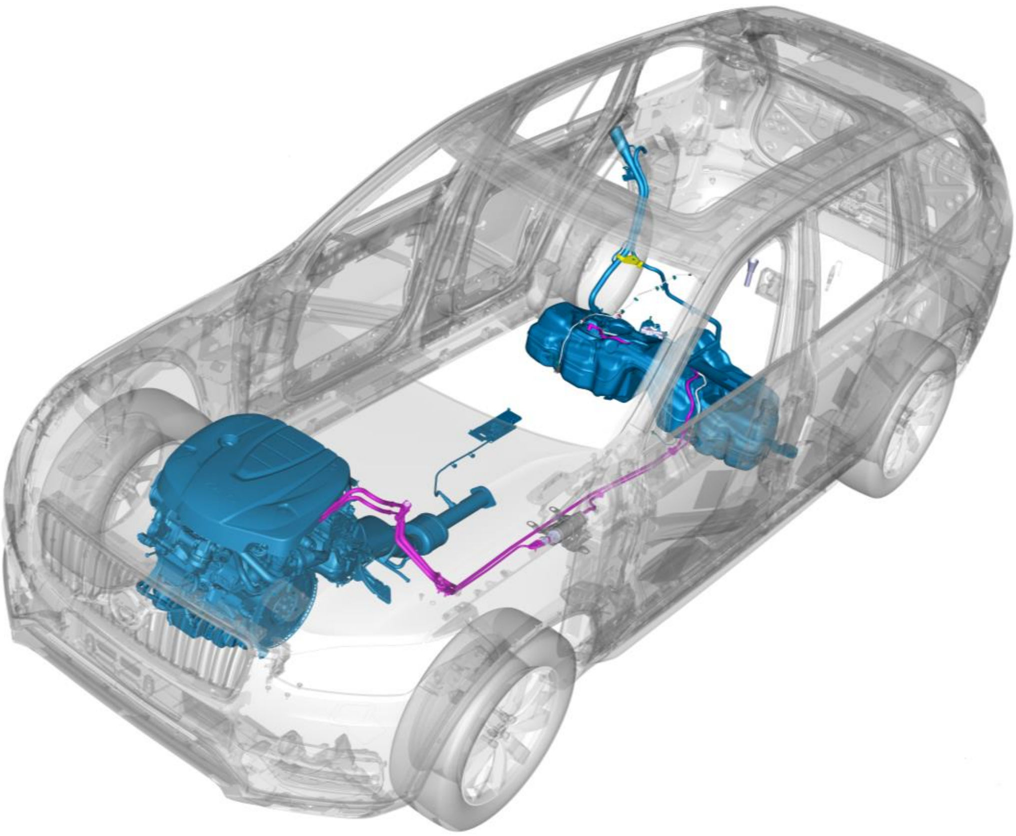
CHALMERS
UNIVERSITY OF TECHNOLOGY



Design for Packaging and Crash Protection of Fuel Lines of Powertrain for Cars

Master's thesis in Product Development

WENTING HU
JINGXI YAN

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

Design for Packaging and Crash Protection of Fuel Lines of Powertrain for Cars

Master thesis in Product Development

WENTING HU
JINGXI YAN

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2015

Design for Packaging and Crash Protection of Fuel Lines of Powertrain for Cars

WENTING HU, JINGXI YAN

Department of Product and Production Development

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Cover:

Part of the powertrain system in Volvo cars, consisting of engine and fuel tank in blue, and fuel lines in purple which is the research target of this thesis.

Chalmers Reproservice

Gothenburg, Sweden 2015

Abstract

This master thesis is carried out at Volvo Car Corporation together with the Department of Product and Production Development of Chalmers University of Technology in Gothenburg. Volvo Car Corporation (VCC) is a car manufacturer located in Gothenburg, Sweden. The core brand value of VCC is safety, which is also the reason of this thesis existing. To keep and strengthen the leadership in automotive manufacturing on safety issues, VCC is aiming for the peak performance on car safety.

The purpose of this master thesis is to develop a concept of fuel lines of powertrain in cars to minimize crash damage and with lower cost. The current solution of fuel lines for crash protection is to cover fuel pipes with high-strength stainless steel tubes. According to crash simulation, the section of fuel lines behind the engine has high risk of being broken during car crash.

To have a full view of the fuel delivery system, interviews were conducted with crash simulation engineers and fuel lines design engineers. The development process started from brainstorming to think out of the box and many innovative ideas were generated. The first concept selection was performed among single concepts before they were synthesized. After concepts synthesis, two more rounds of concept evaluations were carried out to find the best concept. The difficult part of all the evaluations was the lack of correct information, which is necessary to make an accurate evaluation.

