics of FDM 3D printing in conjunction with the automotive industry. Such as, materials, large-scale applications, environmental pressure and customisation. Freedom camping is an important context as vehicle habitation has become an increasingly popular pastime, suggesting this research is timely.

Overall, this thesis aims to use CAD modelling and FDM 3D printing as a design tool to capitalise on digital vehicle data for the production of a bespoke habitable sleeping space tailored directly to a Range Rover. The research will identify the validity of FDM 3D printing as a manufacturing method in comparison with conventional methods. Resulting in a unique customised application through vehicle surface language that could not be achieved with traditional manufacturing methods.

CHAPTER OVERVIEW:

ONE: BACKGROUND RESEARCH

The background research chapter sought to build the overall theoretical framework for this research through in-depth literature studies. Specifically this chapter breaks down FDM 3D printing as a process and manufacturing tool. Alongside this, the automotive industry is assessed, in order to gain relevant knowledge about customisation and environmental issues that work to further justify FDM 3D printing as a valid manufacturing method.

TWO: PRECEDENT CONCEPTS

This chapter reviews multiple precedent concepts that were instrumental in inspiring the design process and building a strong context behind the research. Each of the precedent concepts discussed played a role in influencing design thinking throughout this research.

THREE: CASE STUDIES

Three case studies were employed within this chapter to help refine the context of this research and reinforce why FDM 3D printing was selected. The first case study looks to understand Range Rover as a brand, analysing key themes and significant design cues throughout their heritage. The second case study focuses on the context of freedom camping and the legislation in New Zealand, whilst also discussing potential market gaps. The final case study identifies and evaluates large-scale FDM style technology that holds the capability of printing objects as big as 5m x 5m x 5m.

FOUR: METHODOLOGIES

The methodologies chapter distinguishes the two primary methodologies employed; research for design and research through design. Furthermore, this chapter breaks down the chosen methods, discussing their specific role and significance within this research.

FIVE: DESIGN PHASE ONE

Chapter five enters the design process discussing why Range Rover was the vehicle of choice for this project. Following this, the initial design process and corresponding concepts are discussed and evaluated through methods of sketching, rendering and reflective design analysis.

SIX: DESIGN PHASE TWO

This chapter discusses and reflects the second phase of the design process. Exterior and interior form development is highlighted through CAD progression and renderings of concepts. The middle section examines and reflects on capsule accessibility and the ergonomics of movement into and within the sleeping environment. The final section of design phase two explores FDM 3D printing materials and qualities to decipher the optimum material for prototype production. Alongside this, interior fabrics are explored to understand the feel of the space through materiality with the intent of perceiving luxury.

SEVEN: DESIGN SOLUTION

Chapter seven identifies and analyses the final design solution produced from this research. The final output is broken into multiple sections that examine and evaluate the refined features of the sleeping environment. The subsequent sections include final CAD development, final exterior form, accessibility, final interior development, aerodynamics, Range Rover attachment and contextual narrative. Following this, the design solution is critically analysed through a reflective design analysis, eluding to future speculations regarding the application of habitable environments for self driving vehicles.

EIGHT: CONCLUSION

This chapter concludes the research, background research is reviewed and reiterated in conjunction with the design process. The analyses of the design solution and the research as a whole evokes an informed response to the research question.

Figure 2. ‘Night Tides’ Range Rover Sport with sleeper attachment.

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BACKGROUND RESEARCH

Gaining knowledge through the study of scholarly literature and relevant contextual information has been crucial in reinforcing the conceptual development of this research. Moreover, the literature and contexts reviewed in the following pages have built a framework to support the research proposition and the methodologies employed, as well as providing myself with a critical understanding of the various topics covered in this thesis. This literature review investigates 3D printing technologies in relation with the automotive industry. The focus of this literature study is to explore whether 3D printing technologies, primarily Fused Deposition Modelling (FDM), is a viable form of manufacturing for the automotive industry on a large-scale. Furthermore, the research aims to interpret the environmental and economic implications of FDM technology. In conjunction with these implications, the research explores the prospect of FDM within the context of a habitable automotive space and identifies a potential market for low volume, complex customisation and personalisation.

ADDITIVE MANUFACTURING:

In the last decade, Additive Manufacturing (AM) colloquially known as 3D printing has emerged as an influential manufacturing process. In the early stages of 3D printing, it was mainly used for prototyping and tooling. Though in recent years the advancements and benefits in the technology have led to it being used for final part production. Notable examples of these AM technologies include Digital Light Processing (DLP) and Stereolithography (SLA) in which photosensitive resin is cured by a laser or light source (Dudek, 2013). Selective Laser Sintering (SLS) uses a carbon dioxide laser to sinter and fuse powdered material to create a three-dimensional object (Dudek, 2013). Fused Deposition Modelling (FDM) involves a material being heated until molten and extruded through a special nozzle building cross sections of the model layer upon layer to create a three-dimensional object (Dudek, 2013). Each of these 3D printing technologies allows the user to create a physical object straight from computer aided drawing (CAD) software as described in figure 3.

Figure 3. 'Additive manufacturing process flow' explains the process required to produce an object through AM, from Deloitte University Press.

In comparison to conventional forms of manufacturing (e.g., injection moulding, casting, stamping and machining), 3D printing offers various benefits critical to the development of numerous industries. 3D printing allows the user to create complex forms that could not be previously produced through traditional tool based methods. 3D printing opens the door for personalisation and design freedom, whereas conventional methods are only aimed at the masses. Potentially, the most critical advantage of AM technology is the environmental benefits. Conventional subtractive methods create large quantities of waste material and use excessive amounts of energy when operating (Campbell, Williams, Ivanova & Garrett, 2011). 3D printing, on the other hand, is far more efficient and considered the 'green' option of manufacturing (Campbell et al., 2011). 3D printing creates virtually zero waste and limits the amount of energy used. Furthermore, AM technologies have the capability to use environmentally friendly materials and even recycled materials, reducing the carbon footprint of the end product.

Although AM technologies possess many benefits, there are also limitations that hold the technology back from challenging traditional manufacturing technologies in some applications. With regard to mass production, 3D printing is far slower than a conventional process such as injection moulding. A 3D printer is capable of building a 38 millimetre cube in about an hour. Whereas an injection moulding machine is capable of making several similar parts in under a minute (Campbell et al., 2011). With that being said, the limitation is only justifiable for the production of thousands of one common object. When producing a customisable product or a small volume of products, 3D printing is the preferred process (Campbell et al., 2011). Current AM technologies are limited to materials such as liquid, solid, and powder polymers; powder metals; and ceramics. Due to these material limitations, it is difficult to achieve uniformity of production quality (Campbell et al., 2011). In order for AM technologies to become a dominant manufacturing process throughout a variety of applications, there must be a further exploration of materials.

FUSED DEPOSITION MODELLING (FDM):

FDM is one of the most common forms of 3D printing technology. FDM systems are relatively inexpensive and only require machining costs, this is composed of material costs and post-processing costs (Dudek, 2013). In relation to other forms of 3D printing, FDM produces far less scrap than processes such as SLA and SLS (Dudek, 2013). Many materials used in the FDM process are able to be recycled, ensuring there is little to no waste. FDM has quickly developed a number of materials it can utilise, alongside thermoplastics, a number of composites incorporating metals, ceramics and plant fibres have emerged.

FDM 3D printing has emerged as a valid manufacturing tool within the automotive industry due to a number of important features:

- 3D printing is more cost effective (e.g. No initial tooling cost, reduced waste, recyclable materials.)
- 3D printing is able to create lightweight and low energy parts, necessary within the automotive industry.
- 3D printing is a single process, only requiring digital models. The technology offers complete geometric freedom as each object is produced using computer aided drawing (CAD) software.
- 3D scanning and digital CAD modelling acts as a digital foundation and can be used to customise a design tailored to any vehicle type/model. Therefore 3D printing possesses the ability to manufacture bespoke, complex forms stylised for different vehicle models.
- Customisation allows companies to introduce many more internal/external features to a vehicle (e.g. digital coach building). (Berman 2012)

FDM 3D PRINTING MATERIALS:

Currently FDM 3D printing materials are dominated by thermoplastics including Acrylonitrile butadiene styrene (ABS), Polylactic Acid (PLA) polycarbonate (PC) and polyphenylsulfone (PPSF) (Bak, 2003). With that being said, Bak states that the abundance of thermoplastics has helped to strengthen the material properties of FDM technology (2003). This is due to the ease of composite material creation, thermoplastics can be custom blended with a second material, notable examples include wood, metals alloys and ceramics. A composite material is essentially a blend of two different materials with vastly different properties than if the materials were utilised singularly. The appeal of composite materials is that they are lighter, stronger and stiffer than most other structural materials (Happian-Smith, 2001).

FDM 3D printing has the capability to create parts that are lightweight, only using material where it is needed whilst also reducing scraps. Traditional processes have reached their limit regarding lightweight manufacturing (Kaluza, Kleemann, Broch, Herrmann, & Vietor, 2016). Whereas lightweight 3D printed geometries ensure to reduce fuel consumption and increase energy cost savings across a vehicle's lifespan. Energy cost savings account for one-third of total cost savings in the automotive and aerospace sectors (Gebler, Schoot Uiterkamp, & Visser, 2014). Moreover, 3D printing vehicle parts using composite materials would increase the recyclability and reusability percentage of each vehicle and it's accessories, as many of these thermoplastic composite materials are mechanically strong and biodegradable.

Sustainable thermoplastic composite materials are a mixture of a biodegradable polymer such as PLA (Polylactic Acid) reinforced with a fibre (AL-Oqla & Sapuan, 2014). Through traditional processes, fibreglass was often used for its mechanical properties although it is highly volatile to the environment. This has caused automotive companies to switch to composite fibres such as plant fibres. Notable fibres include; flax, cellulose, hemp, ramie and jute (Koronis, Silva, & Fontul, 2013). Studies have shown that these plant fibres when mixed with thermoplastic matrices possess similar mechanical qualities to fibreglass, making them a viable option for manufacturing in the automotive sector (Koronis et al., 2013).

LARGE-SCALE FDM 3D PRINTING:

FDM 3D printing has initially been applied in a number of industries such as automotive, aerospace, medical and architecture. Though in most applications the technology has been used for rapid prototyping, low volume production and small customised parts (Berman, 2012). In recent times, FDM processes have progressed, including the scale of the technology. Unfortunately, the large-scale technology is still in a development stage within the automotive industry and requires more exploration before it can become a dominant manufacturing process (Srinivasan & Bassan, 2012). With that being said, large-scale FDM 3D printing is still rapidly advancing throughout the automotive industry and an emerging company, Local Motors is challenging the automotive giants with a focus on large-scale FDM technology. Local Motors has utilised a co-creation and collaborative strategy through low volume vehicle manufacturing of open source designs. These vehicles are being manufactured in various 'micro factories' that have been built across the US. Local Motors have a firm aim in developing 3D printing processes and materials for the automotive industry and have already produced notable examples such as 'Strati' the world's first 3D printed electric car and 'LM3D Swim' the world's first road ready 3D printed electric car. (McCue, T. 2015)

FDM large-scale technology has also breached other sectors such as the Aerospace and Architecture industries. Stratasys have developed the 'Robotic Composite 3D Demonstrator' that is essentially an FDM 3D printer on the end of a robotic arm. Stratasys have been developing this technology in partnership with Boeing and Ford, two major players in the aerospace and automotive sectors. Whilst the robotic demonstrator is mainly used for small intricate parts, the technology possesses the capability to print lightweight and strong objects such as aeroplane panels in a single process, aiding in reducing cost (Stratasys, 2017). Moreover, the technology completely defies geometric limitations, through an 8 axis motion system, meaning material can be applied anywhere reducing the need for support structure that is accompanied with most regular FDM 3D printers (Stratasys, 2017). Within the Architecture industry, A Dutch design company Dus Architects has began building a canal house in Amsterdam by 3D printing its parts using a giant FDM 3D printer called the "KamerMaker" (Hager, Golonka, & Putanowicz, 2016). The printer uses a biodegradable thermoplastic. The printer is mobile and able to be transported on site, the reason for this is to eliminate waste and reduce transport costs (Hager et al., 2016). The main aim of the operation was to discover and share the benefits of 3D printing in the architecture and construction industries.

ENVIRONMENTAL PRESSURE ON THE AUTOMOTIVE INDUSTRY:

In the last two decades, the automotive industry has increasingly received pressure from government and environmental organisations regarding the environmental impact of a vehicle during its life cycle. The life cycle of an automobile involves the manufacturing processes and materials, the energy consumption during its lifespan and the end of life strategy (e.g. recycling and reusability). Alongside this added pressure, composite materials have offered various environmental and economic benefits. The advantages of this ‘green’ initiative have acted as a driving force for many automobile companies to take a sustainable approach and comply with government guidelines.

According to the European Commission’s 2000/53/EG environmental directive, by 2006 85% of the weight of a car must be recyclable and reusable. Furthermore, in 2015 the percentage increased to 95% (Koronis et al., 2013). Composite materials have been steadily increasing in volume and popularity within automotive processes and parts, further aligning with the EU directive. In saying this, many composite parts that are produced are using traditional manufacturing methods (Koronis et al., 2013). This opens the door for evolving technologies such as 3D printing to further push the automotive industry towards a sustainable future.

CUSTOMISATION IN THE AUTOMOTIVE INDUSTRY:

In the present day, customisation of a vehicle is limited to the extent of changing colours and paint types on the exterior of the vehicle, choice of upholstery materials and colours, and integration of different technological and physical accessories. Automotive manufacturers choose to escalate the variety of products on the market to cater for customers complex demands (Alford, Sackett and Nedler, 2000). In reality, the customer is only able to choose from a mass of products, and are not having any influence on the design or manufacturing processes and is unable to change the product in any way. This also requires the automotive company to anticipate customers market requirements. An example of this is Volvo's YCC car 'designed for women'. This vehicle required very little maintenance. Furthermore, it featured extra space for 'stuff' beside the driver, folding cinema seats in the back and interchangeable upholstery panels (Laurier, Brown, & Lorimer, 2005). Alford et al., consider the reason for limited customisation is due to strategic business models revolving around mass customisation and high volume production to cater for increased demand and lower costs (2000). Furthermore, customisation in the automotive sector is restricted from production technologies and supply chain constraints (Weller, Kleer and Piller, 2015).

The automotive industry has always held a focus on the driver and the passenger, swaying away from complex customisation (Laurier et al., 2005). Overall, there is little focus on how the space within the automobile is utilised, even with large functional vehicles, they all possess similar internal qualities. Moreover, complex customisation and personalisation is scarce among the major automotive companies, typically, complex customisation is more readily available through high end vehicle manufacturers or bespoke low volume vehicle manufacturers. However, FDM offers the opportunity for high-quality, luxurious parts.

AM Technologies such as 3D printing possess the ability to revolutionise the automotive industry through the inclusion of bespoke complex customisation. 3D printing allows products to be optimized for its intended function rather than being limited to stock designs created through traditional manufacturing methods (Weller et al., 2015). Furthermore, 3D printing technology creates potential opportunities to allow the consumer to choose how the automotive space is designed to fit their demands. As a result of this, product variety can become infinite without incurring additional costs that would be associated with conventional manufacturing methods (Weller et al., 2015). Although customisation and variety generally imply increased costs, product customization potentially gives an increase in the customers perceived product value and, consequently, improves their willingness to pay (Fogliatto, Silveira and Borenstein, 2012). Moreover, it is identified that "in order to sustain the provision of high variety tailored to customer needs, manufacturers must seek cost-effective capabilities to counter increasing costs and manage growing complexity" (Alford et al., 2000). FDM 3D printing is a cost effective and sustainable manufacturing process that can work to restrain the increasing costs related with customisation. Currently FDM 3D printing technology is only capable to produce highly customised products at low volumes, but with further exploration and development 3D printing technology has the potential to successfully sustain high volume complex customisation in the automotive industry.

2

PRECEDENT CONCEPTS

The following precedents and the coinciding concepts served to create a surrounding context for this research project. The specific images have provided inspiration and important contextual knowledge that have shaped the design considerations and decisions highlighted throughout this thesis.

INTERIOR ARCHITECTURE:

Interior architecture has been a key field of inspiration as it involves the design and layout of an internal space. The ability to change the feel of a space is an important concept in this research, especially designing to create comfort within a small interior space. As seen to the right in figure 2, Zaha Hadid designed apartments for the Ronald McDonald charity house in Hamburg. The space is modern and bold with strong angles and a illustrates a beautiful use of lighting. The use of interior angles, lighting, colours and materials is an area of great consideration in the design practice phase.

Figure 4. Ronald McDonald charity house in Hamburg designed by Zaha Hadid Architects.

MICRO LIVING:

The idea of micro living has become a far more relevant concept as overpopulation and housing crisis has raised significant issues. Contextually this concept is vital to this research as micro living is an example of how to utilise a small space efficiently. Various solutions have arisen in this field, below in figure 3 James Law Cybertecture has produced an ‘Opod’. A housing unit designed inside a 2.5m diameter concrete pipe for 1-2 persons (2017). The Opod is a stackable strong structure and uses the space effectively to fit all amenities including living, bathroom and cooking areas. Alongside this efficient use of space, the lighting, materials and space saving furniture work exceedingly well to make a concrete tube an appealing place to live.

Figure 5. ‘Opod Tube Housing’ micro apartments in concrete pipes designed to ease Hong Kong’s housing crisis from James Law Cybertecture.

MOBILE VEHICLE HABITATION:

People adapt, use, hire and purchase vehicles specifically for travelling and camping. Contextually it was important to understand the different forms of vehicle habitation and why people choose a mobile home over a hotel or B&B. The concept of vehicle habitation is a broad term and can differ from living in fully furnished motorhome to sleeping on a blow up mattress laid down in the rear of a vehicle. Generally vehicle habitation depends on the cost and situation involved. Mobile homes range in size, form and price, varying from luxury motorhomes, caravans, campervans, rooftop tents and modified vehicles. In figure 4 is an example of a roof top tent designed by Autohome in conjunction with Mini for the all wheel drive Mini Countryman. The roof top tent has become increasingly popular in recent times as it is a relatively inexpensive accessory and allows the user sleep above their vehicle. Furthermore, the roof top tent is compact, lightweight and relatively easy to erect. The attraction of a roof top tent opposed to a hotel or B&B is that the user is able to travel to more isolated places, ideal for a scenic traveller.

On the other side of the spectrum, luxury motorhomes have been a popular form of mobile home in the last decade with design and technology rapidly advancing. Moreover, these motorhomes play a large part in the tourism industry, particularly in New Zealand. Although luxury motorhomes are reasonably expensive, they appeal to the older and wealthier generations. The vehicles are very large in size, limiting them from accessing an area that a smaller, nimble vehicle may find easy. With that being said, luxury motorhomes act as a hotel on wheels and allows the user to travel from place to place with added comfort. Additionally these motorhomes are self-contained and hold various amenities. In figure 5 is an interior of a Swift Bolero, a high end motorhome.

Figure 6. Autohome AirTop roof top tent designed in partnership with Mini from BMW Group.

Figure 7. Interior shots of a Swift Bolero, photographed at Iconic Motorhomes.

CONCEPT VEHICLES:

Concept vehicles have provided this research with inspiration for the design process phase regarding the integration of luxury and future high-tech applications. Concepts cars produced by the major automotive companies boast innovative technological solutions specifically within the design and engineering sectors. Furthermore, these vehicles often carry unique design traits associated with the vehicle manufacturer. In figure 6, the Vision Mercedes-Maybach 6 Cabriolet by Daimler AG demonstrates “the ultimate in luxury of the future” (2017). The Vision Mercedes-Maybach 6 Cabriolet has been designed as an electric car and the battery sits in the underbody of the car allowing the space to be utilised in an unconventional way. The front of the vehicle where the engine would normally sit hosts space for storage. The exterior of the vehicle is stretched and fluid, distinguished by sharp feature lines and elegant lighting. The interior unveils the ultimate in luxury with the combination of emotional intelligence, the soft curves and material palette creates a luxurious yet high-tech experience.

Figure 8. The Vision Mercedes-Maybach 6 Cabriolet, electric concept vehicle from Daimler AG.

BESPOKE COACH BUILDING:

Coach building can be defined as a manufacturer of bodies for passenger-carrying vehicles. Custom or bespoke coachbuilding dates back to 1450 in Hungary where the first reported horse carriage was built for the aristocracy and gentry (Burgess, 1881). Automotive custom coach building emerged in the early 1920's and flourished into the golden age of automobile design. During this time, bespoke vehicles were a necessity for people of wealth and position to accompany their life of luxury (Coachbuilt.com, 2015). Furthermore, the automobile became a symbol of modern society, and served as a medium for artistic and personal expression for both the designers and owners (Coachbuilt.com, 2015). Custom coachbuilders emerged in force during the golden age (1920 -1945) producing ultra-luxury vehicles sold as chassis only. The production of bespoke luxury vehicles began to limit from the great depression in 1929 and dramatically reduced post world war II (Coachbuilt.com, 2015). Moreover, the introduction of unibody construction, where the body of the vehicle is fused with the chassis caused custom coachbuilding to become a uneconomic practice. Many of the custom coachbuilders either closed down or reformed their business towards other pursuits, although some managed to survive and are still active today, notable examples include Zagato and Pininfarina.