In the result, there is one concept standing out which is to replace the protection pipe with a sandwich metal tube. The new concept has a better performance than the current solution with limited cost increase. Sandwich metal is invented in recent years and becoming a phenomenon in a great deal of industries. The sandwich metal material, which is selected to produce the protection pipes in the new concept, is made of 304 stainless steel as the skin layers and 304 stainless steel fiber as the core layer. These sandwich metal pipes have higher stiffness and energy absorption ability than stainless steel pipes. They are capable of protecting fuel lines from any leakage in car crash. Meanwhile, since the sandwich metal is still a novelty and under development, the cost of producing protection pipes from it is anticipated to be higher than current pipes. However, since their performance is overwhelmingly better than stainless steel, the limited economy disadvantage is acceptable. In addition, a substitute concept is kept because its excellence potential to realize zero fuel leakage in car crash.

Keywords
Volvo Car Corporation, Powertrain, Crash Protection, Fuel Lines, Product Development, Sandwich Metal

Preface

This report represents the master thesis "Design for Packaging and Crash Protection of Fuel Lines of Powertrain for Cars" which has been performed at the department of PT Geometry at R&D in Volvo Car Corporation during the first half year of 2015.

The report mainly focuses on the study of the segment of fuel lines that have high risk of damage in a frontal car crash. The purpose of having this thesis is that Volvo would like to have new concept ideas that come out of the box and still have reliability. In the result of this thesis, there are two proposals that meet the requirements being developed.

We thankfully acknowledge the significant contribution and support provided by all the people who have been involved in this project. Especially we are indebted to our supervisor Torbjörn Andersson for his knowledge sharing, support and feedback in our daily work. In addition, we would like to thank Erik Fredholm and Anders Sandahl for their support to all our questions regarding the fuel system and the frontal crash simulation. Moreover, our thanks to Eva Haglund who provided the opportunity that we can work on the thesis in Volvo Car Corporation and Kjell Hävell who came out with this thesis. Finally, thanks again for all the support from the engineers of the Department of PT Geometry and Department of EVAP System and Fuel Lines.

Gothenburg, 2015-06-12

Wenting Hu
Jingxi Yan

Table of Contents

1. INTRODUCTION **1**

1.1 BACKGROUND **1**
1.2 PURPOSE **1**
1.3 RESEARCH QUESTIONS **1**
1.4 DELIMITATIONS **1**
1.5 REPORT OUTLINE **2**

2. PRE STUDY **3**

2.1 TECHNICAL BACKGROUND **3**
2.1.1 FUEL LINES SYSTEM OF DIESEL ENGINE 3
2.1.2 FUEL SYSTEM OF GASOLINE ENGINE 5
2.1.3 CURRENT SOLUTION OF FUEL LINES PROTECTION 5
2.2 INTERVIEW **7**
2.3 BENCHMARKING **7**
2.4 TARGET REQUIREMENT **8**

3. GENERATION OF CONCEPTS **11**

3.1 REQUIREMENT SPECIFICATION **11**
3.2 FUNCTION TREE **11**
3.3 CONCEPT GENERATION **12**

4. EVALUATION AND SELECTION OF CONCEPTS **17**

4.1 METHODOLOGY **17**
4.2 CONCEPT EVALUATION 1 **17**
4.3 CONCEPT EVALUATION 2 **18**
4.4 CONCEPT EVALUATION 3 **19**
4.5 FINAL CONCEPT **19**

5. DETAIL DESIGN **21**

5.1 SELECTION OF SANDWICH MATERIAL **21**
5.1.1 TYPES OF SANDWICH PANEL 21
5.1.2 SELECTION OF FIBER 22
5.2 PRODUCT ARCHITECTURE **23**
5.3 CALCULATION AND SIMULATION **25**
5.3.1 BLUNT PROJECTILE IMPACT CALCULATION 25
5.3.2 SIMULATION 26

6. COST ESTIMATION **31**

6.1 REFERENCE PRODUCT COST **31**
6.2 COST ESTIMATION OF FINAL CONCEPT **31**
6.2.1 MATERIAL COST 32
6.2.2 MANUFACTURING PROCESS AND COST 33

7. SUBSTITUTE CONCEPT **37**

7.1 CONCEPT ARCHITECTURE 37
7.2 CONCEPT ANALYSIS 38
7.3 CAD MODEL 40

8. DISCUSSION 43

8.1 DISCUSSION OF THE CONCEPT GENERATION 43
8.2 DISCUSSION OF THE CONCEPT SELECTION 44
8.3 DISCUSSION OF THE SIMULATION 45
8.4 DISCUSSION OF COST ESTIMATION 46
8.5 DISCUSSION OF SUBSTITUTE CONCEPT 47

9. CONCLUSIONS 49

10. FUTURE WORK 51

11. REFERENCE 53

12. APPENDIX 55

APPENDIX 1: INTERVIEWS 56
APPENDIX 2: PICTURE OF SIMULATION SCENARIO 58
APPENDIX 3: CONCEPT EVALUATION 1 59
APPENDIX 4: CONCEPT EVALUATION 2 60
APPENDIX 5: CONCEPT EVALUATION 3 61
APPENDIX 6: MATLAB SCRIPT OF CURRENT MATERIAL ENERGY ABSORBING 62
APPENDIX 7: EXPERIENCE LEARNING CURVE 65

1. Introduction

This section contains the background of this project, and brief introduction about Volvo Car Cooperation. The purpose, research questions, delimitations, timetable, and report outline are also included in here.

1.1 Background

Volvo core value: safety, quality, environmental. (Core Value of Volvo Cars, 2015) Safety is an issue that involves every area of a car, Volvo Car Corporation has the top technology in car safety currently and still keeps developing safe cars to strengthen this competitiveness. Fuel pipes to a car is like the blood supply system to a human body. Fuel system is one of the most hazardous part in a car that needs to be handled carefully without doubts. During the crash, there are many sparks generated by broken electrical lines that are very close to the fuel lines. Since fuel pipes carry flammable liquid, once fuel leakage happens, there is high risk to cause fire. Therefore, the safety issue of the fuel lines is remarkably necessary and important.

1.2 Purpose

The purpose of this thesis is to develop a concept solution of fuel lines for crash protection of cars. This solution is expected to be applied to the future cars. In this thesis, the crash scenarios taken into consideration is only limited to the frontal crash since it is one of the most common and catastrophic crash types. With the function of crash protection being guaranteed, a lower cost of fuel line is preferred to be explored as well.

Another reason for having this thesis is to break the stereotype of thinking in an automotive manufacturer with long history. An "out of box" design is anticipated to provide an insight for new generation cars.

1.3 Research questions

The research aims at developing a fuel line solution for crash protection with decreased price. The thesis will answer the following questions:

What will happen to the fuel lines when a frontal crash occurs?

How to balance the performance and cost of the product?

How to evaluate the cost and manufacturing feasibility in a proper way?

1.4 Delimitations

This research focused on the crash protection of fuel lines, and all the studies are based on the All New XC 90 diesel engine. The fuel lines system functionality is not the main focus of this project. During this project, only frontal crash is studied, and the other situations of crash are not the focus here. In addition, all the conceptual solutions of this project were proposals to VCC for future design. If these solutions are going to reality, there will be gaps existing between the theoretical estimated data and the real data.

1.5 Report outline

This report aims at presenting the work conducted throughout the thesis work. It allows the readers to have an understanding of the development work as well as a basic knowledge of fuel lines.
The entire report contains nine parts: pre-study, concept generation, concept evaluation, detailed design for final concept, cost estimation, substitute concept, discussion, conclusion and future work.

2. Pre Study

In this chapter, the basic information of fuel lines system of diesel engine and gasoline engine is introduced, and the current solution and target requirements are included as well.

2.1 Technical background

The fuel lines system for diesel engine is chosen as the research object for the thesis project although the project aims at looking for new protection solutions of fuel lines in all combustion engine cars. Since the fuel system of diesel engine is more complicated than the one for gasoline engine, taking the fuel lines for diesel engine as the research object would be more significant. In addition, diesel engines have much larger market in Europe. They have been used in automobiles gradually since the 1930s and still serve in a wide popularity. Currently, the average for diesel engines accounts for nearly 80% of the total sold amount of Volvo cars.

2.1.1 Fuel lines system of diesel engine

As currently used all over the world, diesel fuel has gained almost exclusively from gasoline. Before diesel was used as engine fuel, its potential use was neglected and only treated as an additive fuel to gasoline. When the auto-ignition combustion engine was developed in the 19^{th} century, diesel was first used to replace gasoline due to gasoline's resistance to auto-ignition. Initially, several technical problems prevented diesel from being ideal energy fuel. Most diesel freezes at common winter temperatures, typically around −8.1 °C, while it also vaporizes at temperatures between 149 °C and 371 °C. Moreover, the high level of sulfur content in diesel made it harmful to environment. However, with the assistance of necessary additives, diesel has met the following demands to be qualified as engine fuel.

- Cleanliness
- Oxidation stability
- Flow ability at low temperatures
- Lubrication reliability
- Low sulfur content (Mollenhauer and Tschoeke, 2009).

After the initial problems were solved, diesel fuel has reached commercial success thanks to its better efficiency and lower cost.

As mentioned before, the diesel engine is an auto-ignition combustion engine. It uses the heat from hot air to trigger ignition and burn the injected fuel. Principally, diesel engines are energy converters that convert fuel energy to mechanical energy by supplying the heat released by combustion in an engine to a thermodynamic cycle (Mollenhauer and Tschoeke, 2009). By using fuel injectors, heat is produced from compressing air into the combustion chamber to ignite the diesel. This contrasts to the gasoline engines that use a spark plug to ignite the air-fuel mixture.

The fuel lines system is essential in storing and delivering the diesel that an engine needs to run. Figure 1 shows the fuel lines system of a diesel engine.