Contextually custom coachbuilding is a significant concept as this research aims to produce a vision of a bespoke habitable sleeping environment attached to a Range Rover Sport. Large Scale FDM 3D printing technology discussed in chapter two has the potential to act as the medium for bespoke digital coachbuilding, a new era of customised design within the automotive industry. Furthermore, the practice of coachbuilding targeted the same market that this design output is focused on. Figure 7 displays a Rolls-Royce Silver Ghost Torpedo “Pall Mall Tourer”, this vehicle was custom built by Brewster and Co, a well known coachbuilding firm particularly for working with Rolls-Royce in the United States. This specific model featured throughout the early stages of the golden age and was sold as a separate chassis. Customised bodies and interiors were produced by coachbuilders for various high end customers, resulting in different colourways, body trimming features and interior materials.

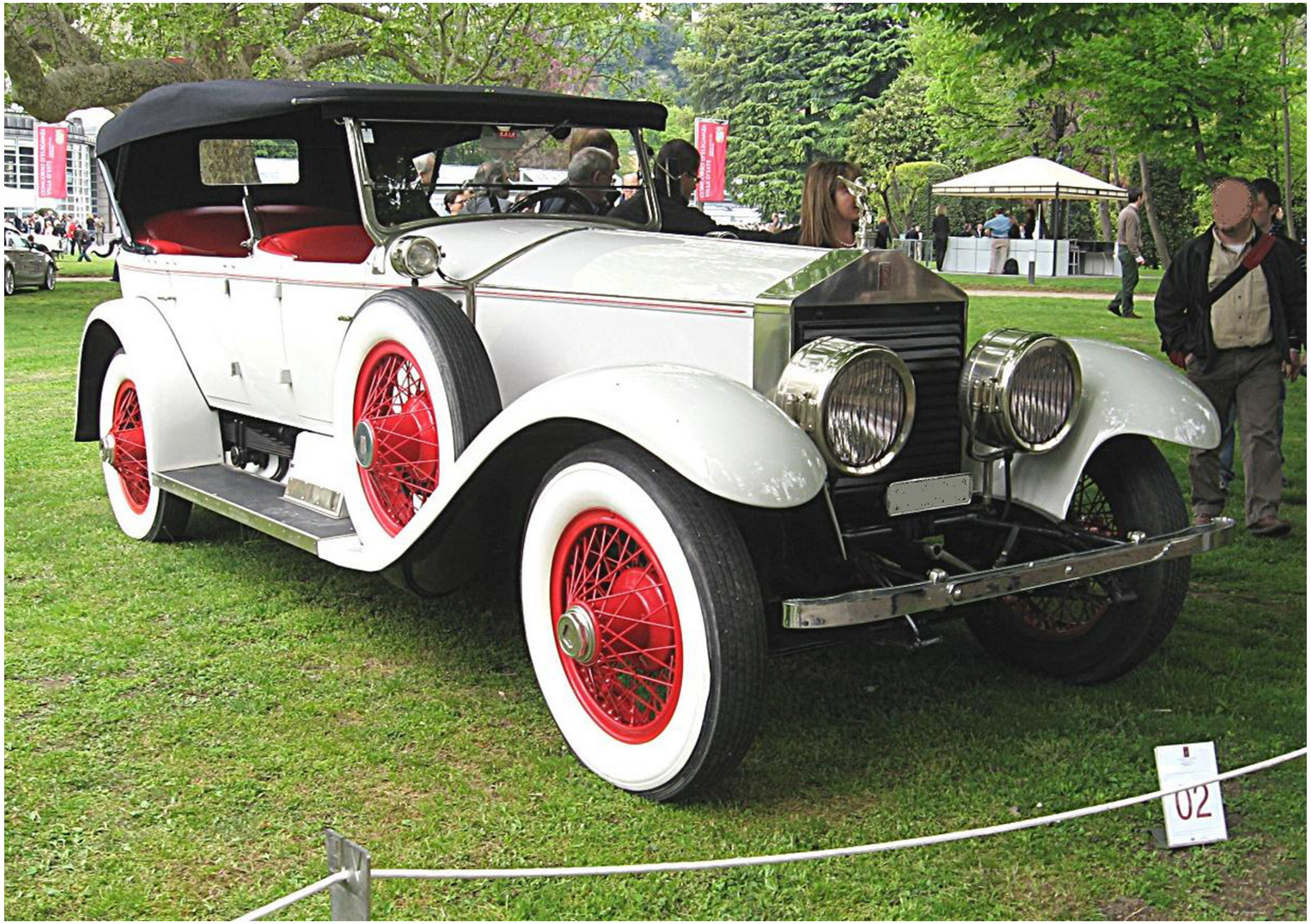


Figure 9. 1925 Rolls-Royce Silver Ghost Torpedo “Pall Mall Tourer”, coachbuilt by Brewster & Co, from wikimedia commons.

INTERIOR DETAILING: CARRIAGES AND RAILROAD CARS

During the Victorian era luxury carriages and railroad cars were the main mode of transport for the wealthy. These carriages and railroad cars were intricately detailed with lavish materials, embellishments and furnishings. The Victorian style has been a prominent form of inspiration as this era was excellent at emphasizing luxury and comfort. Contextually interior detailing is a vital concept as it allows the space to perceive a particular feel through use of materials, textures, patterns and furnishings. Figure eight features an image of Queen Victoria's railway carriage, this is a prime example of Victorian style; bold, rich colours, wooden furnishings, gold and beaded embellishments, velvet and silk walls and the combination of button tufting and quilted textures.

Figure 10. Railway carriage, London & North Western Railway, Queen Victoria's Saloon, built Wolverton Works, 1869, from The Board of Trustees of the Science Museum.

GLAMPING:

The term 'glamping' can be defined as a form of camping involving accommodation and amenities more luxurious than those associated with traditional camping. The concept of glamping has become an increasingly popular style of camping as it allows people to live within stunning nature settings with the addition of modern luxury. Furthermore, glamping enables the camper to experience wild and isolated parts of the world without having to sacrifice comfort. Glamping has emerged throughout New Zealand with businesses arising specifically created to provide a luxury camping experience. PurePods situated in the South Island have built luxury all-glass pods in remote areas allowing users to be surrounded by nature with the added bonus of lavish facilities. Figure 9 is another example of glamping, Wagonstays situated in Canterbury have created a luxury B&B through the modification of old wagons. Glamping is significant concept as this research aims to utilise the idea of glamping through an automotive context.

Figure 11. Kirwee Wagonstays, a 'glamping' B&B built using old wagons, from Wikimedia Commons.

3

CASE STUDIES

The following chapter highlights key contextual concepts through in depth case studies. Each of the concepts discussed provide further contextualisation and justification for the design process and final design phases.

CASE STUDY ONE:
RANGE ROVER HISTORY AND HERITAGE

This case study is focused towards exploring the history and development of Range Rover and it's vehicle models to gain a comprehensive understanding of the brands heritage, key themes and crucial design cues. With that knowledge on hand it will provide justification of design selection through out the iterative design process.

The Range Rover began in the 1970's and has evolved into the present day becoming world renowned for being the most luxurious SUV. The sophisticated elegant design incorporated with the most advanced technology has allowed the Range Rover and its offspring models to be set apart from the rest and lead the field of luxury SUVs.

ABOVE: *Figure 12.* Range Rover Velar - first prototype.

1969: The Range Rover Velar prototype, this was a prototype of the soon to be Range Rover Classic. The designers/engineers used 'Velar' over the prototypes to hide its real identity. Velar is derived from the Italian word velare meaning to veil or cover (Land Rover, 2018).

ABOVE: *Figure 13.* Three-Door Range Rover Classic.

1970: First production three door Range Rover. This was the first vehicle to provide permanent four wheel drive and feature a split tailgate, clamshell bonnet and continuous character line.

ABOVE: *Figure 14.* Five door Range Rover Classic.

1981: The five door Range Rover classic was made 11 years after the 3 door classic was released, adding more versatility to the popular model. The distinguishing features of the Range Rover began to become far more evident.

ABOVE: *Figure 15.* Range Rover Second Generation.

1994: The second generation Range Rover, a more luxurious upgrade to the classic was packed with new design features that have made it an iconic vehicle. The recognisable silhouette and specific design accents have made the Range Rover a world renowned luxury SUV.

ABOVE: *Figure 16.* Range Rover Generation Three.

2001: The third generation Range Rover provided even more luxury for the Range Rover fanbase. This was also the first Range Rover to be built with a monocoque single shell body. The design inspiration was taken from the tapering of the Italian Riva speedboat (Land Rover, 2018).

ABOVE: *Figure 17.* Range Rover Sport.

ABOVE: *Figure 18.* Range Rover Evoque.

2005: The Range Rover Sport was introduced. The iconic side gill was upgraded to give the Sport its own identity. The Sport offered buyers the same luxury paired with increased dynamic performance. Features included different engine options, one being a Supercharged 4.2 litre petrol engine. The Range Rover Sport also promoted a cross linked air suspension which allowed vehicle owners to adjust the riding height, increasing comfort for on and off road.

2011: The Range Rover Evoque, a luxurious cross-coupe was introduced in 2011. The vehicle included numerous characteristics of the LRX concept car in conjunction with classic Range Rover features. The cross-coupe was an ideal solution for city dwellers as it was compact in size.

ABOVE: *Figure 19.* Range Rover Generation Four.

2012: The fourth generation of Range Rover released in 2012 and featured Land Rover's first light weight aluminium body. The vehicle was large in size and luxury, retaining the A-line and updating the gill with some vertical feature lines. It also featured the next generation of Land Rover's Terrain Response System.

ABOVE: *Figure 20.* Range Rover Hybrid.

2013*:* The Range Rover Hybrid was the first hybrid Range Rover produced. The vehicle featured improved fuel economy and reduced emissions, though this did not reduce capability.

ABOVE: *Figure 21.* Range Rover Sport Generation Two.

2013: The second generation Range Rover Sport was also introduced in 2013, an upgraded and tumblehome version of its predecessor. The vehicle featured an updated gill surrounded by a sharp crease line. The Sport generation two was also provided with increased efficiency in the form of a 3 litre V6 engine. This is the model I have designed with.

ABOVE: *Figure 22.* The Range Rover Sport SVR.

2015: The Range Rover Sport SVR was all about high performance, the vehicle was produced by the special vehicle operations team and featured optimum power. This is the fastest Range Rover ever produced.

ABOVE: *Figure 23.* Range Rover SVAutobiography.

2015: The Range Rover SVAutobiography was Land Rover's model for redefining luxury. The SVAutobiography offered buyers customisation of detail with a wide range of colour palettes, material finishes and interior detailing. This attention to detail offered a premium luxury experience with emphasis on customer integration.

ABOVE: *Figure 24.* Range Rover Velar.

2017: The Range Rover Velar is Land Rover's latest luxury SUV model. The vehicle symbolises luxury through the new clean and sleek design. The Velar retains the iconic A-line with more tumblehome than recent models. The Velar sits lower than previous Range Rover models with an elongated, fluid stance. All of the classic Range Rover design cues are accentuated and drawn out, the new gill and character line between the wheels are beautiful examples of the sleek surface language injected into the Velar model.

The information discussed in this case study has provided this research with a number of observations;

- Since their foundation, Range Rover has become a design advocate of the luxury SUV. The iconic silhouette and A-line has remained very similar. Although this silhouette remains very much alike, subtle alterations of the silhouette and overall surface language adapt the purpose of the vehicle. Models such as the Range Rover Sport, SVR and Velar have more tumblehome than others, indicating they are sportier and faster. The idea of tumblehome can be seen through their design cues, the Velar is specifically sleek and elongated, this is reciprocated through the lights, pillars and cant rail. Other models of the Range Rover bloodline possess more luxury based surface languages. The SVAutobiography, third generation and fourth generation Range Rovers were more sizeable, with less tumblehome. The pillars ran at a higher angle, giving these models a tall, luxurious stance.

- Several consistent design cues were evident throughout the Range Rover bloodline; the continuous character line running from tailight to headlight, the silhouette featuring a sharp backlight angle, gills on each wing panel and the character line running between the wheels, flowing towards the tailgate.

CASE STUDY TWO: FREEDOM CAMPING

This case study focuses on the concept of freedom camping and the situation within New Zealand. Moreover, this case study seeks to identify market gaps within the tourism and freedom camping sectors.

The context of habitation within vehicles, especially freedom camping has become an extremely popular interest within the tourism industry and people with vehicles in general (Keenan, 2013). Keenan defines freedom camping as camping 'freely' on public land rather than a registered campground (2013). The concept of freedom camping is a huge sector of tourism in New Zealand due to the reputation of beautiful, green landscapes. Freedom camping has produced a lot of interest, both positive and negative. In New Zealand, local communities expressed significant concern environmentally and socially over the popular leisure activity. In turn, this raised a large amount of media interest, resulting in calls for tighter management from district councils (Keenan, 2013).

These issues with freedom camping have led to the introduction of The New Zealand Freedom Camping Act 2011, outlining legislation to define freedom camping and enforce tighter laws surrounding the activity. Importantly, any waste produced during the act of freedom camping must be disposed of into 'an appropriate waste receptacle', this includes rubbish bins, public toilets or bulk waste disposal units (New Zealand Government, 2017).

Although freedom camping laws are stringent in New Zealand, the market for habitable vehicles such as recreational vehicles (RV), campervans, caravans and rooftop tents has boomed, with an increase of technology built purposefully for freedom camping. Various businesses have emerged offering a range of habitable vehicles for purchase and hire. Jucy is a notable example based in New Zealand and Australia. Jucy offer various self-contained and non self-contained campervans, modified with hard shell extensions or rooftop tents. Jucy and other similar companies in the market are aimed at tourists and holidayers as a relatively inexpensive form of travelling New Zealand and camping.

The information discussed in this case study has provided this research with a number of observations;

- New Zealand has recently cracked down on freedom camping and implemented legislation that has enforced tighter laws around the popular leisure activity. With that being said, various other countries has vastly different views and laws surrounding freedom camping. For example, in England, Northern Ireland and Wales, freedom camping is completely illegal with the exception of Dartmoor as virtually all of the land is owned, therefore the camper must use designated campgrounds or ask the landowner for permission (Lewis, 2016). Scotland however, allows freedom camping on most unenclosed land as long as you follow the simple policy; “leave no trace” (Lewis, 2016).

- The enforcement of the New Zealand Freedom Camping Act 2011 requires freedom campers to respect their environment, act sustainably and clean up after themselves to avoid receiving infringements with local government. This is a much needed piece of legislation to ensure the popular leisure activity does not receive further scrutiny. Moreover, when designing a habitable environment it is necessary to abide to this legislation and include simple forms of waste disposal such as portable toilet and sealed rubbish bin.

- Specifically within New Zealand, there are many companies providing habitable vehicles for freedom camping. With that being said, many of these businesses are relatively inexpensive and do not emphasize luxury. The companies that do provide luxury are all utilising large, bulky mobile homes that in some instances could not reach certain areas due to vehicle design. This is a potential gap in the market for a product that emphasizes luxury, yet fits to a practical vehicle. Additionally, the introduction of a more lavish mobile habitat on the market has the potential to change negative perspectives on freedom camping. Moreover, with the introduction of businesses such as ‘Campable’, which set up various freedom camping spots across New Zealand through private owners, presents a potential venture for luxury mobile camping experiences.

CASE STUDY THREE:
LARGE SCALE CUSTOM 3D PRINTERS

The following case study investigates an emerging 3D printing company BLB Industries who have recently teamed up with NorDan a Swedish door and window manufacturer to produce a custom large-scale 3D printer capable of printing full size products. The purpose of this case study is to further justify why 3D printing is an viable form of manufacturing for large-scale applications.

NorDan who have always held a strong sustainable approach to manufacturing decided to make a move towards 3D printing enabling them to offer clients cutting edge technology for the design and production of windows and doors (3ders.org, 2018). The 3D printer was custom built by BLB industries who specialise in custom builds utilising Fused Granular Fabrication (FGF). FGF is an offspring of FDM and creates physical objects through the same process of printing the material layer by layer onto a printing platform. The difference between FGF and FDM is that FDM uses a thermoplastic filament which is melted through a heated extruder whereas FGF uses granular plastic that is melted first and then fed through an extruder at a constant speed (BLB Industries, 2018). BLB Industries explain that FGF is most commonly used for prototyping, though end-products can be fabricated with post-processing techniques (2018).

The resulting custom 3D printer featured a dual extruder system allowing for multi-material printing. The printer is capable of building up to 2.5m x 1.5m x 1.5m, with an extrusion rate of 14 kg of plastic per hour. Furthermore, larger parts would be able to be produced, they would just require to be assembled post-printing (3ders.org, 2018). Currently, the 3D printer is in operation at NorDan's facility, producing prototypes and various commercial end-products.

BLB Industries further specify that they are capable of producing custom machines with build sizes of up to 5m x 5m x 5m. Multiple extruders are available enabling multi-colour and multi-material printing. Different nozzles are readily accessible with three standard sizes; small (0.6mm - 2mm) with a maximum output of 1 kg per hour, medium (2mm - 8mm) with a maximum output of 14 kg per hour and large (6mm - 14mm) with a maximum output of 35 kg per hour. Larger nozzles are utilised for faster, cheaper and stronger structures whereas smaller nozzles produce finer details at a slower rate (BLB Industries, 2018). Moreover, the FGF technology can use various granular thermoplastics and biocomposites. NorDan was particularly interested in the use of sustainable biocomposites, such as wood, cork, straw and hemp (3ders.org, 2018).

The information discussed in this case study has provided this research with a number of observations;

- NorDan's collaboration with BLB Industries is promising result for the application of large-scale 3D printing in various industries. Furthermore, the FGF technology has an extremely close relationship with FDM technology in both the process and materials utilised.

- BLB Industries custom machines maximum build size of 5m x 5m x 5m is considerably sizeable and would comfortably fit the design output of this research; a habitable sleeping environment attached to a Range Rover. Moreover, it can be positively speculated that the maximum build dimensions would be suitable for various other large-scale applications within the automotive and aerospace sectors. With that being said, ultra large-scale applications would require post-processing to develop an end-product.

4

METHODOLOGIES

The research methods applied in this thesis are categorised under two predominant methodologies, Research for Design (RfD) and Research through Design (RtD). These two modes of research work in conjunction to support and reinforce the objective of the research in examining the use of large-scale FDM 3D printing technology for the production of a habitable sleeping environment attached to a Range Rover Sport.

Methodologies Synopsis

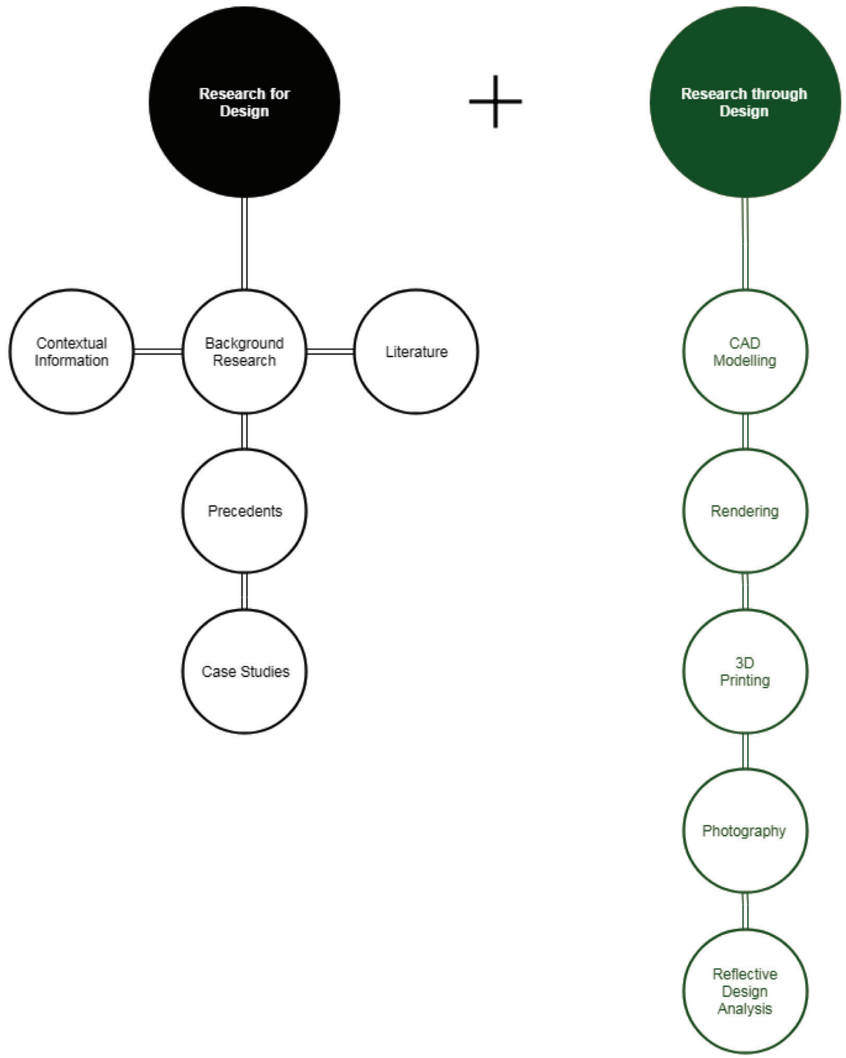


Figure 25. Methodologies Synopsis. Breaking down the methods utilised under Research for Design (theory) and Research through Design (practice).

RESEARCH FOR DESIGN:

Research for design provides the basis for the theoretical framework that supports and bolsters the intended design inquiry. Jonas describes RfD as a mode of research that is used to generate knowledge and understanding for a design/inquiring system, with the intention of improving and strengthening the design/inquiry process (2014). The ability to gain knowledge before the design project has begun, allows the designer to enter the design process with a comprehensive understanding of the relevant theoretical fields. Furthermore, RfD helps to strengthen the structure and refine the scope of the design practice, producing a more robust design process. Three research methods were utilised within the RfD methodology, background research, precedent concepts and case studies.