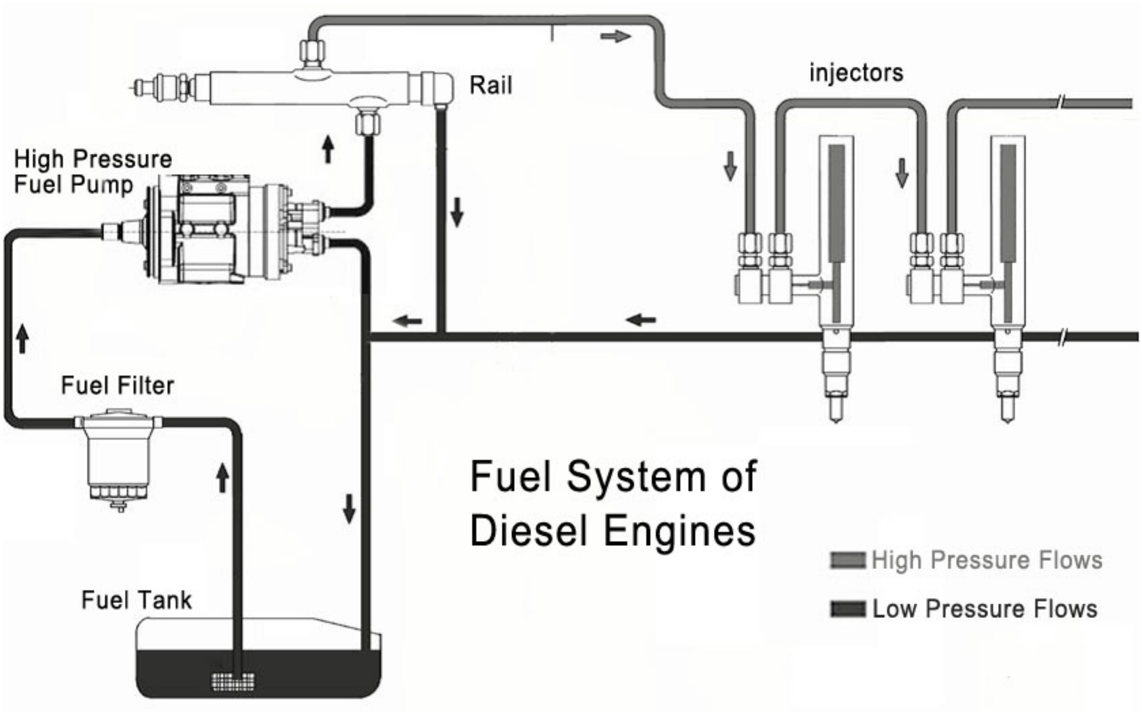


Figure 1. Fuel system of diesel engine

Fuel tank:
The fuel tank is a safe container for fuel. When a vehicle is filling up at a fuel station, the fuel travels down the filler pipe and into the tank. The fuel is stored in the tank and released to feed engines. Recent years has seen the fuel tank becoming more complicated. Nowadays, it usually houses the fuel pump and has more controls to prevent vapors emission.

Fuel filter:
Clean fuel is critical to engine life and performance. Fuel filter helps to screen out the contaminants from fuel, like dirt and rust.

High Pressure Fuel Pump:
A high-pressure fuel pump is installed after the fuel filter. It provides well-timed high-pressure fuel pulses to the injection system. Fuel pumps mounted to the engine use the motion of the engine to pump the fuel.

Rail System:
The rail system accumulates high-pressure fuel in the common rail and injects the fuel into the engine cylinder, allowing high-pressure injection independent from the engine speed. As a result, the rail system can reduce harmful materials such as nitrogen oxides and particulate matter in emissions and generates more engine power. (Denso, 2009)

Fuel injectors:
Fuel injectors are tiny valves, which admit fuel into the combustion engine. Most modern cars are equipped with fuel injection instead of a carburetor to mix the fuel and air. By injecting the fuel close to the cylinder head the fuel stays as tiny particles, it burns better than the liquid fuel does. This has resulted in lower emissions and better fuel economy.

How fuel travels
Fuel is supplied from the tank and then it passes through filters to reach the high-pressure fuel pump. From the pump, an accurately controlled amount of fuel is sent to the injectors through the rail. By the

work of injectors, the fuel enters the combustion chambers as a fine spray. In the cylinder chambers, the hot compressed air enters as well, then ignites the fuel and thus begins the power stroke.

The excess fuel supply of the fuel pump flows back to the tank because the pump always sends more fuel than will actually be needed for the engine to run. Diesel fuel serves more functions than just offering flammable fuel. It also plays the roles of lubricant and coolant for tightly tolerant parts inside the injection system. The overflow quantity from rail and injectors also returns to the tank.

2.1.2 Fuel system of gasoline engine

The gasoline engine differs from the diesel engine in their ways to initiate the combustion process. In gasoline engine, the fuel and air is pre-mixed in injection system and ignited by a spark plug. To the fuel delivery system, gasoline engine is similar with diesel engine except for one part. Gasoline engine powertrain has no return pipe but a purge pipe, which is to store gasoline evaporation for further use.

All the above differences come from the different properties of gasoline and diesel. Generally, diesel engine has more complicated engine structure and fuel lines system. Therefore, diesel engine is taken as the research object of the thesis project and report. The following contents are all within the research of fuel delivery system of diesel engine.