METHODS:

Background Research:

Background research is a vital method of inquiry and can be broken down into two subcategories; literature and contextual information, meaning non-scholarly sources of information including articles and websites associated with key concepts. The background research chapter acts as the theoretical backbone for this thesis, gathering beneficial information on AM as a whole, FDM 3D printing processes and materials, and current applications, developments and limitations of large-scale FDM 3D printing. Furthermore, the background research method has gained significant knowledge surrounding the automotive industry's negative environmental reputation. Additionally, mass customisation is discussed in consideration with 3D printing and the positive implications the technology provides.

Precedent Concepts:

Precedent concepts have assisted as a method of inspiration and knowledge generation regarding ideas that have helped form the broader scope of this research. Moreover, the precedent concepts discussed have influenced design decisions throughout the design process and final design phases.

Case Studies:

Case Studies have provided this research with in depth analyses surrounding concepts that are most vital to this research. The case study method has focused on three predominant concepts; the history and heritage of Range Rover, freedom camping and large-scale custom 3D printers. Each of the case studies have provided the researcher with a greater understanding of each concept. Furthermore, the case studies identified key observations that succeeded to inform and aid the researcher through design thinking and decision making within the design process and final design phases.

RESEARCH THROUGH DESIGN:

Research through design acts as the foundation of design practice. Zimmerman, Stolterman and Forlizzi define RtD as an inquiry process revolving around the making of a product, service, environment or system. (2010) The RtD methodology demonstrates both the design practice and the end product as the basis of the research. Various methods are employed to develop the design process, allowing the designer to critically analyse the methods applied and their design decisions. Chow states that RtD produces both knowledge of and knowledge for design (2010). Design analysis or reflective practice plays a vital role through RtD as designers are continuously gathering relevant information and evaluating each step throughout the design process, learning what methods applied are suitable for the successful development of the intended product. Jonas describes design as the basis of how humans make their world. (2007) With that being said, RtD gives designers the opportunity to produce their ideal design solution for any given situation. Zimmerman, Stolterman and Forlizzi emphasize how design researchers see RtD as a means of expanding the scope and focus of designers, by challenging current perceptions on the role and form of technology. The aim of this thesis is directly related to the application of FDM 3D printing for the production of habitable sleeping environments, highlighting the technology’s ability to oppose traditional methods of design practice within the automotive industry. This will be achieved through multiple methods including sketching, CAD modelling, rendering, FDM 3D printing, photography and reflective design analysis.

METHODS:

Sketching:

Sketching is an ideal option for form generation and visualisation within the preliminary design phase as it allows the designer to rapidly produce concepts that can then be further explored through CAD. Simple 2D profile sketching was utilised in this research, specifically in the initial design phase. Sketching profiles above the Range Rover was a quick method to help understand how certain angles and curves would look. Sketching also served as a rapid reflective tool for the analysis of renders further through the design process.

CAD Modelling:

CAD modelling or 3D modelling is a primary design tool that is used to design products for manufacturing. The world has become digital, meaning that most end-products will have been developed through CAD software, including vehicles. CAD utilises digital data which is abundant within the automotive industry, CAD modelling in this research began through the purchase of a high detail digital model of a Range Rover Sport. Rhino was the predominant software employed in this thesis, the program was used to design all of the 3D models in preparation for rendering and 3D printing. Moreover, CAD modelling assisted as a primary method in the development and refinement of the habitable concepts produced. The iterative use of Rhino in the initial design stage enabled a critical analysis and evaluation of each concept to help refine the exterior form. In the latter stages of the design process, Rhino assisted in further development through the addition of details and design cues to help stylise and connect the concepts with the vehicle.

Photography:

Photography is an important design tool for the development phase of the design process. Photographs are a clear method of process, they are also an easy medium for analysis and evaluation. Within this research photography was used throughout the preliminary design phase to analyse ergonomics and accessibility of entering the habitable environment.

Rendering:

Rendering allows the designer to add high levels of detail to 3D models. Rendering software such as Keyshot holds various materials and textures that can be added and displayed on different parts of the model. Furthermore, rendering software provides the designer with environments to render in, such as outdoor landscapes or indoor lighting environments. Rendering displays a digital representation of what the physical end-product may look like. This research has developed significantly through the mastering of rendering as it presented life-like visions of the 3D concepts produced. Alongside this, rendering softwares enabled the inclusion of human models to fit within the designed space, this allowed each concept to be easily analysed and evaluated adding credibility to the project. Rendering operated as the primary method of development alongside CAD modelling and has been utilised iteratively throughout the design process. Rendering also served as a method for final outputs as it gives a close representation of the end-product.

3D Printing:

3D printing allows the designer to create physical models straight from the digital file in a single process. Moreover, 3D printing presents the research with physical representations of digital concepts, enabling cohesive analysis of both physical and digital models for refinement. Within this research 3D printing, specifically FDM was used to understand scale, materiality and overall feel of the design concepts. FDM 3D printing assisted in analysing, evaluating and refining the final design concept. 3D printing is an important method as it helps to improve and develop features of the concept that may not be recognisable in the digital model.

Reflective Design Analysis:

Reflective design analysis is a vital method throughout the design process. This reflective tool is utilised at each stage of design development to critically analyse and reflect on the design concepts produced. In turn, the analyses and discussions shape and refine the scope of the research, resulting in the best possible design solution. Reflective design analysis is also an important tool for the design solution, enabling the designer to speculate future refinements. Within this research reflective design analysis has been utilised throughout each of the design phases, it was specifically significant in refining the exterior form and design detailing as the habitable environment needed to be stylised with a close relationship to the vehicle.

5

DESIGN PHASE ONE

Within the following chapter, the preliminary design phase is broken down into four sections;

- Why Range Rover?
- Range Rover Sport: Surface Language Analysis
- Initial Form Generation
- Initial Spatial Investigation

Firstly, it is discussed why Range Rover was selected. Secondly, the Range Rover surface language analysis looks into the intricate and iconic design language of the Range Rover Sport. Furthermore, the analysis identifies overall dimensions, fundamental curves within the A-line and various design cues pivotal to the surface language of the vehicle. The third section displays the process of initial form generation through sketches and renders, following this four concepts were developed aiming to match design details of the vehicle. The final section of the chapter demonstrates design thinking and practice surrounding human scale in comparison with the vehicle to decipher how much space the environment requires to be habitable and comfortable.

WHY RANGE ROVER?

From its founding in 1978, Range Rover has risen into a leading force in the automotive industry through mastering the design and production of luxury SUVs. The Range Rover bloodline of vehicles and their iconic silhouette has become a recognised symbol of luxury across the world. Firstly, the word luxury defines why Range Rover was the first choice for this research. Range Rover has continued to emphasize luxury in every element of their vehicles, through pure, seamless design, materiality, colour palettes, attention to detail and interior craftsmanship. Alongside the symbolism of luxury, contemporary Range Rover models all succeed in retaining features of their unique heritage, whilst also utilising the latest technologies to set the standard for luxury SUV design.

The concept of a habitable sleeping environment is a timely idea and currently there are no vehicles or products available for freedom camping that offer luxury and practicality. The Range Rover was an ideal selection for this concept as the digital manifestation of surface language provided an opportunity to embody the luxury of the vehicle through both exterior and interior design, resulting in a bespoke, tailored sleeping environment for the vehicle. Specifically the recent Range Rover Sport (second generation) was selected because the vehicle has been optimised for off road use and sits lower with more tumblehome than a regular Range Rover. The Sport model is the ideal option for travelling to remote places that cumbersome, luxury motorhomes would not possibly be able to reach.

RANGE ROVER SPORT: SURFACE LANGUAGE ANALYSIS

A high-detail CAD model of the most recent Range Rover Sport was purchased under editorial rights for modification for the duration of this research. It was crucial to understand the surface language of this vehicle to make justified design decisions throughout the design process. Every surface is digitally mapped, providing a digital 'cloud' of information that retains the vehicle's individual identity. This surface language analysis highlights significant design cues that are distinguishing of the Range Rover Sport and Range Rovers in general.

DIMENSIONS:

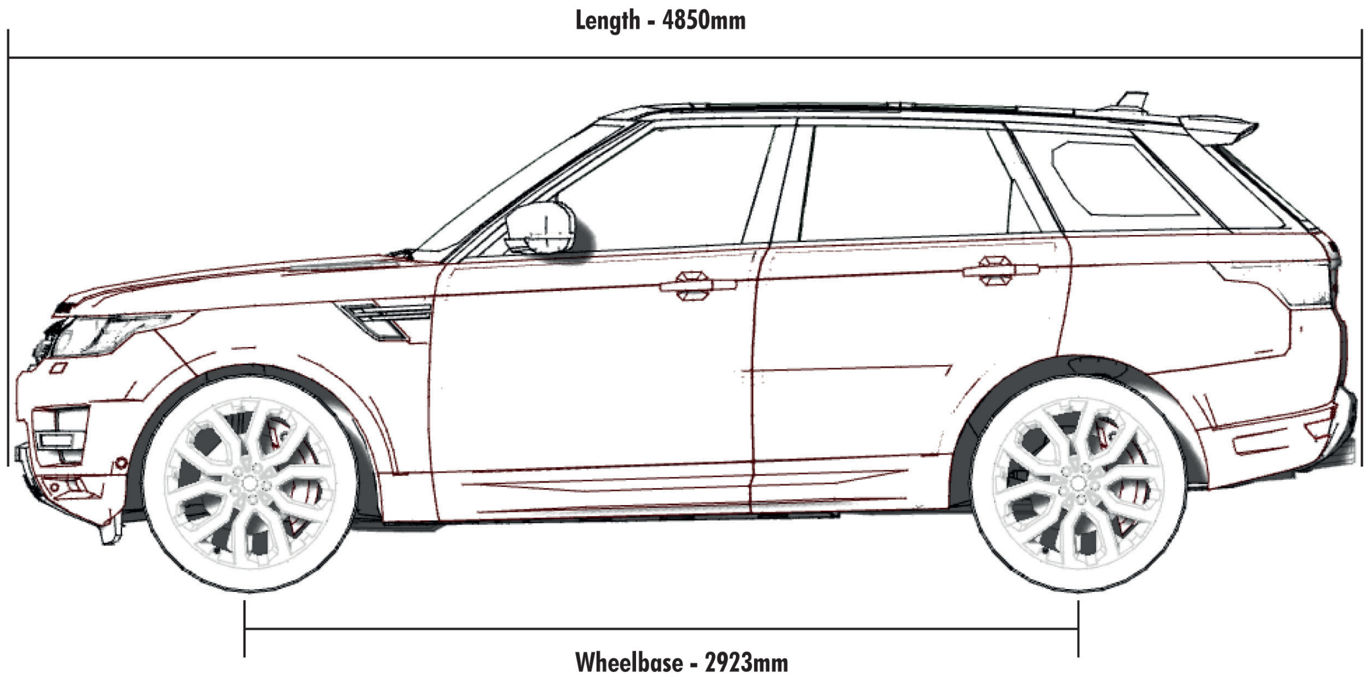


Figure 26. Profile view highlighting the Range Rover Sport dimensions.

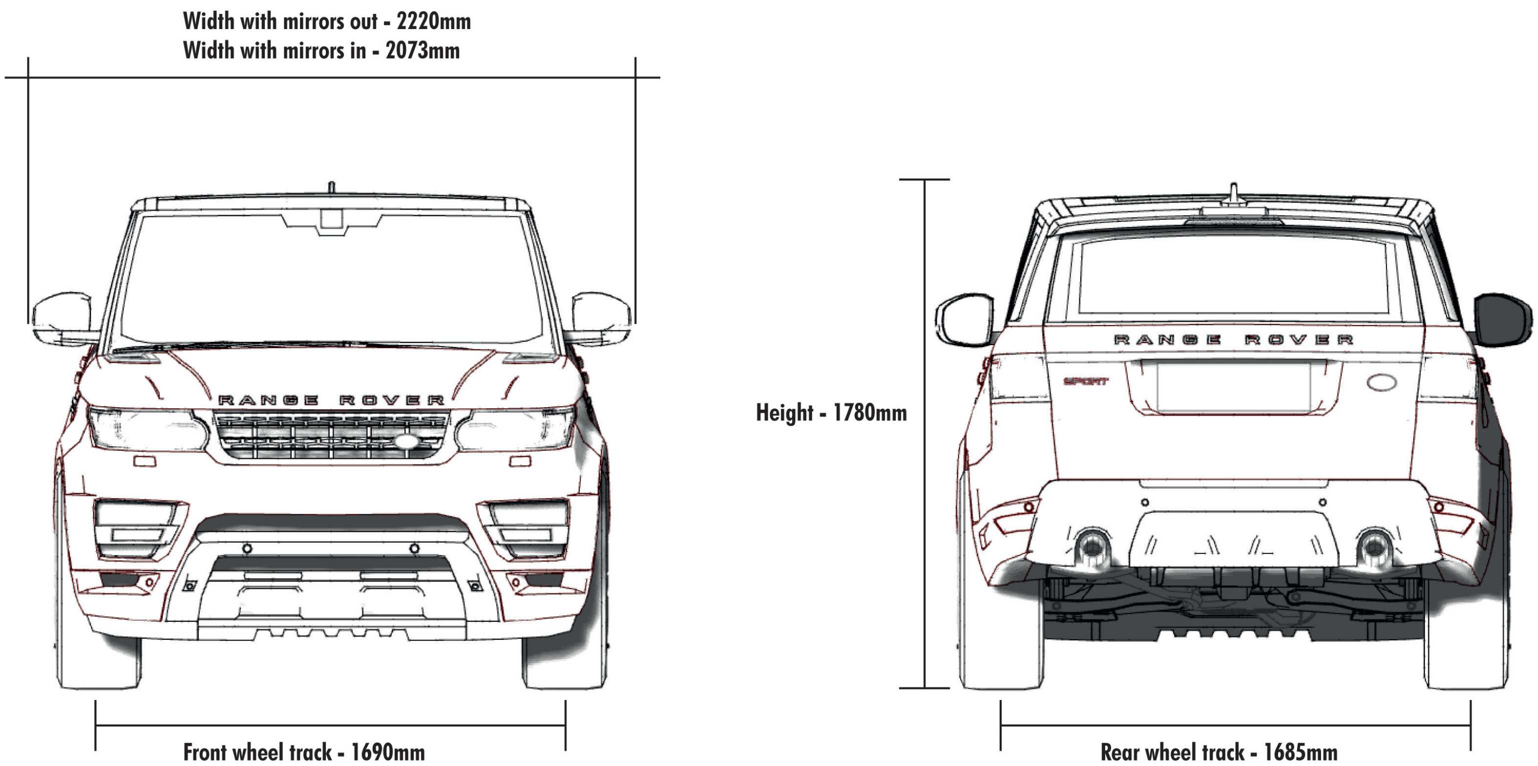


Figure 27. Front and rear views featuring the Range Rover Sport dimensions.

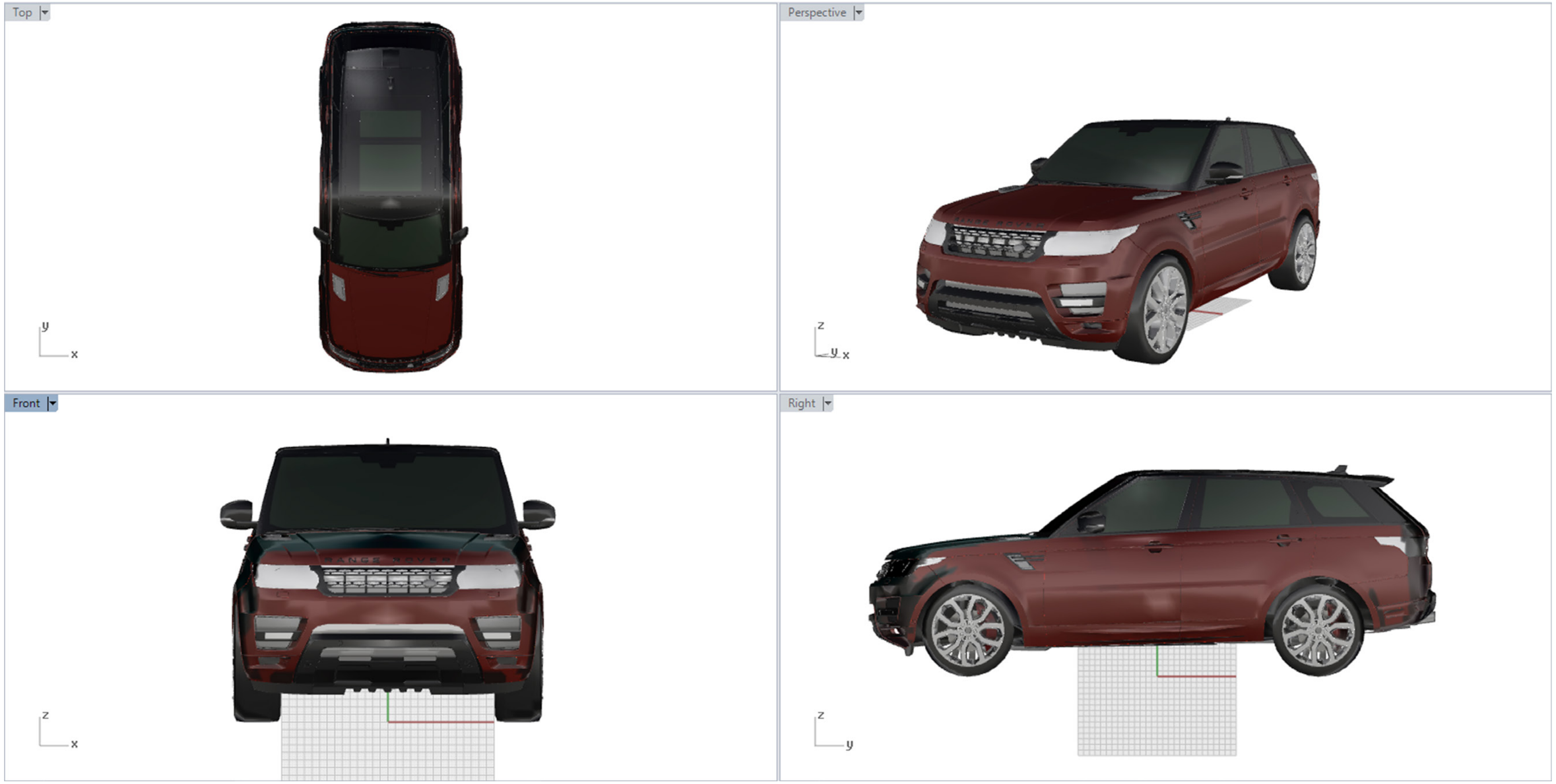


Figure 28. High detail CAD model of the Range Rover SPort.

Figure 29. CAD model of Range Rover Sport, the geometries and surface mapping are highly complex.

SURFACE LANGUAGE:
SIDE PROFILE

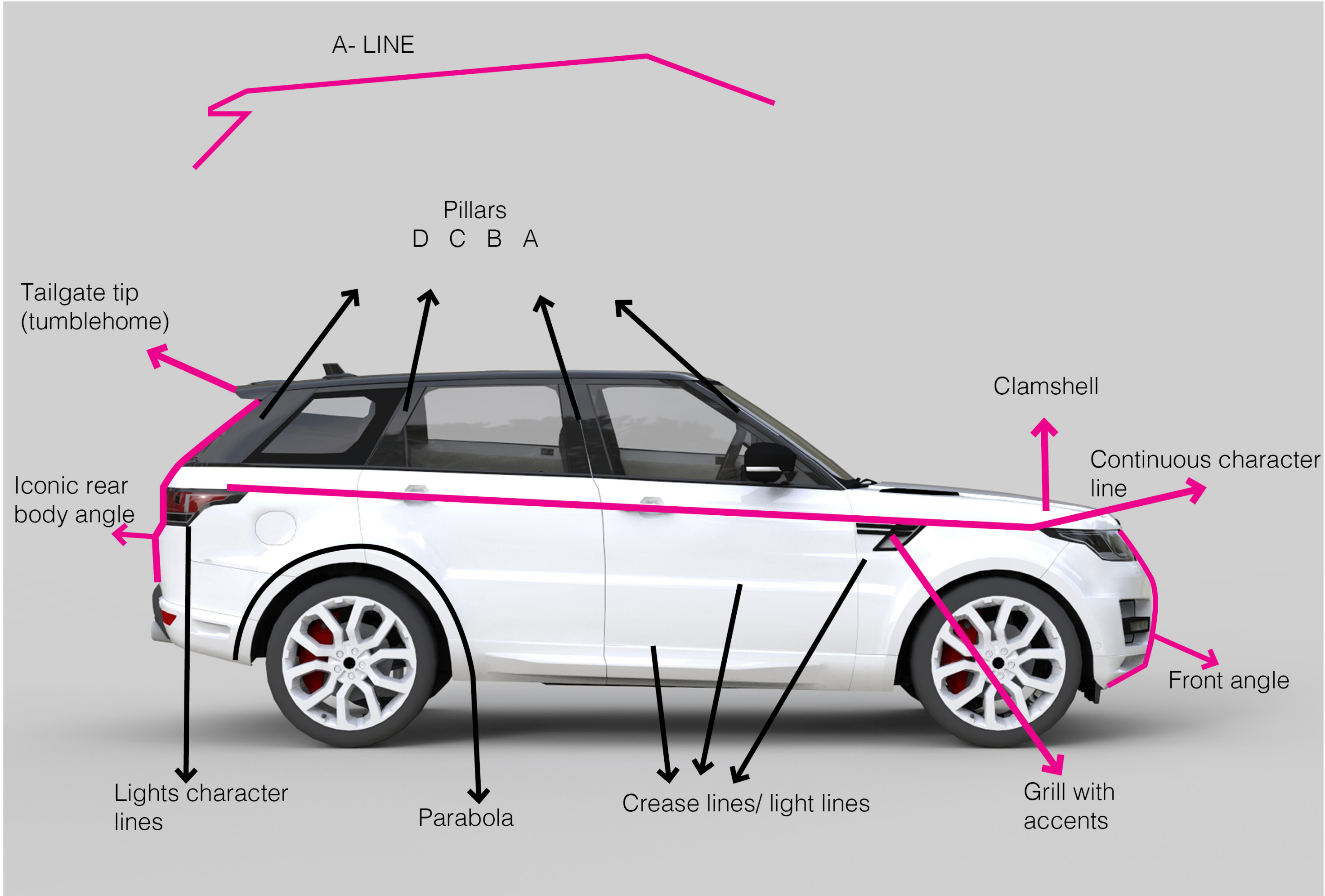


Figure 30. Side profile view identifying significant design cues and surface language of the Range Rover Sport.

SURFACE LANGUAGE:
FRONT PROFILE

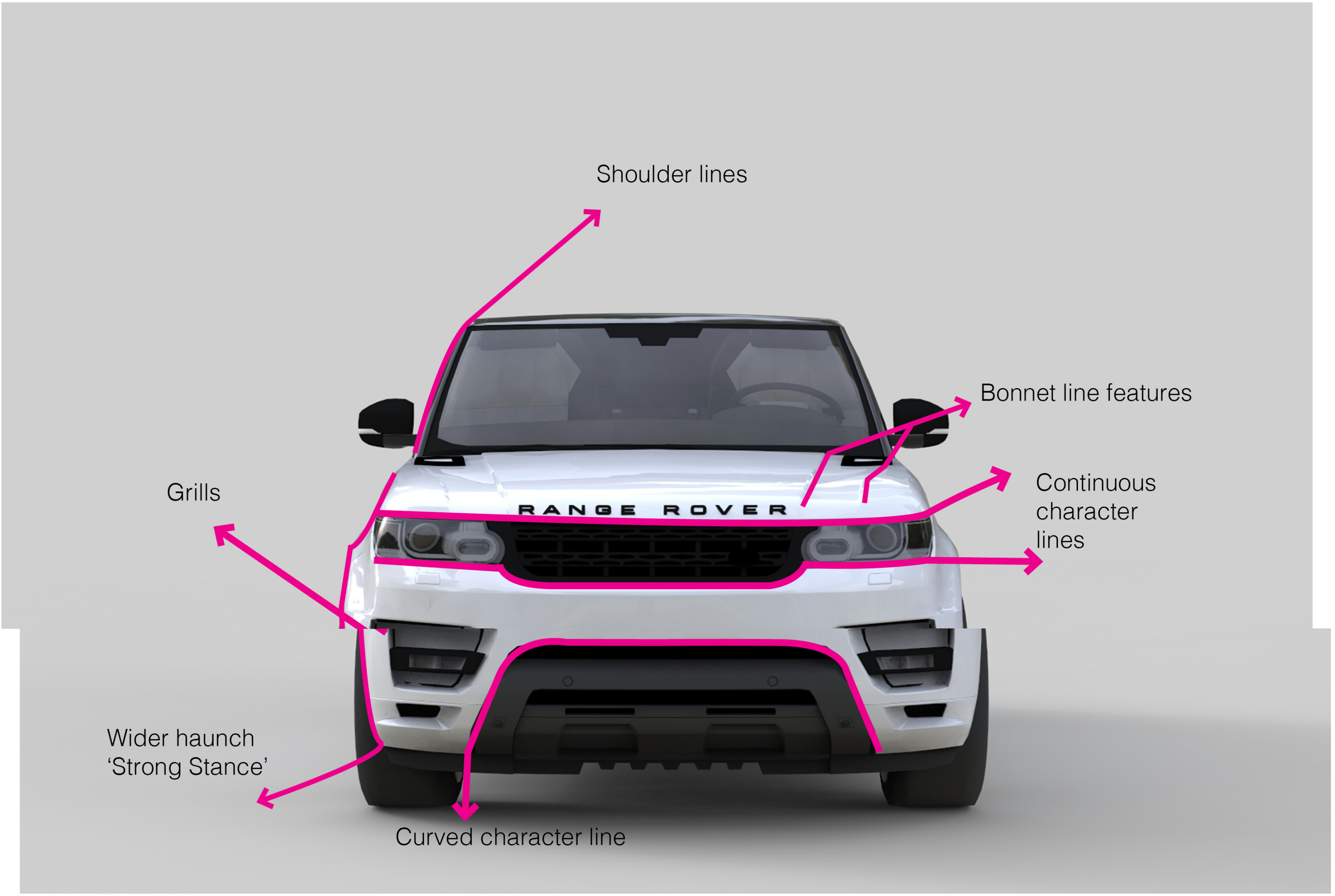


Figure 31. Front profile view identifying significant design cues and surface language of the Range Rover Sport.

SURFACE LANGUAGE: BACK PROFILE

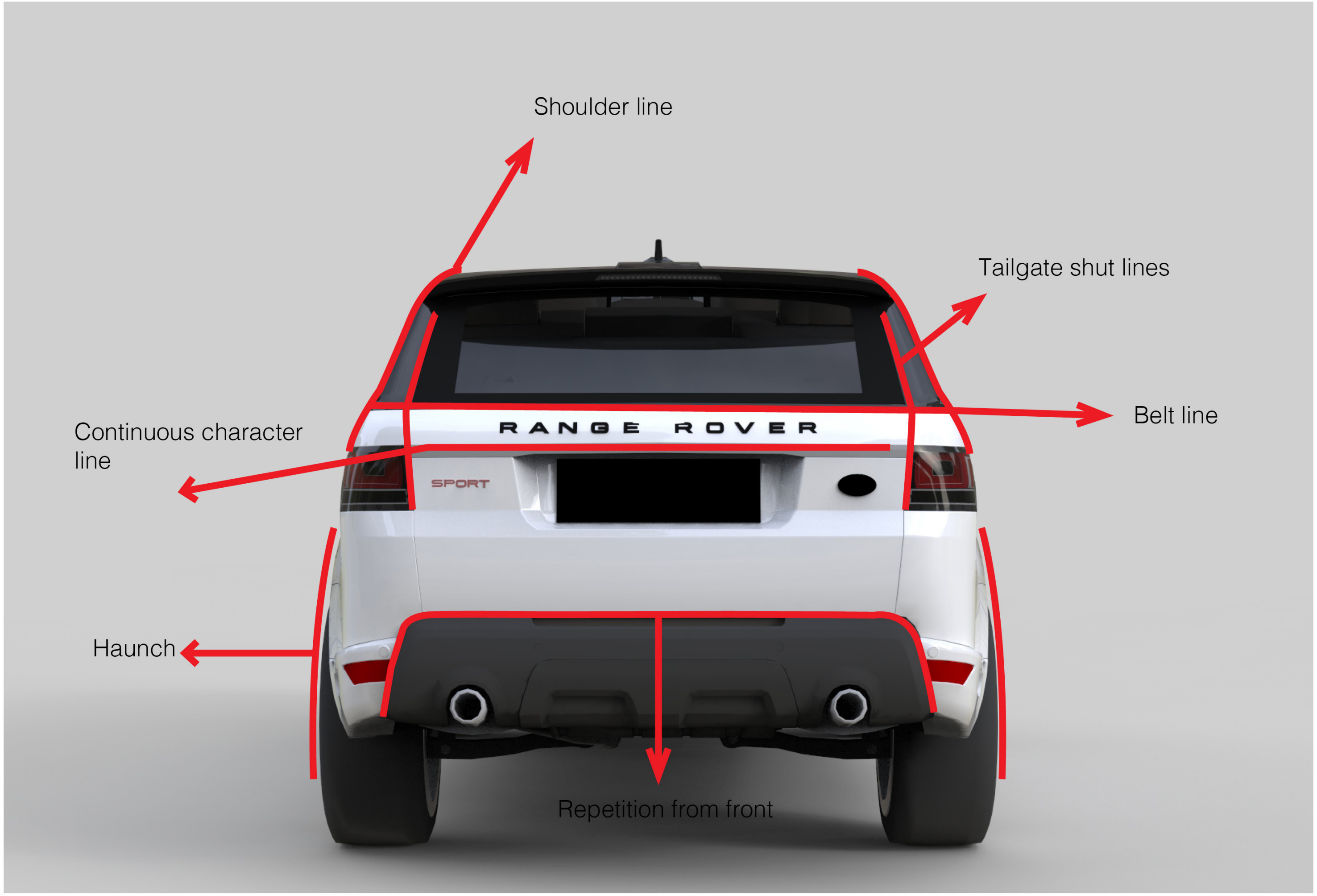


Figure 32. Side profile view identifying significant design cues and surface language of the Range Rover Sport.

The surface language analysis was a necessary starting point as it helped to understand automotive design terms and the Range Rover Sport design language with more ease. Greater knowledge of the surface language thus enabled design cues to be utilised in the design concepts. Numerous key design cues were identified that remain constant throughout the Range Rover bloodline, as discussed in case study one. The silhouette of the Range Rover is a distinguishing feature that has remained similar from day one with a strong rear angle and subtle front radius. Other instances of Range Rover exclusive surface language included the continuous character line running along the side panels from tail light to headlight, the clamshell bonnet and gills on the wing panels. The overall surface language of the vehicle is obviously 'sporty', this is evident through increased tumblehome and a lower screen angle resulting in a more condensed and sleek A-line. The front of the vehicle reiterates the sporty feel through multiple gills, crease lines on the bonnet and a strong stance due to wide haunches. Following this analysis it is determined that specific design cues must be selected to truly embody the vehicle and its overall surface language. The aim is not to design a car on top of a car, it is to take the design language and translate it in a subtle yet parallel way.

INITIAL FORM GENERATION:

The initial forms produced were purely for testing of the CAD software Rhino and rendering software Keyshot. The first shapes were designed without any relationship to the Range Rover, to gain a simple understanding of scale and form above the vehicle. This initial ideation was successful in providing the research with the knowledge that the exterior form of the sleeping environment must be stylised to match the vehicle.

Figure 33. Initial form generation designing directly off the roof.

Figure 34. Continued form ideations.

PROFILE SKETCHES:

Profile sketching over the top of vehicle images was a quick and simple method to develop exterior profiles which can then be taken into Rhino and developed into three dimensional forms. Design cues and curves were replicated above the vehicle. Within these initial sketches the profiles mainly used the front and rear curves of the Range Rover’s silhouette. The crease line accompanying the side gills has been incorporated into the sketches starting from the A-pillar.

Figure 35. Sketch one. Initial profile sketch mirrored the front curve. Original image has been modified, courtesy of Jaguar Land Rover.

Figure 36. Sketch two. Initial profile sketch featuring an enlarged crease line from the gill. Original image has been modified, courtesy of Jaguar Land Rover.

Figure 37. Sketch three. Initial profile sketch incorporating the front curve with a detail coming from the A-pillar. Original image has been modified, courtesy of Jaguar Land Rover.

Figure 38. Sketch four. The crease line from the gill has been flipped into a detail from the A-pillar. Original image has been modified, courtesy of Jaguar Land Rover.

Figure 39. Sketch five. The front curve as been replicated and rotated back, creating a sharp front angle. Original image has been modified, courtesy of Jaguar Land Rover.

Figure 40. Sketch six. The front curve and crease line have been reiterated into the form, the rear curve has flipped the tailgate curve. Original image has been modified, courtesy of Jaguar Land Rover.

CONCEPT ONE:

The first concept aimed to match the profile shown in figure 40. The concept was able to replicate the front curve of the Range Rover's silhouette. The side panels of the concept were drawn out to emphasise the wide haunches that feature on the Range Rover Sport. The rear end of the concept tapered down, reducing in space considerably.

Figure 41. Concept one highlighting the strong stance of the vehicle through the inclusion of ‘hips’.

CONCEPT TWO:

The second concept was much larger than the first concept, sitting tall on the vehicle. This concept, like the first, utilised the Range Rover's front curve and resembled the profile from figure 34. The angles on this concept were sharp, causing them to lack fluidity. The rear end of this concept was more defined, mirroring the backlight of the vehicle. The side panels were kept straight, this seemed to make the concept look taller, the side panels definitely needed to show a relationship to the stance and front silhouette of the Range Rover.

Figure 42. Concept two. Direct matching with the front curve, The flat side panels make the concept look taller.

CONCEPT THREE:

Concept three sat more compact on top of the vehicle, vastly smaller than the other two concepts. More emphasis was put into using design cues from the vehicle. The front curve was smaller but still resembled the forward curve of the Range Rover. Instead of tapering towards the rear of the vehicle, this concept matched the cant rail. Alongside this, a detail on the side panels was included that aimed to replicate the cant rail. The rear curve mirrored the tailgate silhouette, which served as a nice detail. Again, the side panels were straight, contrasting severely from the shoulderlines as seen in the front view of figure 42.

Figure 43. Concept three. This form utilised the tailgate lip to match the rear curve.

CONCEPT FOUR:

The final preliminary concept was the smallest design, yet it felt like it accompanied the vehicle more than the other concepts. The overall form sat very similar to the Range Rover's A-line, with the addition of the front curve. The front curve was slightly altered, elongating the small angle at the bottom of the Range Rover's nose, whilst the bigger front curve of the silhouette was shortened, resulting in the compact side profile. The rear of the vehicle was mirrored more closely than concept three, matching the angle of the backlight and retaining the lip on the tailgate.

Figure 44. Concept four. This concept emphasised the tailgate lip and backlight with a sharp correlating angle.

The preliminary concepts discussed were a quick and iterative method to transform two dimensional profiles into three dimensional forms. Furthermore, CAD modelling was utilised with the purpose of relating the sleeper to the Range Rover. This initial process served as in important mode of research as it was quickly discovered that two dimensional profiles were a challenging visual element to model from. Starting a three dimensional model from only the side profile resulted in loss of accuracy. The side panels would look as intended whereas, the front and rear panels would show little design intent. It was understood that the concepts needed to utilise design cues from the front and rear panels to produce a more cohesive form. Alongside this, the concepts lacked regard to spatial awareness, which led to the next form of inquiry; understanding the use of space and designing with an idea of dimensions.

INITIAL SPATIAL INVESTIGATION:

The fluctuation of size within the initial concepts led to an inquiry investigating how much space would be required for the sleeper to fit one or multiple human beings. The use of space is an important concept as the resulting forms needed to be physically and psychologically comfortable. Moreover, it was determined that the environment would be a shared space. The personal aspect of this research proceeded in the sleeper being designed for a 6 foot male and a 5 foot 5 female. In turn, this allowed for closer spatial accuracy in future concepts. The initial spatial investigation identified roof dimensions of the Range Rover Sport and analysed the preliminary concepts by placing 1:1 human scale models inside section cuts of each form.

Figure 45. Height of the human models in comparison with the Range Rover Sport. The same models will be used throughout the design process.

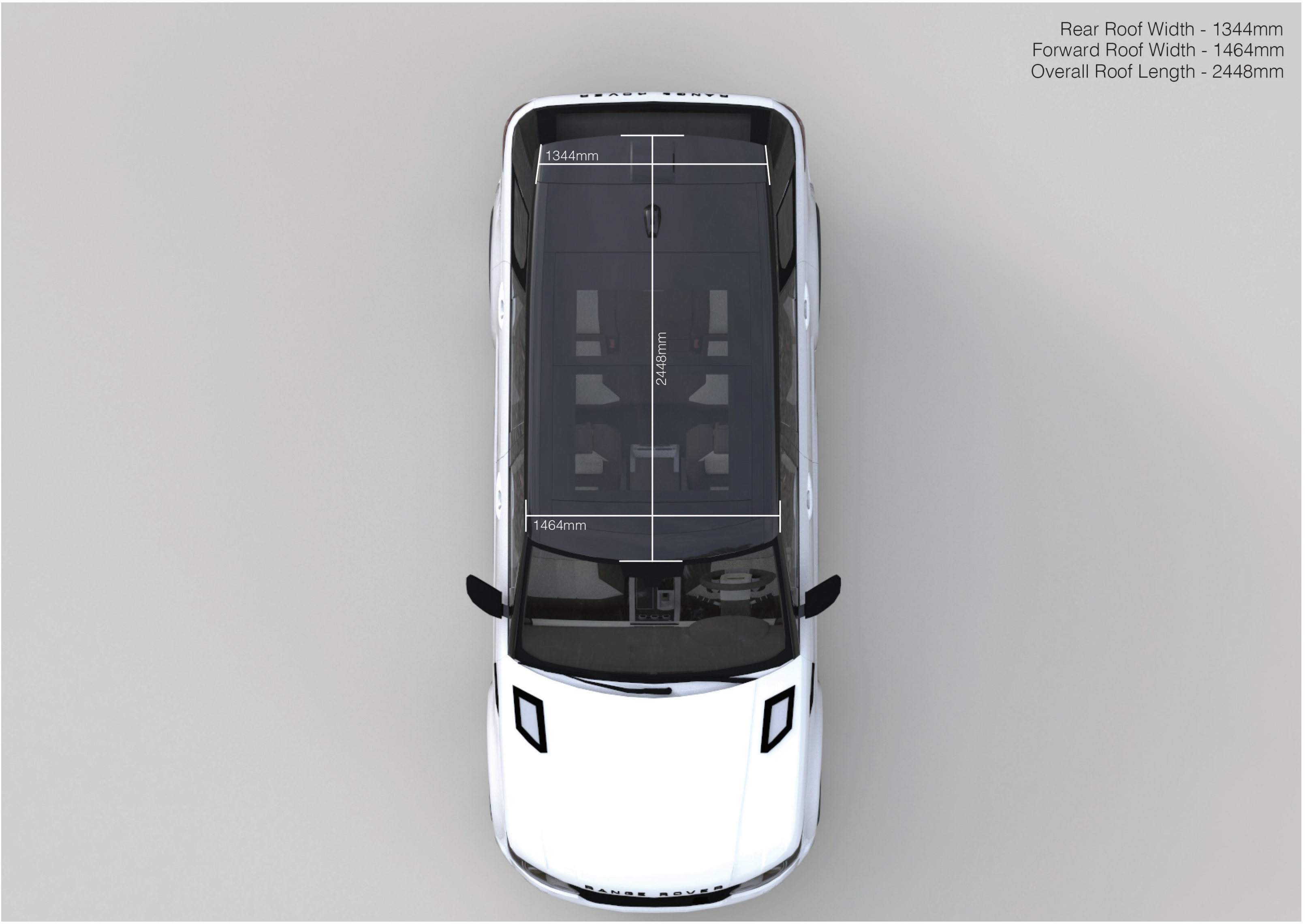


Figure 46. Plan shape of the Range Rover with added roof dimensions.

CONCEPT ONE:

Concept one featured a higher front end, therefore if the user lay with their feet facing the rear of the vehicle they would have more room. The tapered end was seen to problematic as there was very minimal space. Furthermore, the user would have to access the sleeper from the side. The sectional cuts display the lack of height in this concept, both people would not be able to sit up straight, which could lead to claustrophobia.

Figure 47. Section cuts with two 1:1 scale humans inside to help understand space within the form, the first concept was too low for the people to sit up.

CONCEPT TWO:

Concept two was the largest of the four, the exterior form looked considerably sizeable on top of the vehicle. With that being said, the interior space was just about right. Both people were able to sit up comfortably. It was immediately determined that the sleeper would need to be substantial to fit both people. Alongside this, the exterior form would need to flow with the vehicle to avoid it looking excessively big.

Figure 48. Section cuts of concept two reveal there is far more space than concept one.

CONCEPT THREE AND FOUR:

Concept three and four both appeared more compact and visually they matched vehicle far better. Unfortunately when sectioned they were instantly too small. The concepts only just fit a person lying down, which resembled a coffin.

This spatial analysis played a vital role in understanding space within digital forms. The sections and inclusion of human models served as an appropriate method of spatial inquiry, leading the research to informed design decisions.