2.1.3 Current solution of fuel lines protection

The current fuel lines system consists of one feed pipe with fuel delivered from the tank to the engine, and one return pipe with fuel flowing from the engine back to the tank. A fuel filter is installed in the feed pipe to prevent impurities in fuel from entering into engine.

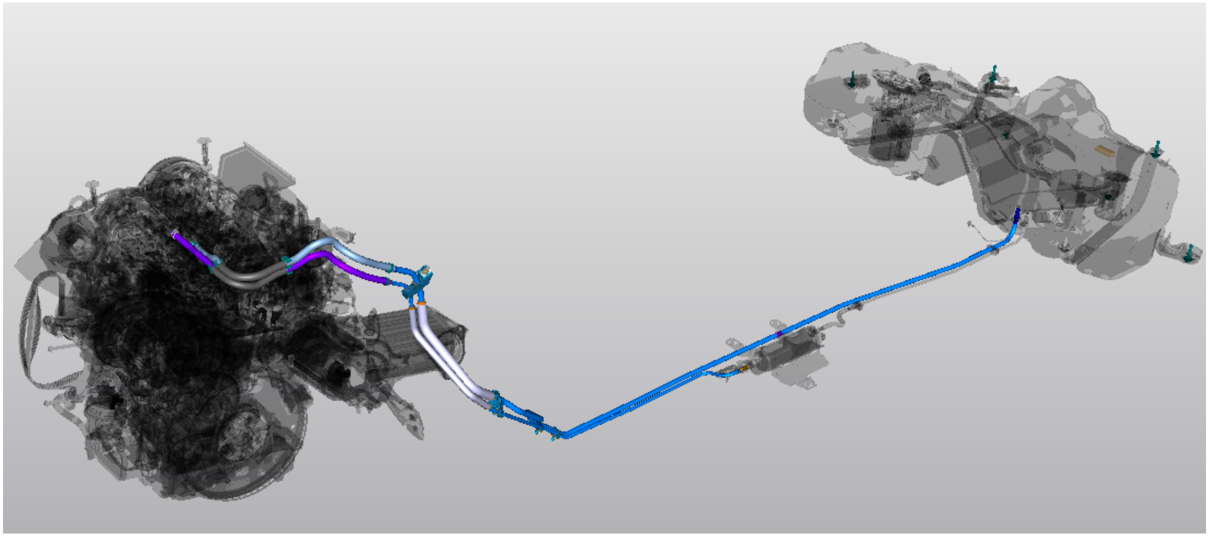


Figure 2. Current solution of fuel pipes

The feed pipe and the return pipe have the same structure, which is illustrated in Figure 3.

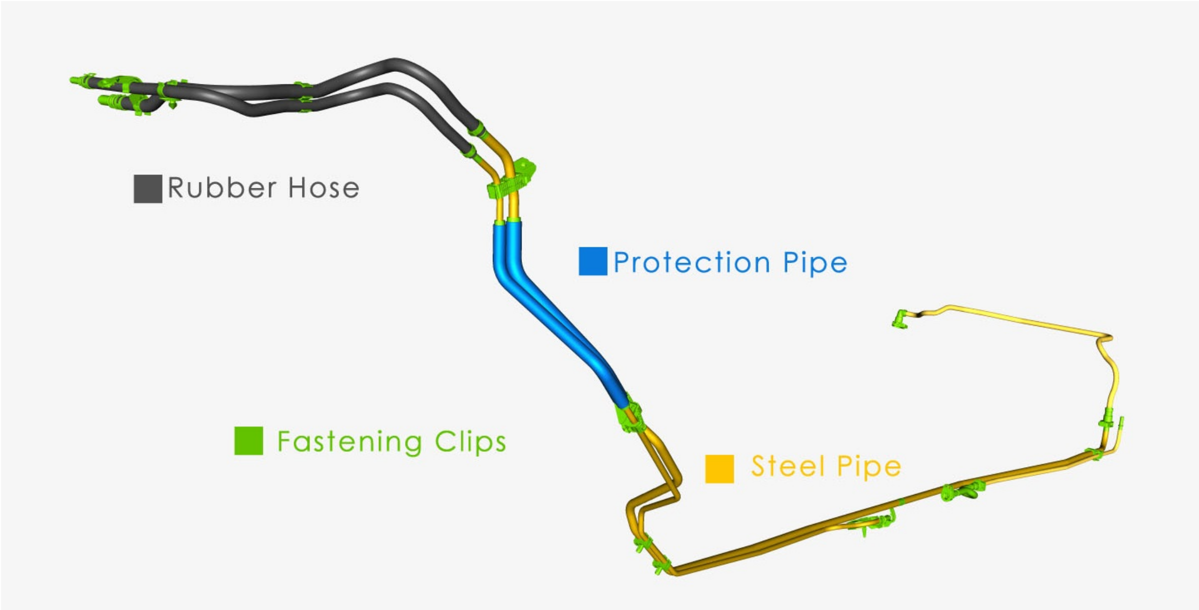


Figure 3 Structure of fuel lines

The grey parts are connected to the engine. These parts are made of reinforced rubber since they have to provide flexibility to engine motion.