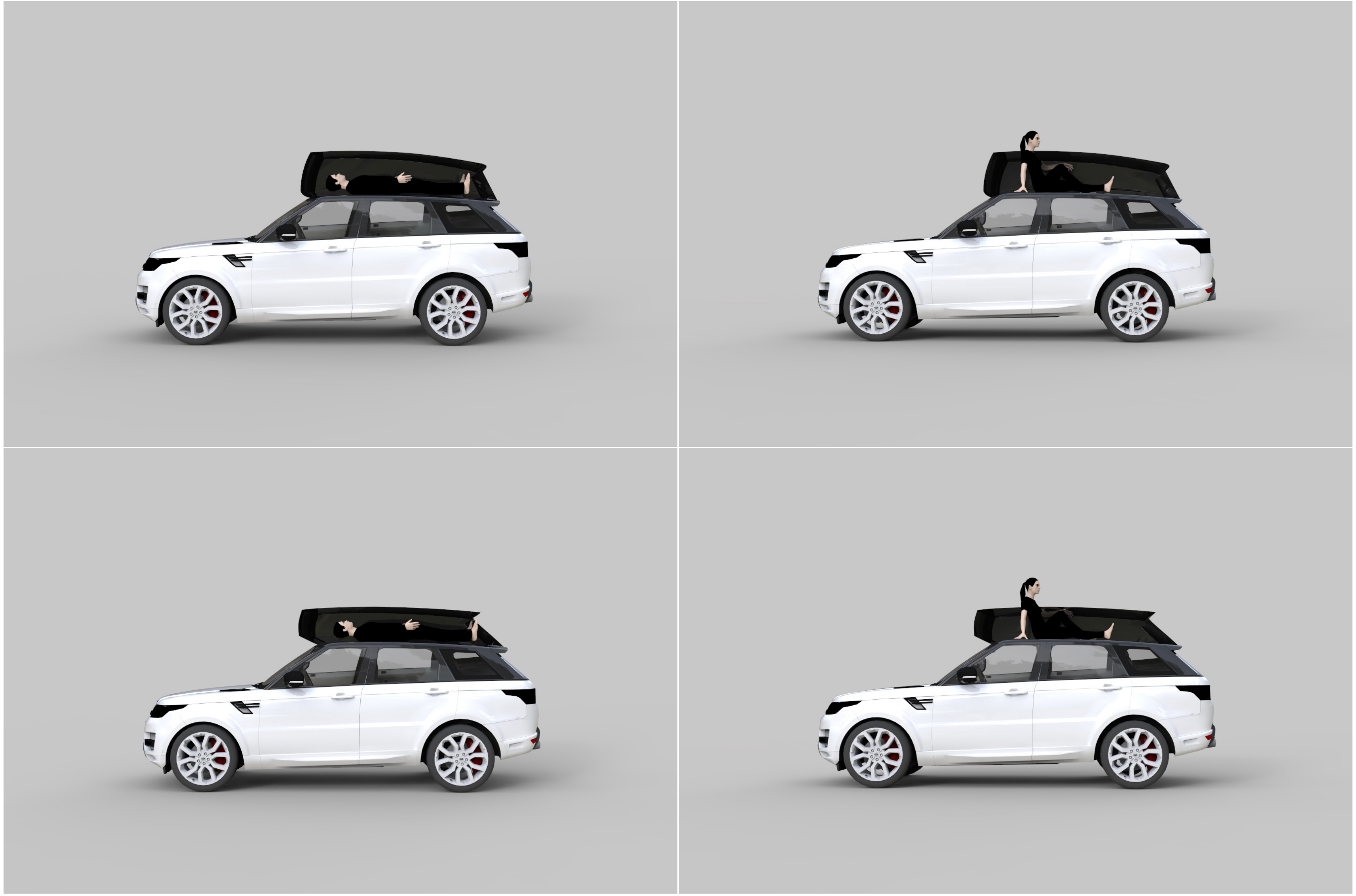


Figure 49. Section cuts exhibiting the tiny amount of space concepts three and four have.

6

DESIGN PHASE TWO

The following chapter is broken down into four predominant sections;

- Exterior form iterations
- Initial interior development
- Ergonomics and Accessibility Investigation
- Material Exploration

Firstly, CAD modelling development and exterior concepts produced throughout the iterative design process are discussed and analysed. These concepts progress through overall form and integration of detail with relation to the surface language of the vehicle. The interior development subsection discusses initial interior iterations, this includes the creation of wall thicknesses and subsequent interior panelling. Thirdly, the ergonomics of climbing up and into the capsule were assessed and analysed. A 1:1 scale physical model of the roof space was built, this provided the research with greater understanding of the physical space required to make the environment habitable. Alongside this, three areas of access were distinguished and analysed, resulting in informed design decisions. The final subsection of this chapter explores and discusses FDM 3D printing materials and their specific qualities for the exterior of the capsule. Furthermore, interior materials are considered. Interior materials are important for the feel and comfortability of the environment, they also needed to portray luxury qualities.

EXTERIOR FORM ITERATIONS:

CAD DEVELOPMENT:

The second set of iterations introduced an improved form of 3D modelling on Rhino. All of the initial concepts were essentially single surfaces or 'skins' created through single lofts and sweeps. This method of modelling was primitive and unable to translate significant details and design cues from the Range Rover. Instead of single lofts and sweeps, specific curves are taken from the vehicle and drawn two dimensionally in the profile and front views as seen in figure 49. These curves were able to be adapted into three dimensional curves through the 'curve from two views' command. Aside from the Range Rover's silhouette, the continuous character line was the first defining detail to be matched and reciprocated within the following iterative concepts. The character line acted as the centre point of the model, surfaces were created through continuous two rail sweeps between the initial roof curve and the continuous character line. The top surface was built using a network surface following the front and profile curves.

Figure 50. Process of designing the second ser of iterations, curves were drawn in the front and side views, each consequent surface was swept as a continuously, building the form from the ground up.

CONCEPT ONE:

The first concept displayed a very soft radius on the rear end, this is accompanied by the subtle matching of the tailgate lip. Accentuated curves were used to highlight the wide haunches, pushing out from the A-pillar. Design cues in the form of crease lines were taken from the bonnet and replicated on the roof of the capsule. The improved method of 3D modelling introduced multiple material rendering, allowing the design to sympathise with the vehicle through material and colour choice. The addition of the continuous character line worked to break up the colour. Alongside this, the matte white utilised on the top half reduced the perceived size of the capsule. Section cuts revealed the concept is too small, more space is needed to allow the people to sit up. This concept featured two iterations of a celestial window, adding more detail. Lastly, branding was translated on to the front surface of the capsule, bringing the two forms closer together and establishing identity.

Figure 51. Concept one featured increased detail through a continuous character line, a celestial window and branding.

CONCEPT TWO:

The second concept was designed surrounding the continuous character line. This was mirrored directly from the side profile of the vehicle, the character line from the headlights was again replicated and extended on the front plane. The two surfaces connected between the continuous character line flowed smoothly due to softer angles compared with concept one. The rear angle of the capsule mirrored the tailgate, though did not include the lip. Metallic and matte materials were used to break up the capsule, the top half was also rendered with a glass top. The overall form slanted forwards which reduced the tumblehome of the Range Rover. Although this concept was slightly too small, the front overhang gave the user more room, identifying a new area of consideration.

Figure 52. Concept two added more space and retained the continuous character line. Materials were expanded, introducing a glass top.

CONCEPT THREE:

Concept three vastly changed from the first two iterations as more space was required to fit the humans comfortably. Furthermore, the capsule needed to be moved forward to allow the tailgate to open. Additionally, the overhang was accentuated offering the user more space, acting as a ‘sleeping bag’ for their legs. This concept incorporated the clamshell bonnet as a point of reference, the curve of the bonnet was mirrored and extended, forming the roof line of the capsule. Crease lines on the bonnet as seen in the front view were matched above, running along the roof. The front character line matching the headlights was compressed to display a closer relationship to the vehicle. Alongside this the rear silhouette of the capsule emulated the backlight angle, this sharp angle resulted in a loss of space at the rear of the environment. More emphasis was put into detail for this concept, unfortunately the method of modelling had reached its extent and began to produce undesirable results such as the unusual curve produced from the overhanging surface.

Figure 53. Concept three successfully fit both people and allowed them to sit up. This form also introduced the overhang for increased space.

CAD DEVELOPMENT:

The previous method of CAD modelling no longer sufficed for increased complexity. A continuous two rail sweep meant that the resulting surface was created between two curves (the roof curve and the continuous character line). It was determined that the sleeping environment needed to be designed panel by panel, following the same digital design process of a vehicle. Panels were produced utilising the ‘curve from two views’ command. This method of modelling enabled design accuracy from individual viewpoints (front, side, top and rear). Each ‘panel’ was designed with specific design cues from the Range Rover. The panels were only required to be in halves because like the vehicle, the capsule was symmetrical. Mirroring the panels before generating surfaces assisted in removing central seam lines. Surface panels were produced through two rail sweeps and then blended together constructing smooth edges.

Figure 54. A new method of CAD modelling was produced, each surface was made panel by panel.

CONCEPT FOUR:

Concept four was the first iteration to be produced with panels, the overall form increased considerably in size providing more vertical space to easily fit both people in a sitting position. The model progressed through detailing such as rear access doors, a front window, a bed and interior panelling. However, the exterior form felt distant from the Range Rover due to a square, static surface language. This concept required substantial external development to embody the Range Rover Sport's significant design features.

Figure 55. Concept four was produced through the new method of CAD. The concept featured more interior detailing, but lacked cohesion to the vehicle.

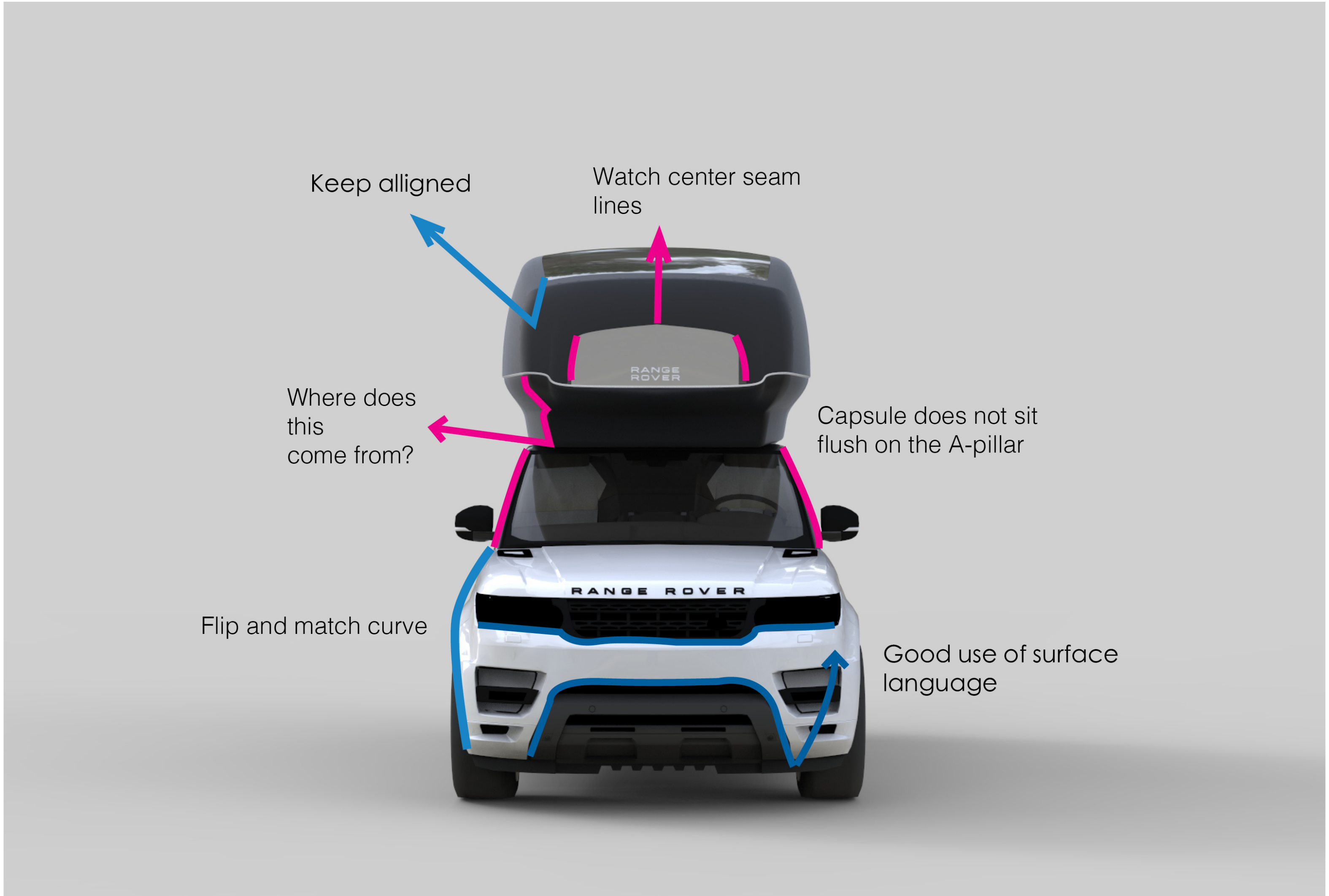


Figure 56. Annotated front view render of concept four identifying issues in pink and design improvements in blue.

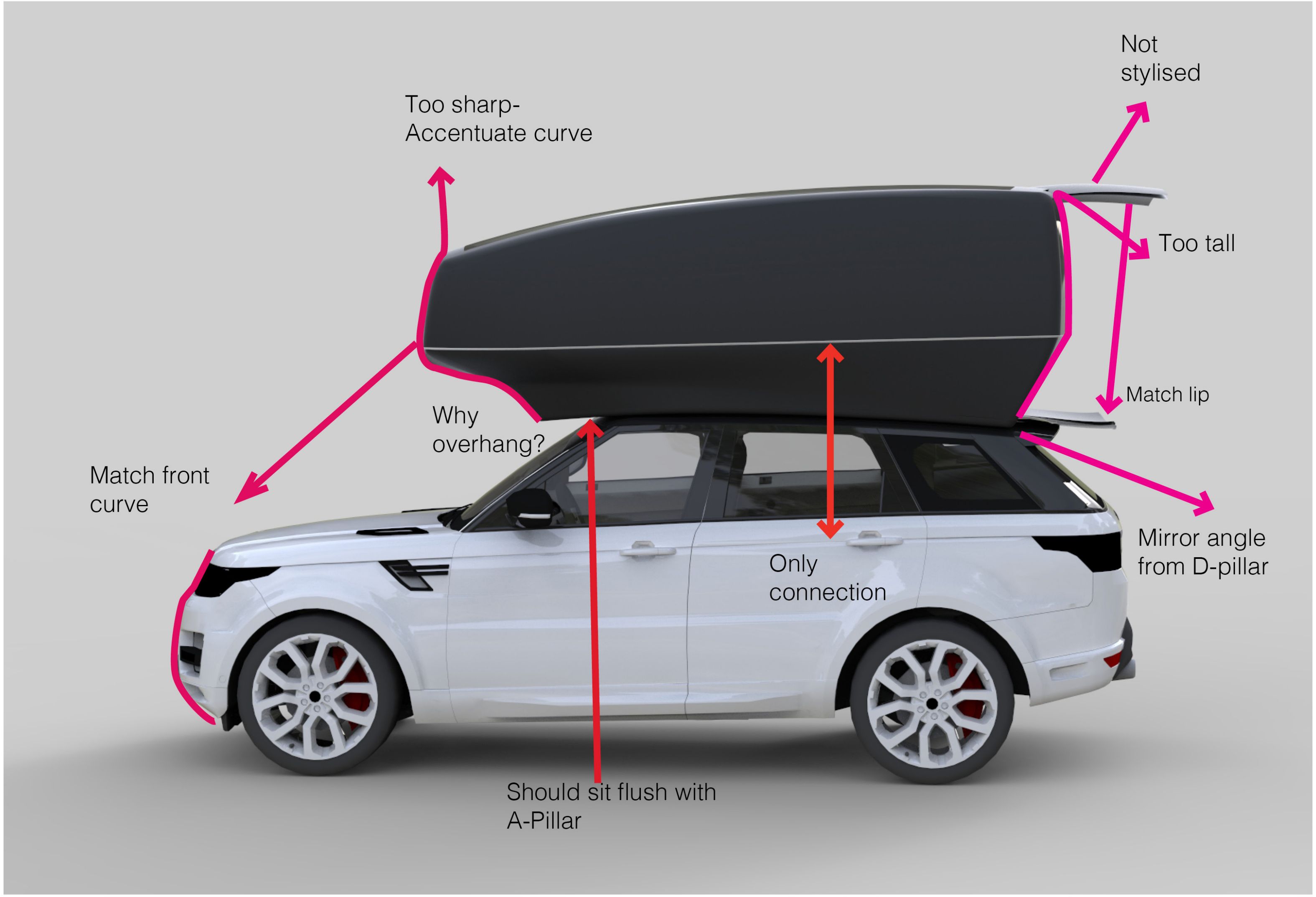


Figure 57. Annotated side view render of concept four identifying issues and design considerations.

INITIAL INTERIOR DEVELOPMENT:

WALL DENSITY AND PANELLING

The panels developed in concept four were extruded to create wall density. The wall thickness and structure is important for FDM 3D printing as the walls need to be solid enough to be manufactured without encountering errors. Furthermore, on a large-scale the prototypes need to be structured with an appropriate wall thickness to become a feasible product. The resulting wall densities enabled the development of interior panelling, which could be adapted and visualised through rendering.

Figure 58. Design development of wall density as opposed to a single shell, additionally, interior panelling and detail had improved.

ERGONOMICS AND ACCESSIBILITY INVESTIGATION:

SIDE ACCESS:

A 1:1 scale platform was built replicating the exact vehicle height (1780mm) and roof dimensions (1344mm x 2448mm). Furthermore, the structure was lined with string at a height of 750mm. This structure was accurately assembled to gather vital information regarding accessibility and ergonomics. A physical representation was required to truly understand how much space would be needed within the sleeping environment. It was also important in addressing access and movement around the space.

The first point of access tested was from the side of the vehicle, this was a practical entrance as it allowed the boot to be open when entering the capsule. When accessing from the side, the user would plant their hands first and twist onto their side. It was quickly realised that 750mm was too small and the environment would need to be at least 1000mm in height to allow ease of access. It was also distingushed that entering from the side would require the ladder to stored within the capsule and somehow open out telescopically.

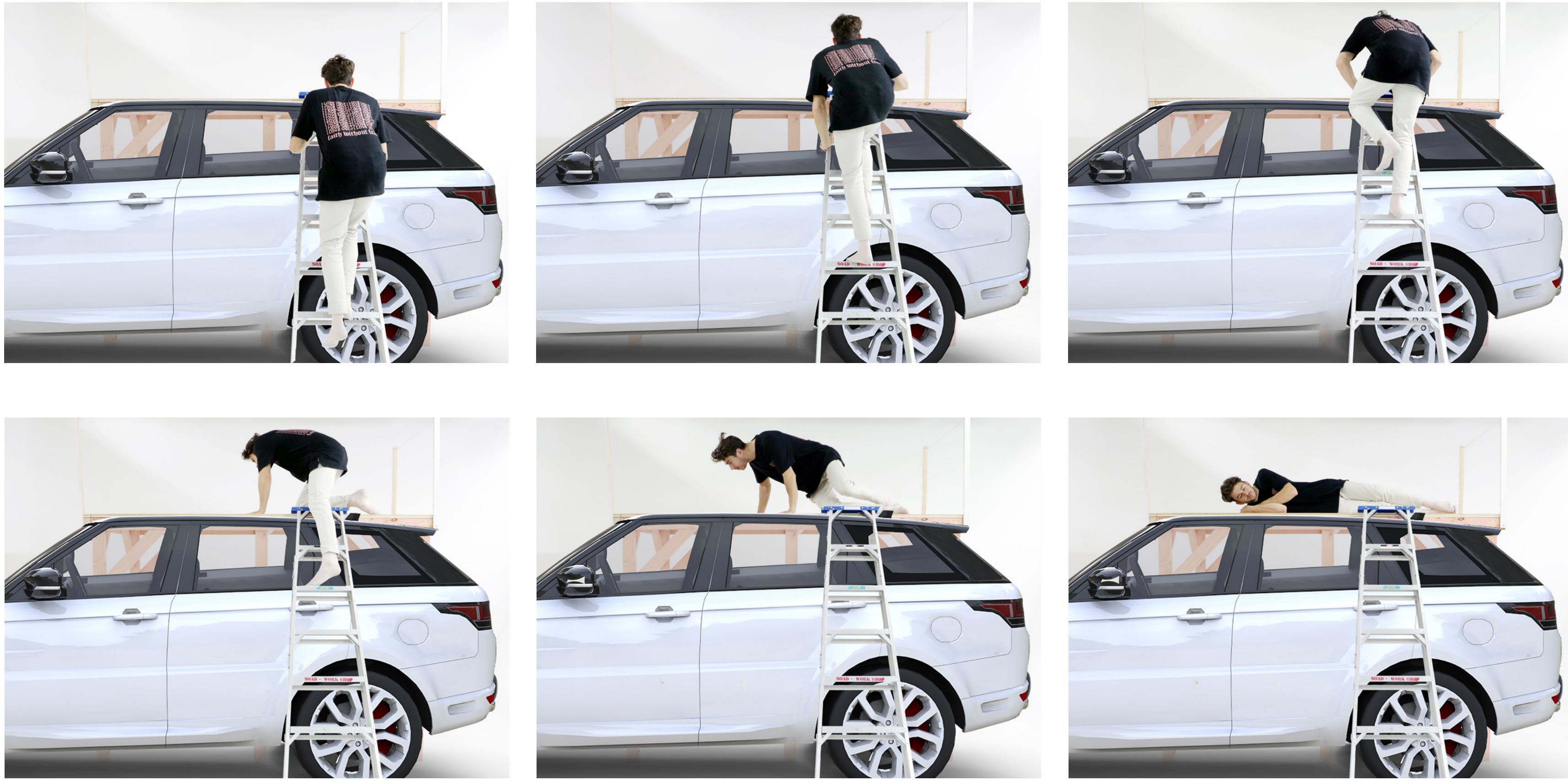


Figure 59. Process of climbing up into the sleeping environment from the side.

REAR ACCESS:

Rear access was considered to be the most practical entrance as the ladder could open out with the door or be attached to the tailgate. However, the boot would have to stay closed when entering the environment. The low height of the string is evident through the users arched back. Ergonomically rear access is more appropriate than the side as the customer is only required to crawl forward rather than twisting their back. Moreover, the rear entrance offers more space to move about because the vertical length of the environment is longer than the horizontal width. Following this investigation the rear entrance was the chosen form of accessibility.

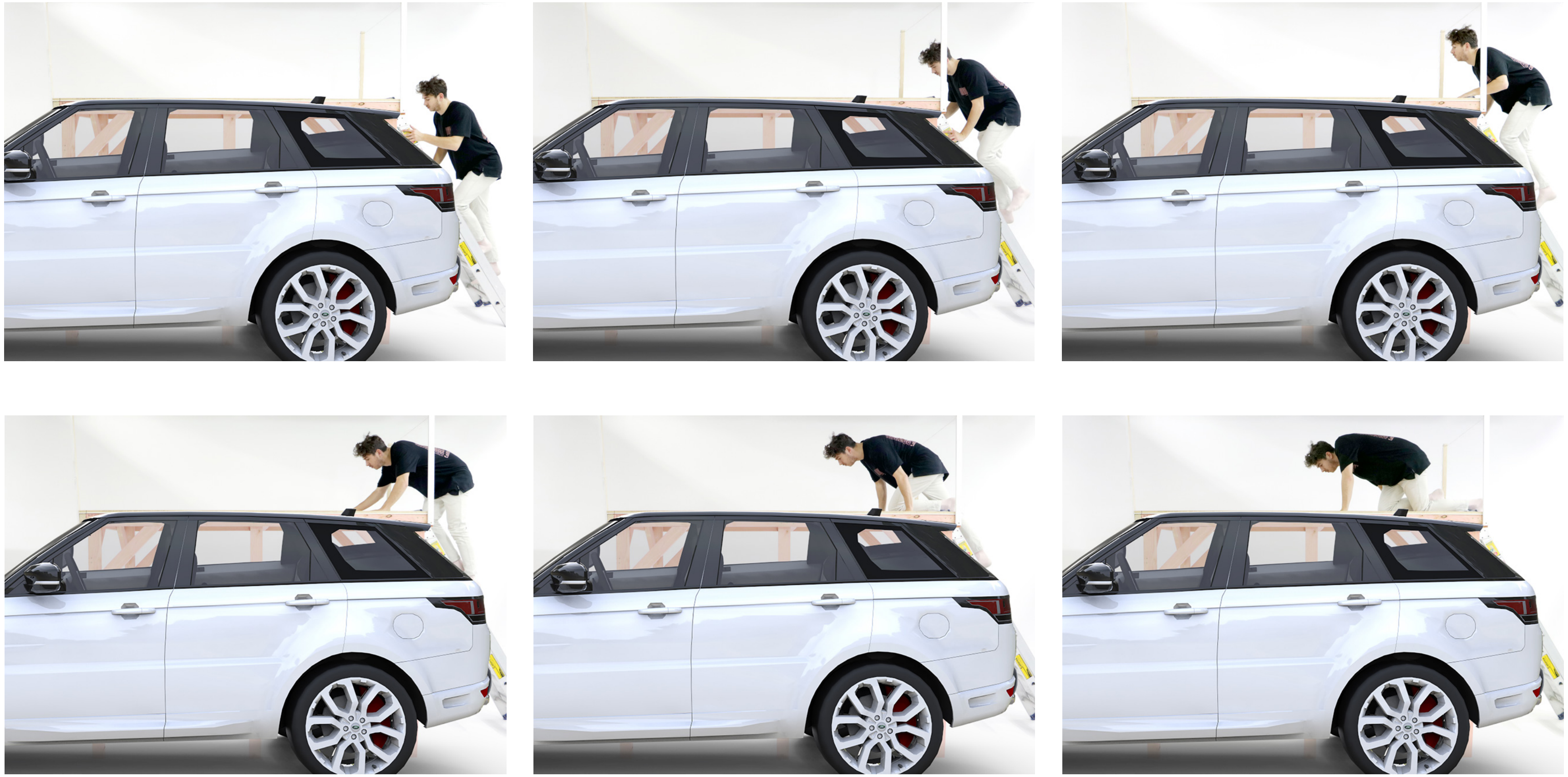


Figure 60. Process of climbing up into the environment from the rear.

INTERIOR ACCESS:

Access from the interior of the car up through the sunroof was the initial concept for entering the sleeping environment. Ideally, the user would not have to deal with weather conditions and could comfortably reach the capsule through a small trap door. The user measuring 6ft tall in the interior accessibility test stood on a platform at an estimated height that was most probably higher than the footwells in a Range Rover Sport and still struggled to push themselves up. It was determined that entering the capsule would become problematic and more complex if access was from the interior of the vehicle.

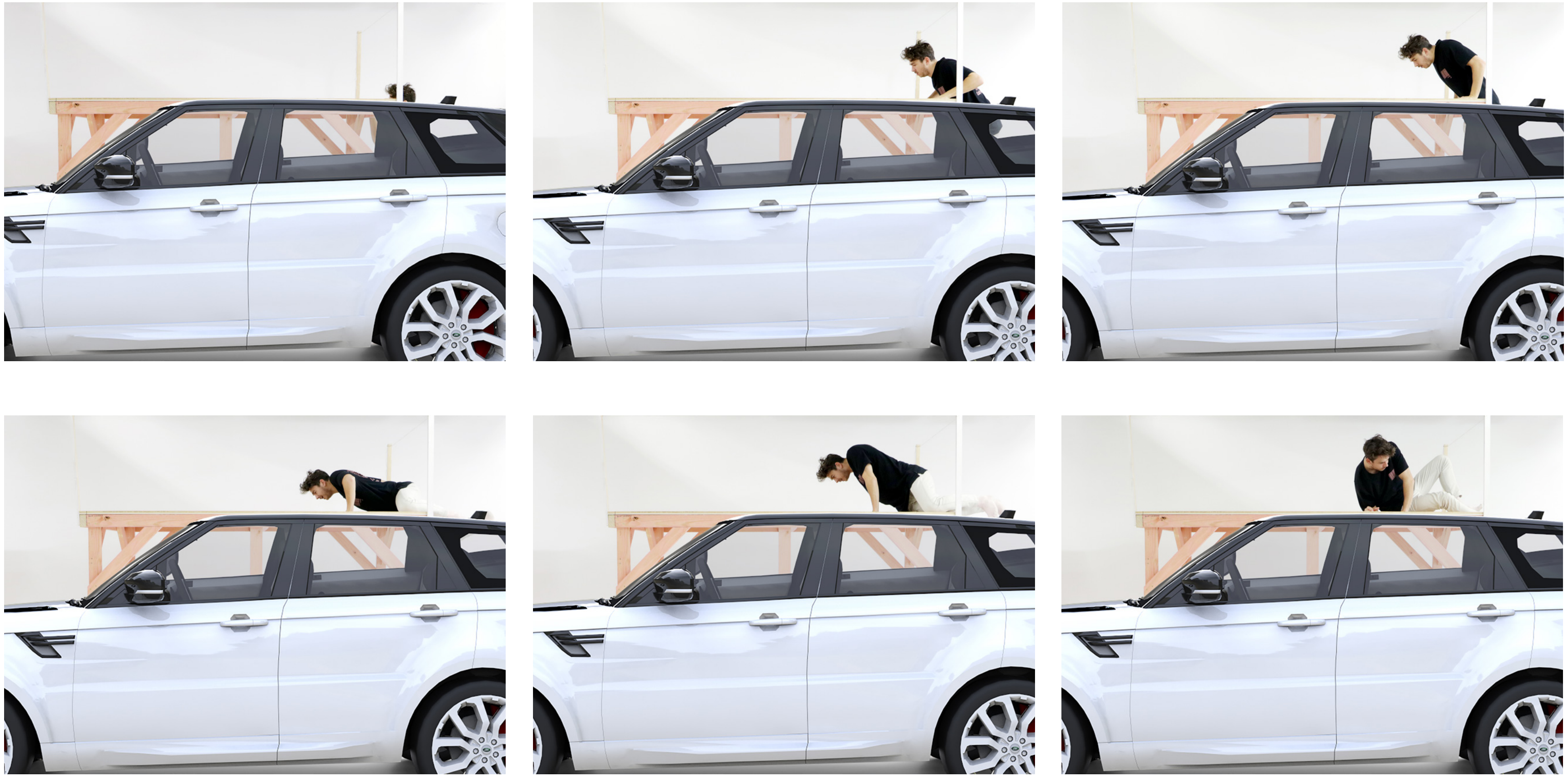


Figure 61. Process of getting up into the environment from the interior of the vehicle.

ERGONOMICS WITHIN THE CAPSULE:

PROFILE VIEW:

The ergonomics investigation was specifically important in identifying appropriate heights and widths required to fit two humans (1829mm and 1651mm). The concept of a 'bespoke' shared sleeping environment and the use of FDM 3D printing allows the prototype to be designed specifically to the users dimensions or preferences, ensuring a comfortable fit. Furthermore, investigation also provided the research with knowledge surrounding how people move when accessing and inhabiting a small space.

This is a personal exploration and the proposed requirements of the sleeping space were that the tallest user could sit up right without hitting their head. In figure 62 the user is sitting in an almost upright position and is above the 750mm line. Therefore the space needs to sit above this figure. A height was estimated between 1000mm and 1500mm. When lying down the user is comfortably within the 750mm.

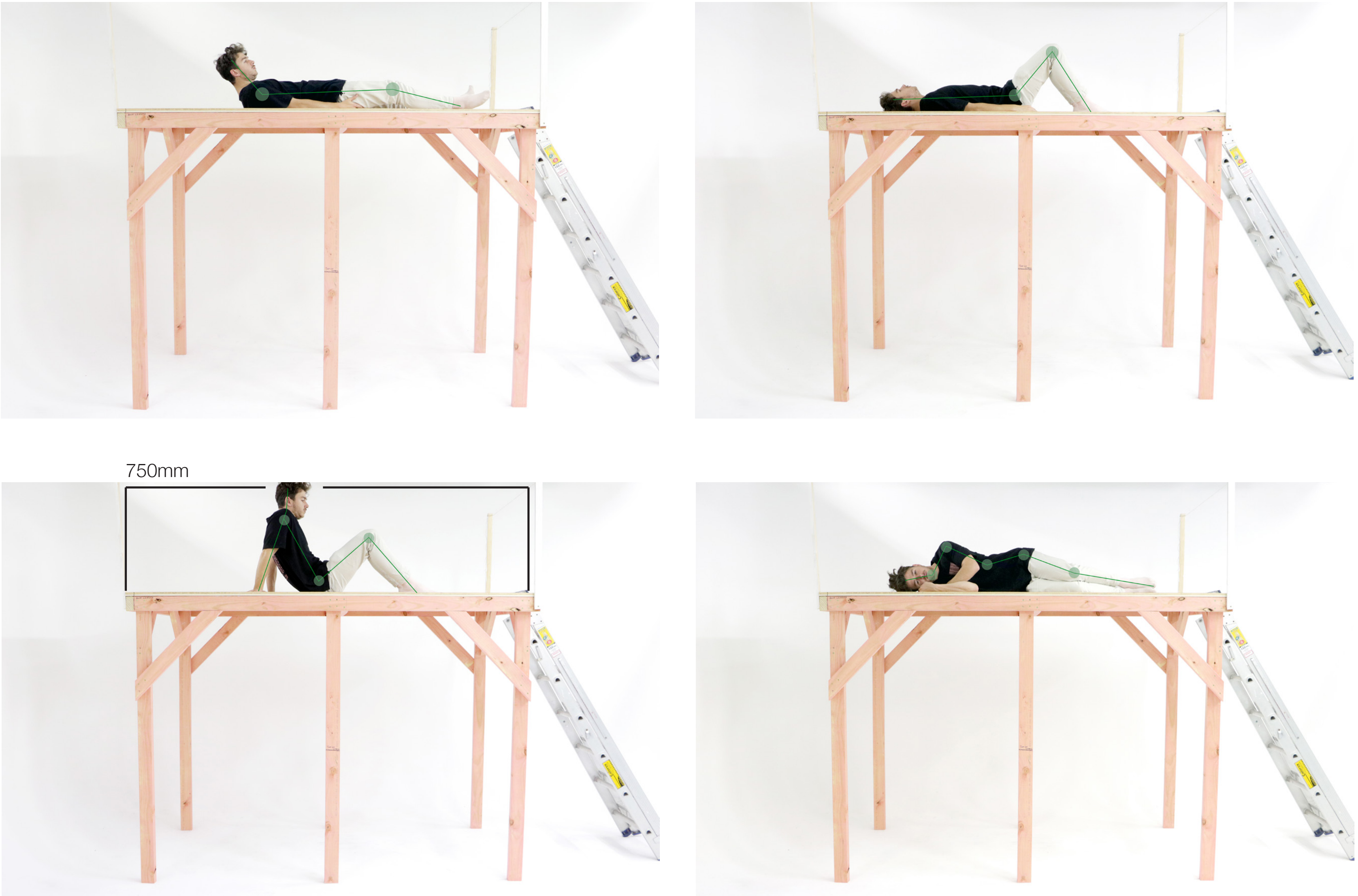


Figure 62. Profile view of different positions that are common within small sleeping spaces.

TOP VIEW:

The ergonomic study from the top view investigated roof space for the intended couple in multiple positions related to sleeping. The results of this study concluded that the roof space provided enough room for the couple to comfortably sleep in multiple positions. Extra width would be required in the side walls to allow the couple to spread out.

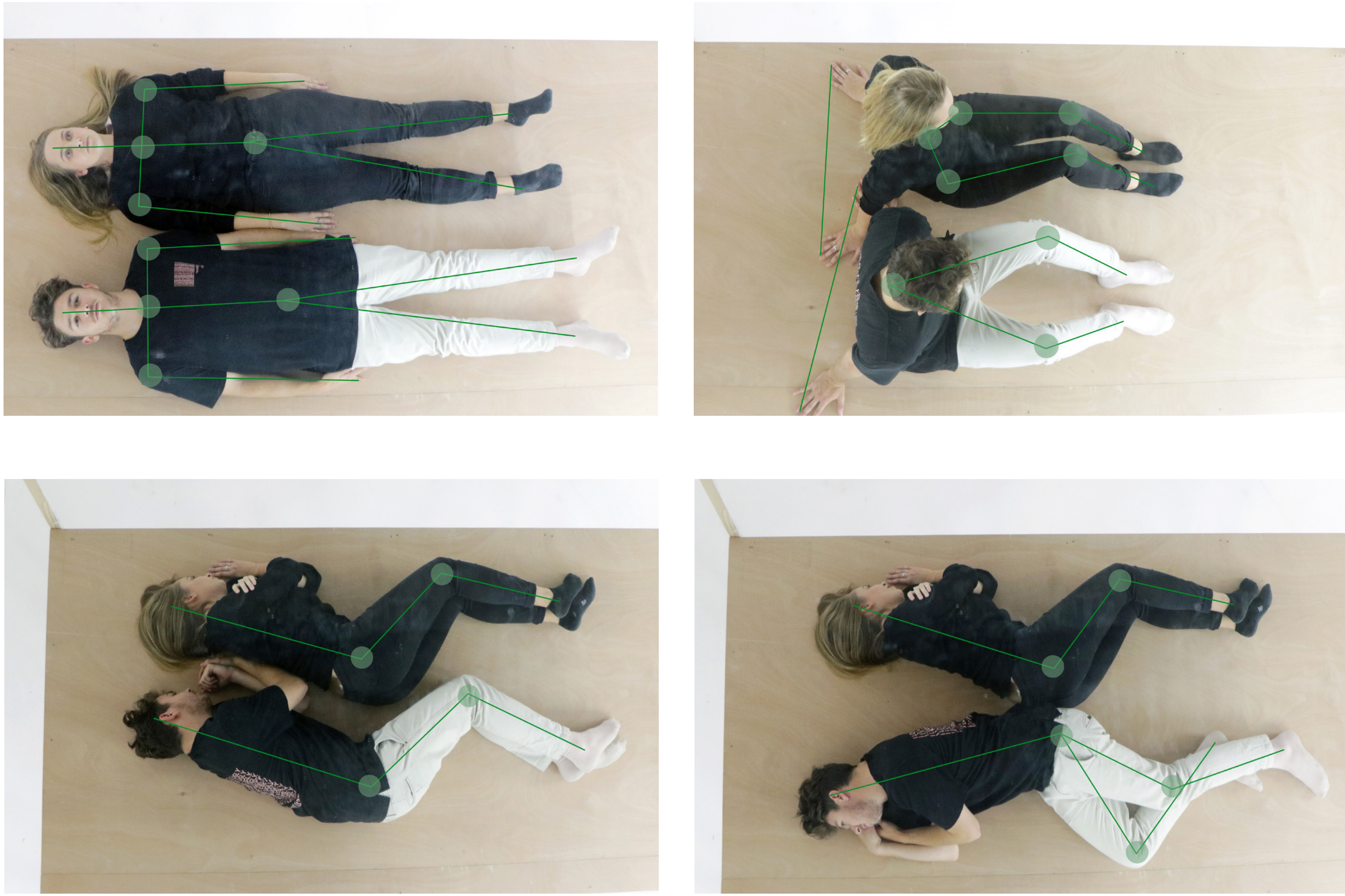


Figure 63. Top view of typical positions within a sleeping space.

MATERIAL EXPLORATIONS:

EXTERIOR:

Although large-scale resources were not able to be utilised, multiple FDM materials were obtained and explored through small-scale 3D printers. All of the materials used in this exploration were biodegradable and recyclable, promoting them as valid materials for use in the automotive industry. Three materials featured in this exploration;

- PLA (Polyactic Acid - a biodegradable thermoplastic)
- Wood fibre composite (Composite blend of wood shavings and PLA)
- Carbon fibre composite (Composite blend of carbon fibres and PLA)

Composite materials were utilised in this testing due to their highlighted structural properties discussed in the FDM 3D printing materials subsection of the background research chapter.

Three 1:1 scale details were printed with each material. Within the three prints, different percentages of infill were employed to assess the material weight, strength and printing quality.

Carbon fibre was clearly the strongest and lightest material as it was far less brittle than the wood composite and PLA. The carbon fibre prints had a slight flex, whereas the PLA and wood composite remained solid and hard. With that being said, the PLA and wood composite were still structurally strong. In terms of print quality, the wood composite printed the best, but all of the materials succeeded without encountering problems. The difference in weight between infill percentages was astounding, infill gradation could prove as useful tool for structurally reinforcing large-scale 3D prints.

Figure 64. PLA. Three 1:1 scale details showing the difference in material density for the potential use of gradial infill. The details density ranges from 15% to 65% to 85%.

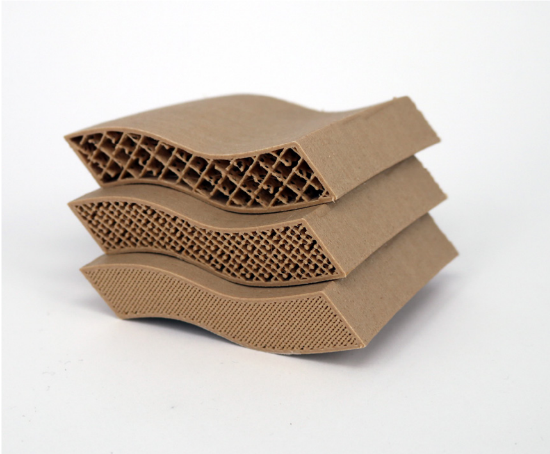


Figure 65. Wood composite. Three 1:1 scale details showing the difference in material density for the potential use of gradial infill. The details density ranges from 15% to 65% to 85%.

Figure 66. Carbon fibre composite. Three 1:1 scale details showing the difference in material density for the potential use of gradial infill. The details density ranges from 15% to 65% to 85%.

INTERIOR:

Interior material exploration served as a form of inquiry into physical materials that could be used within the sleeping environment to portray luxury and comfort. Internal spaces are dependent on materials to alter the perceived feeling. A material palette was produced highlighting samples of lavish fabrics that help to embody the Range Rover 'luxury' style which cannot be understood through renders. Furthermore, detail sections of the final concept were printed and lined with fabrics from the palette to display the relationship of luxury materials and high quality 3D prints.

Figure 67. Interior material palette. A range of fabrics were explored to understand how materiality could influence luxury.

7

DESIGN SOLUTION

The following chapter is broken down into seven predominant sections that exhibit the design solutions produced from this research;

- Final CAD development
- Final exterior form
- Accessibility
- Final interior development
- Aerodynamics
- Range Rover attachment
- Contextual narrative

Each of these concepts and their subsequent design solutions are identified and discussed through a reflective design analysis. Following these sections, a reflection evaluates and analyses the success of the refined concepts with regard to the thesis question. Additionally, future speculations are distinguished with concluding thoughts on the future applications of this research.

FINAL CAD DEVELOPMENT:

The CAD process remained the same, creating the capsule through panels of curves in each view, followed by two rail sweeps to create the surfaces. The resulting surface panels were extruded to form wall density and blended together to ensure smooth edges. An image was taken of the Range Rover Sport with its tailgate open, this picture was used as a reference when designing the rear of the capsule. The use of this image was vital in creating harmony between the back of the sleeping space and the rear of the . The tailgate could now be opened and sit flush against the capsule as seen in figure 68.