Connected with the rubber hoses are steel pipes and their other end connects to the fuel tank at the rear. The yellow parts are indicated as steel pipes but are actually constructed from composite materials. Their inner layer is made of nylon. Between nylon and steel, there is multi coating to strengthen their function. These composite pipes have good performance-cost efficiency. They give necessary steel strength to protect from possible strikes on bumpy roads, and also cost and weigh less than steel.

There is one part of steel pipes covered by the blue protection because this part of pipe is the most vulnerable part owing to its location behind battery and transmission. If any serious frontal car crash happens, it would be the direct place to be damaged. Thus, there are two protection tubes made of high-strength stainless steel to prevent the fuel pipes from hits.

The two protection pipes have the same length, 300mm. The diameters of the protection pipes are shown below in Figure 3. The return pipe has larger diameter owing to the higher fluid pressure inside.

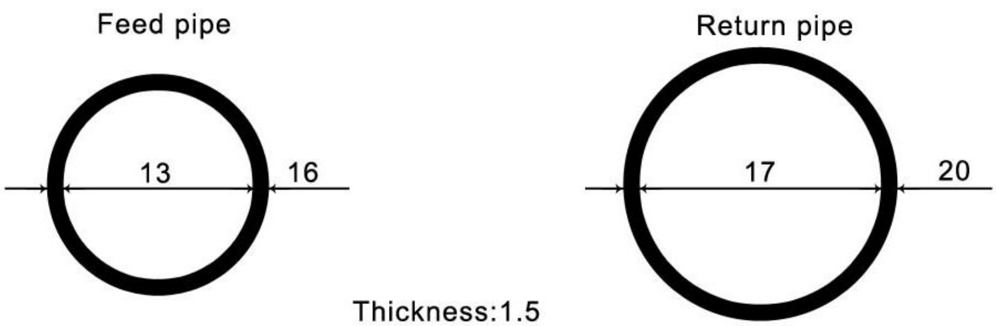


Figure 4. Diameters of feed pipe and return pipe. [Unit: mm]

In this project, the focus of research is the protection pipes and their inner steel pipe. Alternative solutions for better packaging and lower cost of protection pipe will be pursued.

2.2 Interview

In this phase, three interviews with three engineers were conducted. There are one engineer from Evap-system & fuel lines, one engineer from frontal crash simulation, and the packaging leader. From those different points of view, the full picture of the research problem was created. [Appendix 1]

According to the interview with the fuel lines engineer, fuel lines have two pipes with flows of opposite directions --- return pipe and feed pipe. The return pipe has bigger diameter than the feed pipe owing to the higher fluid pressure inside, also larger return pipe can prevent more pressure from the fuel pump. The fuel lines system is a complex system involving many parameters, for example, fluid volume, turbo accelerating time, connector diameters and seal capability. The environment temperatures of fuel lines are different in different locations. It could be 100 to 130 degrees Celsius near the engine, but in the other locations, it would be just around outside temperature.

The second interview was made with a simulation engineer of frontal crash. According to him, the duration time of a frontal crash usually is 0.1s. Once a crash happens, an engine mount in the front will break itself spontaneously to allow transmission and engine to move backwards to have a buffer for the coming crash force. Because of the backward moving, all the parts of the engine compartment could be squeezed including fuel lines. The broken mounts or other metal chips with have sharp edges may cut or pierce fuel lines to cause leakage. Furthermore, the leaked fuel often result in fire since there are always heat and sparks generated in crash, especially with the electrical cables closely located to fuel pipes. Regarding fuel leakage, there is legal requirement of maximum leakage amount. The current protection solution is based on the simulations that show the estimated vulnerable parts that need protection. [Appendix 2]

2.3 Benchmarking

Benchmarking is the method of comparing one's performance metrics from other companies. There are several automobile manufacturers in the market considered as main competitors to Volvo cars. It is very interesting to look into the solution of fuel line protection.

The fuel lines of chosen vehicles share some basic similarities with the object vehicle. They are all diesel engine SUVs with similar displacements, which make the comparison more significant. Collecting the data of benchmarking demands knowledge from a variety of sources. The relevant information about chosen vehicles was obtained from an internal website

From the collected information, it turned out, besides Volvo, only the German cars have protection of fuel lines, such as BMW, Mercedes and Volkswagen. The picture 5a demonstrates the solution of BMW X5 which uses a metal coverage to protect the fragile part of fuel pipe. Picture 5b is the solution of Mercedes M-class 350. The designs from German brands are all quite similar to each other.

Figure 5a. Example of fuel protection of BMW X5 (Automotive Benchmarking, 2015)

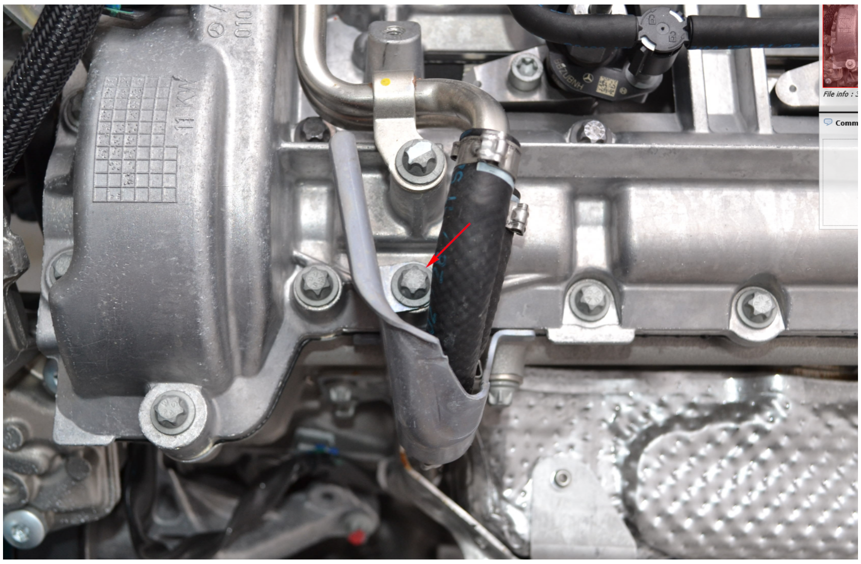


Figure 5b. Example of fuel protection of Mercedes M-Class 350 (Automotive Benchmarking, 2015)

2.4 Target requirement

There are various ways to formulate a requirement-specification list. One of the most widely used is based on the requirement engineering theory of Elizabeth Hull (Hull, Jackson and Dick, 2002). It includes three main parts: criterion, justification and verification that make the list a very complete and detailed one. There are also more simple methods, like a need-metrics matrix, which just demonstrates a clear relationship between needs and metrics.

In this project, the need-metrics matrix is chosen to proceed the specification establishment because it is more appropriate for technology-intensive products. For designing fuel lines in powertrain, the requirements are not from customer needs but mostly from technical research and expert opinions. An important point is that there are many different parts surrounding the fuel lines and conflicts should not appear anywhere. At the beginning of this project, the packaging leader has pointed out most of the basic requirements but not all the detailed information. However, the specifications have to be built immediately after identifying the product requirements. These specifications represent the determination and aspiration of the team, but they are established before one has enough knowledge about technology achievements and constraints. The team's efforts may fail to meet some of the requirement specifications.

Formulating a need-metrics matrix is very efficient and the information in the matrix is easy to communicate. Another benefit of this matrix is its capability of mapping the complex relationship between needs and metrics. In the case of this project, there are more than one metrics generated from one need and one metric resulting from different needs.

The target requirements are based on the interviews with engineers in fuel system and crash simulation, and researching internally and externally. Many different aspects have to be considered in order to list all relative requirements. The first three priority requirements listed are "high ratio of performance to cost", "crash protection", and "optimized packaging". These three-priority requirements were decided because price of a product affects the market competitiveness. At the same time, the new product has to show an improvement on function of crash protection and powertrain packaging relative to the current product. In addition, manufacturing feasibility, no airdrop, no static electricity, no solvent, no corrosion, quality and system demand, preventing engine motion, and maintenance service etc. are the basic functional requirements of the fuel lines.

In Table 1, the left side is the requirement list and the upper side is their quantitative metrics that are able to quantify the requirements. This method is based on Ulrich and Eppinger's requirement metric matrix (Ulrich and Eppinger, 2012, p.75). In this matrix, one requirement can have more than one measurement, and the relationship between requirements and their quantitative properties is not a one-to-one mapping. Moreover, there could be conflicts between all the requirements.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
		Material cost	Manufacturing cost	Material strength	Material toughness	Geometry tolarance	Total Geometry volumn	Total mass	Human body ergomonics	Installation time	Special tool required	Manufacturing ability	Components amounts	Stess concentration	Presure requirement from Engine	Solubility to fuel	Life cycle time	Evap ampunt in EU	Assembly/disassemble time	Material conductivity
1	High performance/cost ratio	•	•	•	•															
2	Crash protection			•	•															
3	Geometry with good balance regarding space of parts related					•														
4	Minimize space of fuel lines package						•													
5	None increasing weight with fuel in total referring to current							•												
6	Assembly friendly design								•	•	•									
7	Manufacturing internally feasible											•								
8	Increase integration degree of components												•							
9	Avoiding ergonomics risks in manufacturing								•											
10	Pressure Drop				•									•						
11	Fuel pressure Tolerance														•					
12	No static electricity																			•
13	No solvent															•				
14	No corrosion															•				
15	Longer Life cycle																•			
16	Legal Demand (Evap)																	•		
17	Engine Motion					•														
18	Mechanical Toughness				•	•														
19	Service/Maintenance								•		•								•	

Table 1. Requirement metric matrix

3.Generation of Concepts

3.1 Requirement specification

Requirement specifications are the quantitative data of the new product, which include the current product parameters as references and their importance with ranking from 1-5. Most of the parameters of the reference solution were provided by the engineers who work with fuel system and crash simulation. The rest were calculated according to the data in TeamCenter. As shown in Table 2, some of the parameters are precise data, like the cost of current product is 51.48 EUR, the geometry tolerance is 10mm, product total mass is 1456g and the component amount is 22. Some of the parameters are ranges due to the uncertainty of material property. For instances, the strength of high strength steel is 510-620 MPa, and its toughness could be various from 119-228 MPa.m$^{1/2}$ (AZO materials, 2015). Some parameters are not measurable or cannot be accessed from reliable resources, such as "material conductivity", "avoid stress concentration", "no special tool required", etc.