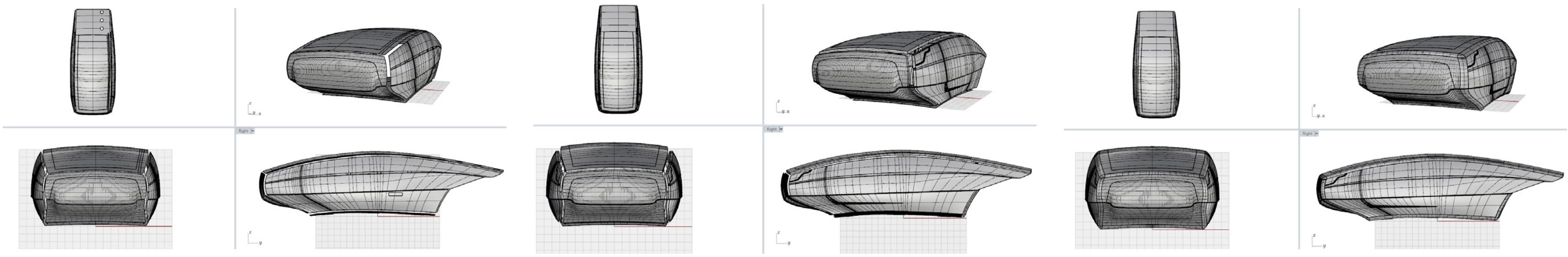


Figure 68. The final CAD process involved designing with direct relation to the vehicle. The curves were drawn against an image of a Range Rover Sport with its tailgate open.

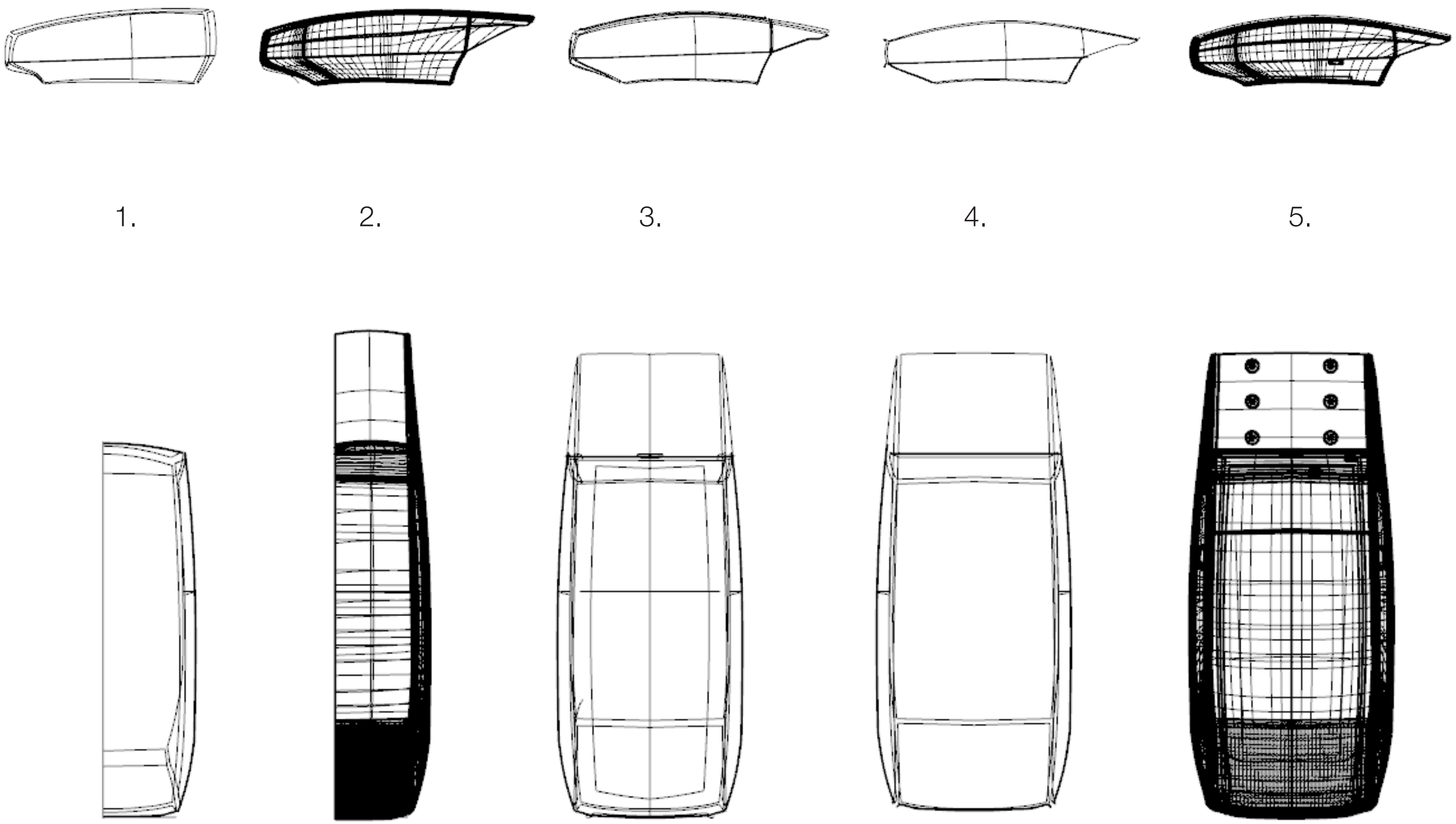


Figure 69. Refinement of models from concept four (1.) to the final product (5.) The overall form was durastically changed.

FINAL EXTERIOR FORM:

DIMENSIONS:

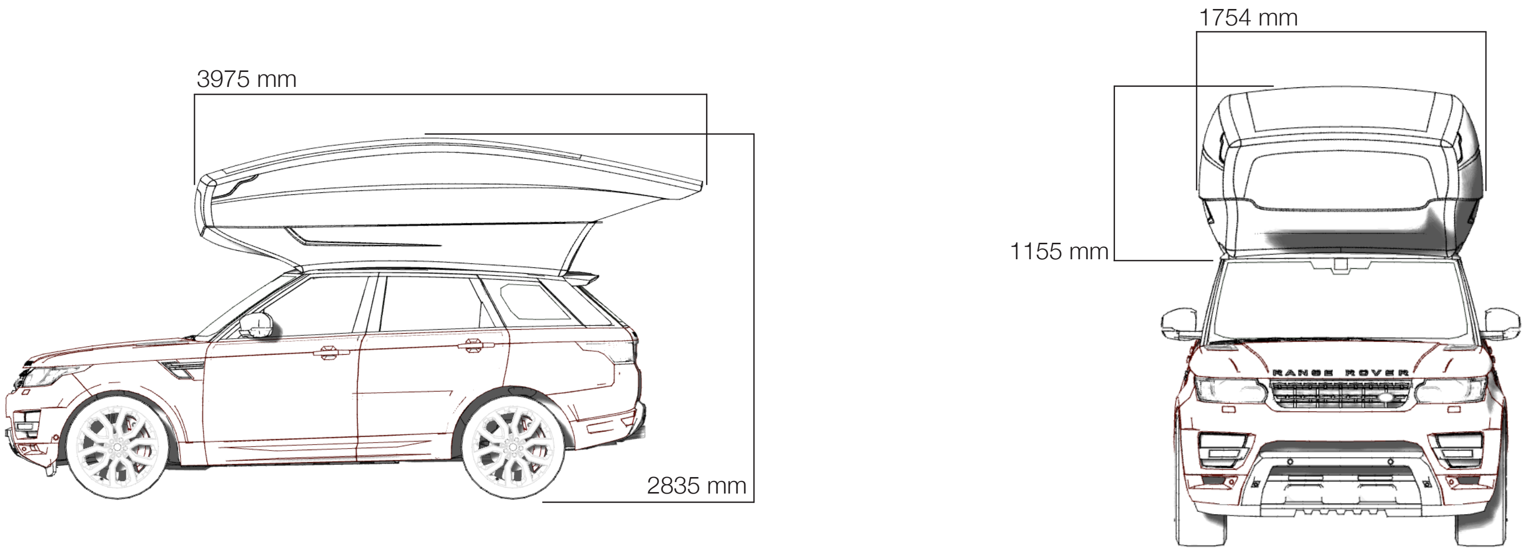


Figure 70. The overall dimensions of the sleeping environment and the height of the vehicle with the capsule attached.

OVERALL FORM:

The design solution resulted in a refined, precise sleeping environment that successfully embodied the overall surface language of the Range Rover Sport. This final concept made the transition from two separate bodies (the vehicle and the capsule), resulting in a cohesive relationship, essentially bonding the environment to the vehicle. The design cues, material choices and surface language that were replicated from the Range Rover functioned to instantly recognise the capsule as bespoke product, specifically 'tailored' for the vehicle. Improvements to the capsules surface language through stylised curves displayed closer connections to the silhouette and A-line of the vehicle. The rear end of the environment was particularly successful as the tailgate could be opened flush against sleeping environment and the accentuated arc provides a feeling of more tumblehome. This example of sympathetic design exhibits the precision that digital vehicle mapping can provide, validating the use of digital vehicle data for bespoke applications.

Figure 71. Overall surface language of the final prototype.

TAILORING AND DETAILS:

Refinement of the concept developed various significant design details that epitomised the surface language of the vehicle. The flow between the Range Rover and the capsule became a smooth connection, whereas in past concepts a sharp contrast disjointed the two bodies. Specifically, the precise positioning of angles in relation to the roof curve enabled the capsule to mould itself on. In figure 72 the flow of surface language is evident at each pillar. The capsule mirrors the angle of the A and D pillars, creating continuity of the surface language. Furthermore, the capsule sits flush along the cant rail of the vehicle.

Every viewpoint displays a surface connection between the vehicle and the capsule. In the rear view, the top curve of the environment directly matches the top curve of the tailgate. Alongside this, the shutlines of the capsule doors resemble the rear silhouette of the vehicle. In the front view, the stance of the Range Rover and the resulting front silhouette is replicated above. The continuous character line flows around capsule and under the front window coinciding with the character line under the headlights and grill. Additionally, the front window was designed based on the bottom character line sitting between the front gills. The side panels accentuate the tumblehome of the vehicle with the addition of the continuous side gill, and a corresponding crease line flows out of the continuous character line. This crease line was mirrored from the side gill as noted in figure 74. Furthermore, the rear curve of the side panel creates the awning in which the tailgate can open up into. The curve of the tailgate was duplicated forming rhe rear curve of the side panel, in turn, the curves harmonised when the tailgate was opened, building the cohesive relationship between the surface language of the vehicle and the sleeping environment.

Figure 72. Exterior details highlighting the cohesiveness between the capsule and the vehicle.

Figure 73. The matching of the tailgate curve allows the boot to sit flush against the capsule.

Figure 74. The gill crease line has been enlarged and elongated on the sleeping capsule.

SURFACE FINISHING AND COLOUR:

Rendered visions of the final sleeping environments utilised combinations of metallic and matte surface finishes that aimed to display examples of finishing qualities to apply over the 3D printed end-product. Surface finishing and the incorporation of colour is an important aspect of visual language for Range Rover, therefore it was vital for the material qualities and colour to flow cohesively with the vehicle.

Figure 75. The ‘Saint’ colourway.

Figure 76. The ‘Spectre’ colourway.

Figure 77. The 'Artemis' colourway.

Figure 78. 'Night Tides' colourway.

Figure 79. The ‘Sumac’ colourway.

PHYSICAL MODELS:

Small-scale 1:14 physical prototypes were 3D printed utilising FDM technology. A 1:14 scale Range Rover Sport model car was purchased with the purpose of placing the prototypes above to gain an understanding of scale and overall surface language. Additionally, small-scale printing proved to be a useful method, simulating the manufacturing process of the full scale prototype. The digital model was split horizontally through the continuous character line, the sections were printed vertically on a 75 degree angle, this assisted in building the model with less raft and greater precision. The final concept was also split vertically through the centre and test printed lying flat on the bed, this method displayed less accuracy as more raft was produced and in turn, the surface detail of the prototype was harder to recognise, requiring more post processing techniques.

Following the material exploration in chapter six it was determined that the carbon fibre composite would be used for the primary final prototype, alongside this two secondary prototypes including a half section were printed utilising the wood composite filament. All of the final prototypes were appropriately sanded and surface finished, to provide the feeling of an end-product. Although FDM large-scale technology holds the capability to print this prototype in one piece. It was distinguished that the best way to produce the product would be through printing each panel, followed by post processing methods and assembly. This would allow for high-quality prints, enabling exterior components such as windows to be fitted with ease.

Figure 80. Final small-scale prototypes at 1:14 scale.

ACCESSIBILITY:

The doors for the sleeping environment were situated at the rear of the capsule, as it was identified during ergonomic and accessibility testing that this would be the most practical point of entry. The Range Rover tailgate is opened through the press of a button, either on the car key or the tailgate itself. This concept employed the same design thinking, with luxury in mind, the user would just have to press a button and the doors would open. The top door opens up into the awning, whereas the bottom door arcs down, revealing a platform. A lightweight carbon fibre ladder is fixed on to the tailgate, this ladder was refined in regard to luxury as it originally appeared as a thin fragile frame. The developed access ladder featured large flat steps, to aid in climbing without fear of slipping. The ladder concept, like the vehicle and the capsule, utilised the similar design thinking, incorporating remote operation to avoid any manual labour. With a press of a button, the telescopic ladder would raise vertically and the hooks would move horizontally, locking in place with the platform. Moulded hand holds were designed into the platform for ease of access.

Figure 81. Accessing the sleeping environment with a telescopic ladder.

FINAL INTERIOR DEVELOPMENT:

MATERIALS AND COMFORT:

Final interior development consisted of refining the material palette and utilising lavish materials to provide a perceived feeling of comfort and luxury within the sleeping environment. Three final interior concepts were produced, the first utilising an all white leather with a button detailing. Leather detailing for decades has been associated with luxury, therefore, it was the first material choice for the interior. Alongside this, leather quilting was also considered as it has been an abundant custom feature within recent Range Rover models. The second material choice was a combination of white leather button tufting and a textured merino wool. The duo tone mixture offers the user the ability to use multiple luxury materials rather than just one continuous material. The duo tone worked well to split the interior, whilst retaining a lavish feel. The idea of woollen lining would also insulate the interior, to keep it warm. The final interior concept introduced a textured egyptian cotton which is known to be the purest cotton in the world. Egyptian cotton is softer, finer and lasts longer than other cottons and the inclusion of this material epitomises luxury. Wooden veneers were also utilised to break up the interior, and different wood types have been used to simulate a bespoke selection of veneers.

Figure 82. Full leather button tufted interior to visualise luxury.

Figure 83. Wool and leather button tufting in a duotone combination.

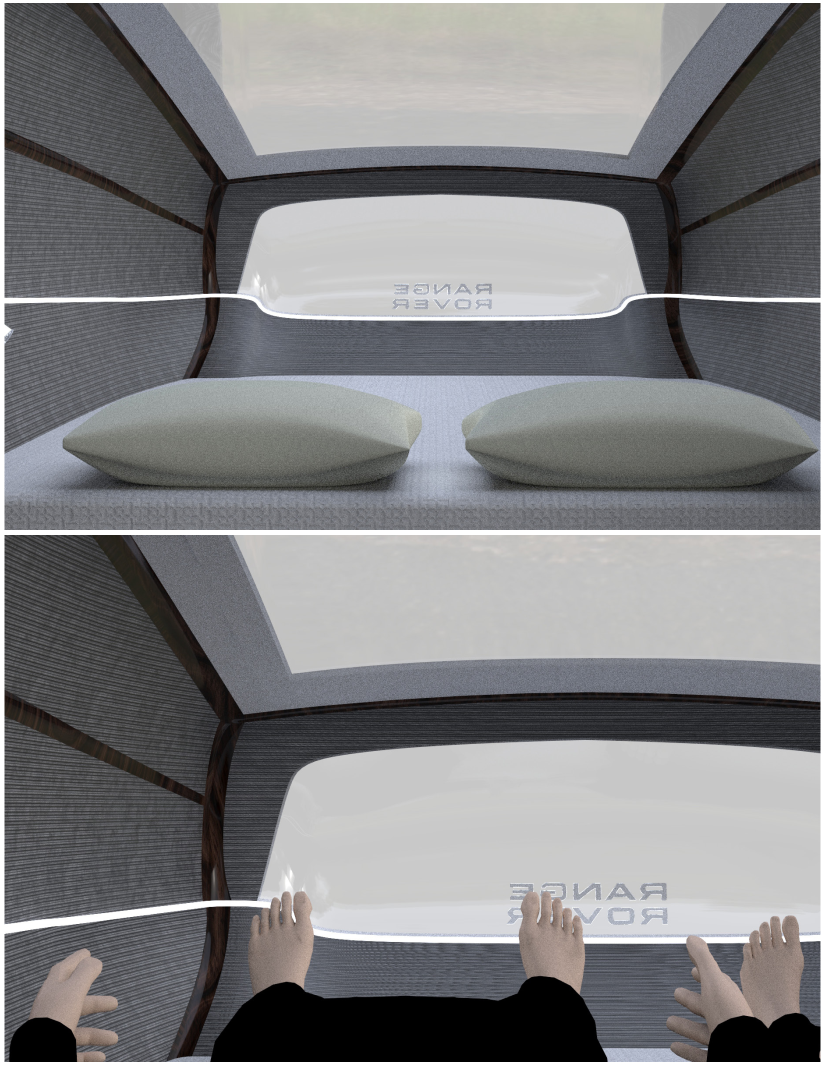


Figure 84. A textured egyptian cotton is the epitomy of luxury.

Figure 85. The interior is comfortable and fits the humans with ease. The interior features a bed, luxury materials, lighting and a personal drinks fridge.

VENTILATION:

The exterior detail that curves along the side panels of the capsule has been designed as a ventilation shutter. As seen in figure 86 the cavity is built within the side walls. The exterior design detail reflects a continuous gill, giving reference to the two feature lines on the gills of the Range Rover Sport. Air is able to flow into the cavity and flow along the length of the side panels. From the interior the ventilation shutter is visioned to be opened and closed remotely enabling the user to control the airflow within the sleeping environment. CAD in conjunction with FDM 3D printing has allowed the possibility of creating complex structures

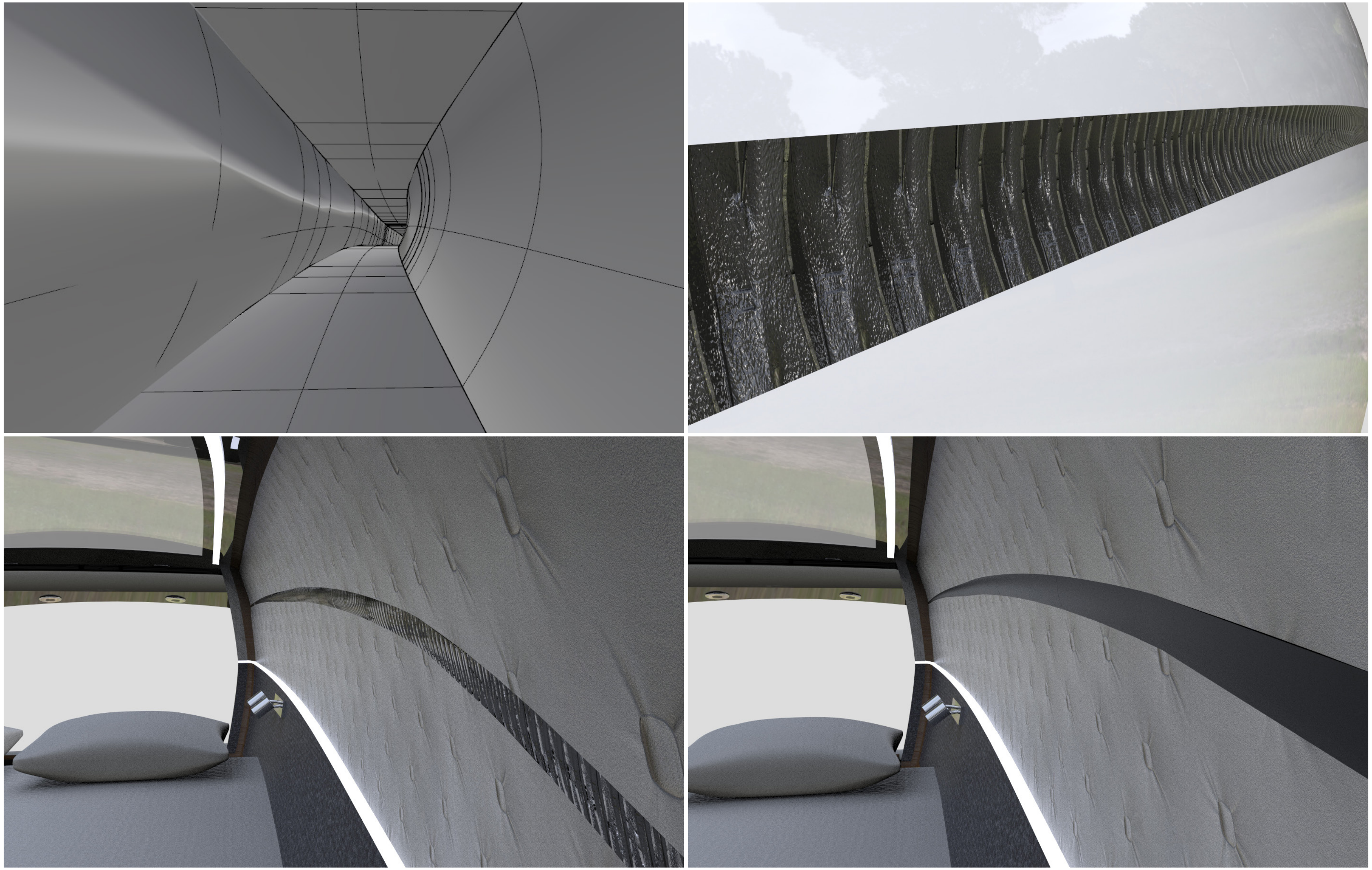


Figure 86. A ventilation shaft has been designed into the side wall panels, keeping a constant airflow when necessary.

LIGHTING:

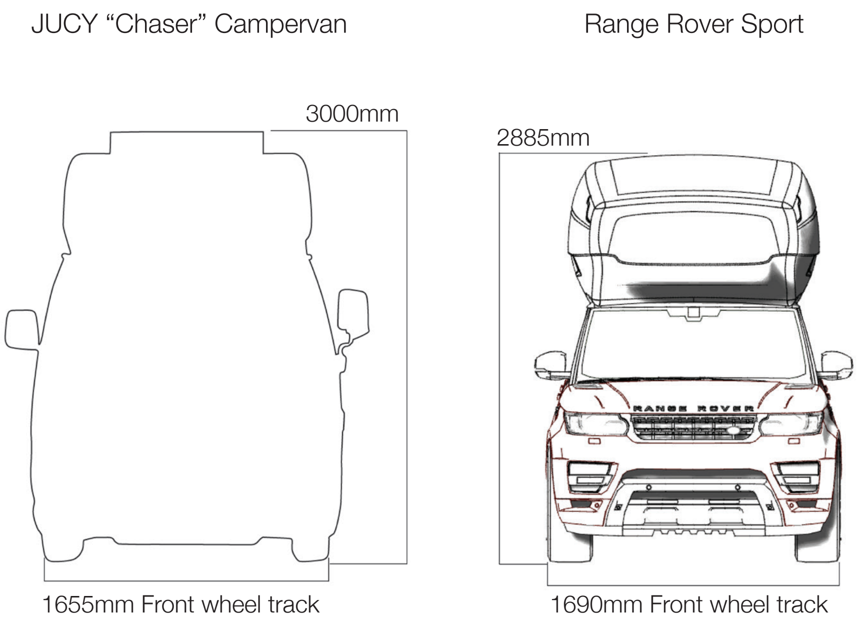
Different forms of lighting were introduced for both practicality and aesthetic. The continuous character line was replicated in the interior of the capsule featuring as a decorative LED strip. In terms of practical lighting, area lights were designed under the rear awning for external use. Internal lighting came in the form of two reading lights, allowing the user to sleep in comfort with close access to a light source, as well as the opportunity to read. For overall internal lighting, two high power LED strips run the length of the roof. A well lit space was important as it helps to perceive the feeling of comfort, whereas a darker space might cause the user to feel more claustrophobic.

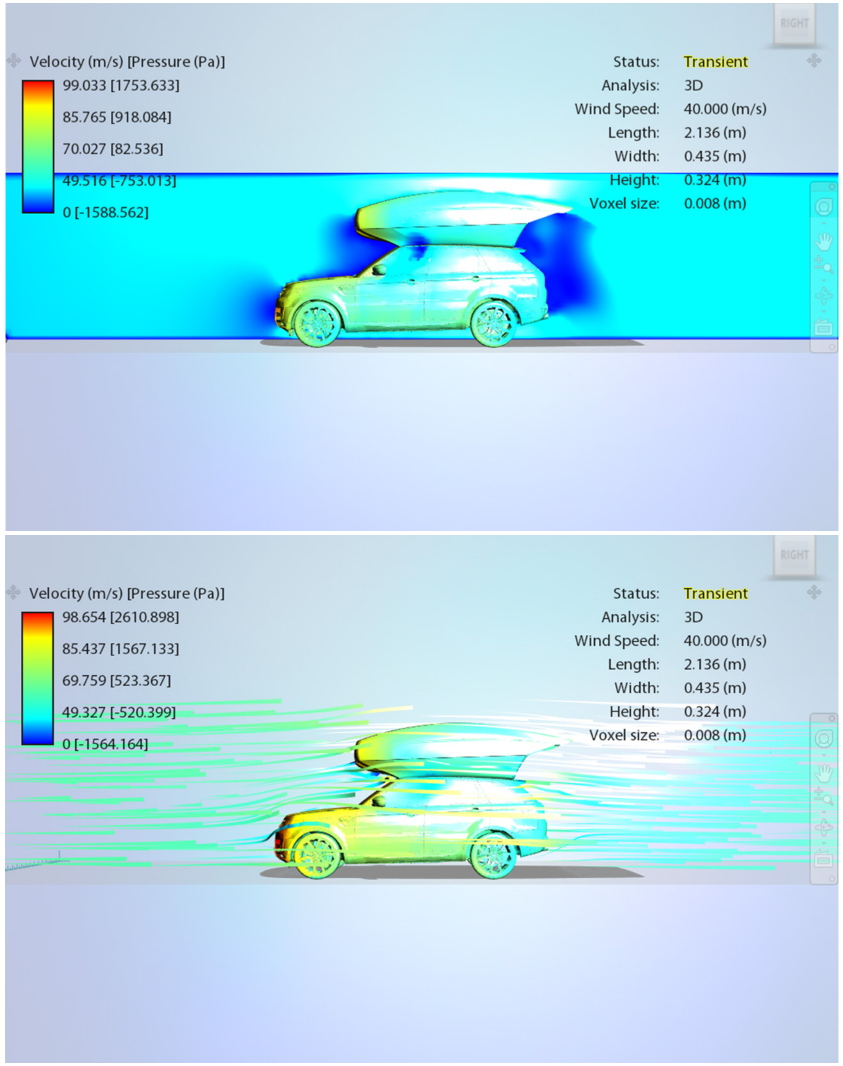
Figure 87. Lighting livens the space, adding more comfort. Reading lights, external lights and decorative led strips are highlighted.

AERODYNAMICS:

Aerodynamics were an important concept as the capsule would indefinitely increase drag due to more surface area. This required aerodynamic design considerations to help reduce the effects of drag and the resulting pressures. The inclusion of the rear awning and elongated surface assisted in controlling drag as it was tapered, mimicking the effect of a boat tail. Alongside this, the roof was designed with more curvature to increase aerodynamic capability. The sleeping environment was simulated in a wind tunnel with winds up to 40 m/s or 144 km/h. The results were reasonably positive as the wake behind the vehicle was not turbulent. Figure 89 shows the Range Rover Sport within this simulation, the blue trail behind the vehicle is the resulting wake. Positively, the wake remains small and not drawn out, justifying the forms design. Although, the average drag coefficient did rise which was to be expected.

In comparison to other hard shell campervans the Range Rover Sport with the addition of the sleeping environment is still more stable and would pose no risk of rolling unless it was in the middle of a tornado or hurricane. Figure 88 shows the comparison between a Jucy van with a hardshell pod and the Range Rover Sport with the capsule on top. The Jucy van sits higher at 3 metres in comparison with 2.885 metres, the Range Rover also has a wider front wheel track ensuring a lower centre of gravity. Furthermore, the Range Rover has a much heavier body at 2134 kg compared with 1700 kg, making it much harder to roll.



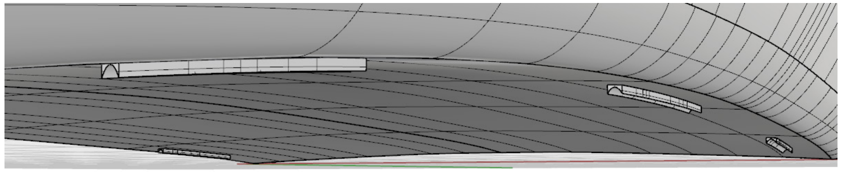


LEFT: *Figure 88*. This diagram compares dimensions between a Jucy campervan and the Range Rover with the capsule attached.

RIGHT: *Figure 89.* The capsule was taken into flow design, a wind tunnel simulator and had positive reults.

RANGE ROVER ATTACHMENT:

The Range Rover Sport has various accessories that are available for towing and carrying. Roof rails or internal flush rails are available with the Range Rover Sport for increased practicality. Figure 90 exhibits three small fixed rail attachments on each side that would enable the sleeping environment to sit flush against the roof. The attachment of the capsule would be as easy as fitting roof racks. Furthermore, the advantages of FDM 3D printing ensure the environment is ultra lightweight.



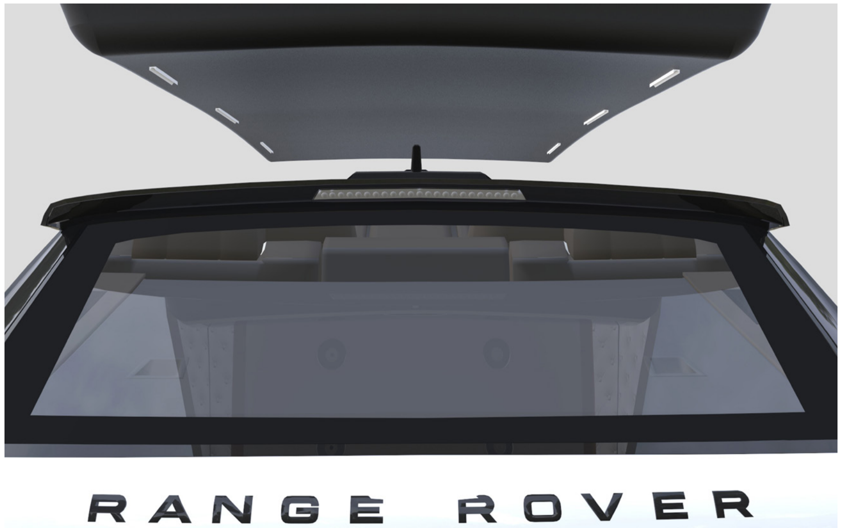


Figure 90. The sleeping environment is attached to the roof rails of the Range Rover.

CONTEXTUAL NARRATIVE:

Range Rover has a history dedicated to exploring, alongside luxury connotations, the vehicles produced have continued to boast practicality. Iconic Range Rover models have been released and tested in unique, untamed landscapes. Therefore it was important to include the context of exploring, as it formed the connection of 'the tailored traveller'. A number of contextual renders were produced to simulate natural landscape scenarios in which the habitable environment could be immersed in.

Figure 91. Visualising the Range Rover in a wilderness scenario to display the concept of exploring.

Figure 92. Visualising the Range Rover surrounding a body of water to display the context of exploring.

Figure 93. Visualising the Range Rover in a rocky environment to display the context of exploring.

Figure 94. Visualising the Range Rover in a beach environment to display the context of exploring.

DESIGN REFLECTION:

The final sleeping environment has been refined throughout the design process to harmonise with the Range Rover Sport. Digital surface language or ‘mapping’ has enabled the capsule to flow with the design features of the vehicle. The overall form of the environment is sympathetic to the vehicle, and the relationship is instantly identifiable. The rear side profile has been designed as an extended awning allowing the boot to be opened flush against the capsule, whilst also covering the user when climbing the ladder. Various design cues significant to the Range Rover have been utilised, notably the continuous character line, silhouette curves, the crease line folding around the gills and the front character line that flows under the headlights. Exterior colours, materials and branding further integrate the two surface languages, the breaking of colour also helps to reduce the perceived size of the capsule.

Alongside the exterior developments, the interior served a different purpose through creating the feeling of luxury. The materials utilised within the interior panels visualised different combinations of materials, texture and patterning. Range Rover has always held an attention to detail, therefore it was important to incorporate high quality materials such as leather, wool, satin and knits. Alongside materials, interior amenities added to the lavish feeling. Although the bed consumed most of the area, lighting and a small fridge was placed in the capsule. Interior development has the potential to be never ending, 3D printing enables built in features to be introduced, allowing the customer to choose any feature that can fit within the space. This could be in the form of a drinks cabinet or storage facilities. The concept of extra accessories could provide a potential market alongside the bespoke sleeping capsule. If the sleeping environment was produced in New Zealand it would be important to introduce a portable toilet and potentially more features that make it easier to live. The ability to access remote places would mean the user needs to clean up after themselves to avoid breaking any legislation surrounding freedom camping.

The CAD process development from continuous sweeping to designing panel by panel immediately increased design precision. Controlling design detail was the key method of integration between the vehicle and the capsule. Although the CAD process improved considerably there was still minor details that didn’t quite fit, an example is the bottom front curve that sat lower than intended (see figure 74). The top roof curve was also overly exaggerated, though it did help to improve tumblehome, and provide a more dynamic feel.

FUTURE SPECULATIONS:

Land Rover have just released prototypes of autonomous self-driving SUV that possesses the ability to travel in any weather or environment. The concept of self driving vehicles is a part of the near future and is an important concept surrounding a habitable sleeping capsule. It can be fairly speculated that the sleeping space could transition into more than just an environment for rest. People could be able to sit above their vehicle in a lavish custom capsule. It is a potential venture for nature or wildlife experiences or a luxury form of travelling in the future.

Figure 95. Visualising a safari park tour in an autonomous self-driving vehicle, with the people sitting up above in the capsule.

8

CONCLUSION

The tailored traveller has focused primarily on the utilisation of digital vehicle mapping as a design tool, for bespoke customisation and personalisation within the automotive industry. This thesis asks the question “Can design use the properties of digital vehicle data in conjunction with large-scale FDM 3D printing to sustainably produce bespoke habitable sleeping environments for an automotive context?” Moreover, the research has aimed to justify why a tailored mobile sleeping environment should be manufactured with FDM 3D printing technologies.

Literature reviewed in this research eludes to mass-customisation reaching the extent of it’s capability and is unable to cater to growing customer demands of bespoke customisation and personalisation. Conventional subtractive methods such as moulding, casting and machining are extremely costly when used for bespoke applications due to tooling changes and mould production. Furthermore, the automotive industry has received substantial environmental pressure from government and media organisations surrounding the environmental effects of vehicle life-cycles. The increasing environmental pressure has required automotive manufacturers to search and explore for more sustainable manufacturing methods and materials.

Alongside this, the concept of vehicle habitation, specifically freedom camping, has become an increasingly popular leisure activity, justifying the timeliness of this research. Although New Zealand has stringent legislation surrounding freedom camping, the concept has continued to grow with the introduction of various vehicles and accessories designed specifically for the activity.

Currently within the automotive industry, FDM 3D printing technology has mostly been developed through rapid prototyping and small-scale end-products, with minimal focus on large scale applications. With that being said, companies such as BLB industries are evolving large-scale 3D printing with the introduction of sizeable custom built printers that are able to produce industrial size parts. Furthermore, FDM technology is capable of producing bespoke geometries, and high quality parts through the medium of digital CAD modelling. Presently, vehicles are all comprised within a digital database, each vehicle model contains its own unique surface map that can be tweaked and developed rapidly. Thus, FDM 3D printing in conjunction with digital CAD modelling establishes itself as the preferred manufacturing method for customisation and personalisation of vehicle models.

This research project followed an iterative journey utilising two predominant methodologies to cohesively develop concepts throughout the design process. The output of these methods resulted in a digital vision of a bespoke habitable sleeping space tailored to a Range Rover Sport using CAD renders. Rendering has been a key development method throughout this thesis, especially the introduction of humans to understand the surrounding interior space and context. The final design was the outcome of a rigorous design process that involved the learning of a new CAD software. Although the final solution did not result in a large-scale physical form, the associating design process, with relation to background theory, definitively utilised digital vehicle data as a tool for bespoke vehicle customisation and stylising.

To conclude, the sleeping environment successfully answered the research question as it was specifically designed to fit to a Range Rover Sport and embodied unique surface language. Alongside this, the bespoke form could only be manufactured through 3D printing technologies as conventional methods would not suffice due to economic and manufacturing process limitations. Overall, the research has identified that the relationship between digital vehicle data and FDM 3D printing has considerable capability to produce bespoke sleeping environments tailored for any vehicle model.

9

REFERENCES

Alford, D., Sackett, P., & Nelder, G. (2000). Mass customisation — an automotive perspective. *International Journal of Production Economics, 65*(1), 99–110. https://doi.org/10.1016/S0925-5273(99)00093-6

AL-Oqla, F. M., & Sapuan, S. M. (2014). Natural fiber reinforced polymer composites in industrial applications: feasibility of date palm fibers for sustainable automotive industry. *Journal of Cleaner Production, 66,* 347–354. https://doi.org/10.1016/j.jclepro.2013.10.050

Bak, D. (2003). Rapid prototyping or rapid production? 3D printing processes move industry towards the latter. *Assembly Automation, 23*(4), 340-345.

Berman, B. (2012). 3-D printing: The new industrial revolution. ***Business Horizons, 55***(2), 155–162. https://doi.org/10.1016/j.bushor.2011.11.003

Burgess, J. (1881). *Inscriptions from the Cave-temples of Western India with Descriptive Notes & C* (No. 10). Government Central Press.

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). Could 3D printing change the world. *Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC.*

Chow, R. (2010). What should be done with the different versions of Research Through Design. *Entwerfen. Wissen. Produzieren. Designforschung Im Anwendungskontext.*

Coachbuilt.com - History of Coachbuilding. (2018). Retrieved from http://www.coachbuilt.com/his/history.htm

Custom Machines. (2018). Retrieved from http://blbindustries.se/3d-printers/custom-machines/

Dudek, P. (2013). FDM 3D Printing Technology in Manufacturing Composite Elements. *Archives of Metallurgy and Materials, 58*(4), 1415–1418. https://doi.org/10.2478/amm-2013-0186

Fogliatto, F. S., Da Silveira, G. J., & Borenstein, D. (2012). The mass customization decade: An updated review of the literature. *International Journal of Production Economics, 138*(1), 14-25.

Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy, 74,* 158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Government, N. Z. (2011). Freedom Camping Act 2011 No 61 (as at 01 March 2017), Public Act 5 Meaning of freedom camp – New Zealand Legislation. Retrieved June 26, 2017, from http://www.legislation.govt.nz/act/public/2011/0061/latest/DLM3742849.html?search=sw_096be8ed8150d99f_vehicle_25_se&p=1&sr=1

Hager, I., Golonka, A., & Putanowicz, R. (2016). 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? *Procedia Engineering, 151*, 292–299. https://doi.org/10.1016/j.proeng.2016.07.357

Happian-Smith, J. (Ed.). (2001). An introduction to modern vehicle design. Elsevier.

Jonas, W. (2007). Design Research and its Meaning to the Methodological Development of the Discipline. *Design research now,* 187-206.

Jonas, W. (2014). *A cybernetic model of design research.* Routledge Handbooks Online. https://doi.org/10.4324/9781315758466.ch2

Kaluza, A., Kleemann, S., Broch, F., Herrmann, C., & Vietor, T. (2016). Analyzing Decision-making in Automotive Design towards Life Cycle Engineering for Hybrid Lightweight Components. *Procedia CIRP, 50,* 825–830. https://doi.org/10.1016/j.procir.2016.05.029

Keenan, J. H. (2013). *Freedom Camping Management: A case study of the Otago and Southland Regions of New Zealand* (Thesis). University of Otago. Retrieved from https://ourarchive.otago.ac.nz/handle/10523/3772

Koronis, G., Silva, A., & Fontul, M. (2013). Green composites: A review of adequate materials for automotive applications. *Composites Part B: Engineering, 44*(1), 120–127. https://doi.org/10.1016/j.compositesb.2012.07.004

Koronis, G., Silva, A., & Fontul, M. (2013). Green composites: A review of adequate materials for automotive applications. *Composites Part B: Engineering, 44*(1), 120–127. https://doi.org/10.1016/j.compositesb.2012.07.004

Laurier, E., Brown, B., & Lorimer, H. (2005). *Habitable Cars: what we do there* (Working Paper). Institute of Geography; The School of Geosciences; The University of Edinburgh. Retrieved from https://www.era.lib.ed.ac.uk/handle/1842/815

Lewin, T., & Borroff, R. (2010). *How to Design Cars Like a Pro.* Motorbooks.

Lewis, A. (2016). Wild Camping UK: Can you camp anywhere?. Retrieved from https://www.woodlandtrust.org.uk/blog/2016/06/wild-camping/

McCue, T. (2015). World's First 3D Printed Road Ready Car: LM3D By Local Motors. Retrieved from https://www.forbes.com/sites/tjmccue/2015/11/13/worlds-first-3d-printed-road-ready-car-lm3d-by-local-motors/#7a553f692aa0

OPod Tube Housing. (2017). Retrieved from http://www.jameslawcybertecture.com/?id=1087&section=projects

Range Rover: A History - Featured Articles - Land Rover. (2018) Retrieved from https://www.landrover.com/explore-land-rover/onelife/heritage/range-rover-history.html

Revelation of luxury: Vision Mercedes-Maybach 6 Cabriolet. (2018). Retrieved from https://www.mercedes-benz.com/en/mercedes-benz/vehicles/passenger-cars/mercedes-maybach/revelation-of-luxury-vision-mercedes-maybach-6-cabriolet/

Stratasys' new Continuous Build 3D Demonstrator uses cloud-controlled 3D print cells for continuous fabrication. (2017). Retrieved from https://www.3ders.org/articles/20170510-stratasys-new-continuous-build-3d-demonstrator-uses-cloud-controlled-3d-print-cells-for-continuous-fabrication.html

Swedish company NorDan to 3D print windows & doors using custom large-scale printer by BLB Industries. (2018). Retrieved from https://www.3ders.org/articles/20180116-nordan-to-3d-print-windows-doors-using-custom-large-scale-printer-by-blb-industries.html

Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3D printing: Market structure models in light of additive manu facturing revisited. *International Journal of Production Economics, 164,* 43–56. https://doi.org/10.1016/j.ijpe.2015.02.020

Zimmerman, J., Stolterman, E., & Forlizzi, J. (2010, August). An analysis and critique of Research through Design: towards a formali zation of a research approach. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems* (pp. 310-319). ACM.