Table 2. Requirement specification

Metric No.		Req. No.	Importance	Units	Current Solution
1. Cost					
	Material cost	1	5	€	51,48
	Manufacturing cost	1	5	€	–
2. Properties					
	Material strength	1,2	5	Mpa	510-620
	Material toughness	1,2,10,18	5	MPa.m$^{1/2}$	119-228
	Geometry tolarance	3,17,18	4	mm	10
	Material conductivity	12	5	subj.	Yes
	Solubility to fuel	13,14	5	subj.	No
3. Performance					
	Total Geometry volumn	4	4	m^3	?
	Total mass	5	4	g	1456,44
	Life cycle time	15	3	year	30
	Avoid Stress concentration	10	5	subj.	Yes
	Pressure requirement	11	5	Bar	1500(HP)
4. Ergonomics					
	Ergomonic stance during installation	6,9,19	2	subj.	Yes
	Installation time	6	3	Min	?
	Special tool required	6,19	2	subj.	No
5. Manufacture					
	Manufacturing feasibility	7	3	subj.	Yes
	Components amounts	8	2	ps.	22
6. Legal					
	Meet Evap Standard	16	5	subj.	Yes
7. Maintenance					
	Assembly/disassemble time	19	3	s	–

3.2 Function Tree

To support concept generation, a function tree was created to establish an overview of the different functions of the product. Function tree is a method to analyze a system by decomposing the main function into sub-functions.

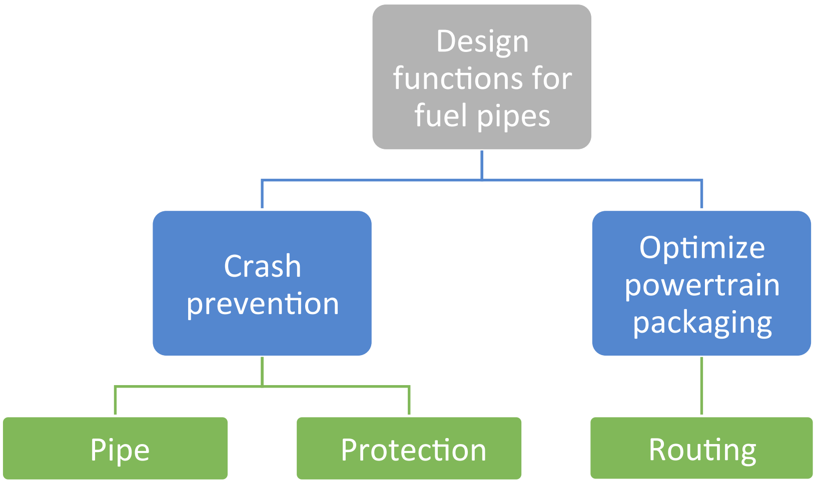


Figure 6. Function tree

The first level states the main function of this product, also the main target – the product has good property in crash prevention and proper packaging design. The second layer are the two main functions of the design: crash protection and optimizing powertrain packaging. In the third layer, three sub-functions were created. The function of inner pipe and protection pipe are to support the function of crash prevention. The function of routing is to support the function of optimizing powertrain packaging.

3.3 Concept generation

Based on the function tree analysis, new concepts were generated on these specific sub-functions to satisfy the overview function. Soon it was discovered that there are difficulties in doing pipe design and routing design very independently. The routing design is much relied on what kind of pipe solution is chosen. Hence, one decided to focus on pipe design first and do the routing design later if it is necessary in the detail design of the final pipe concept.

The ideas and concepts were explored mostly by two methodologies: brainstorming and 6-3-5.

Brainstorming:

Brainstorming is the most common method for idea generation but not only for this step. In the following process, brainstorming still works consciously or unconsciously and gives new idea sparks. As more information was acknowledged, the brainstorming sessions were held multiple times to obtain more and better concepts.

6-3-5

6-3-5 is a more structured and efficient version of brainstorming. It means six people who write down three ideas in 5 minutes, and then swap their worksheet and write down another three ideas based on other participants' ideas in 5 minutes. That is considered as one round of 6-3-5. In this project, there are two people involved, so it is actually 2-3-5. In this case, four rounds were conducted and there were 48 ideas generated at first.

After idea generation with two methods and discussion, there were 21 single concepts created eventually. Single means that they are sub-concepts based on the sub-functions of the function tree. Figure 7 illustrates these 21 single concepts. Category A illustrates the 6 concepts of the inner pipe. Category B shows the 15 concepts of the protection pipes.

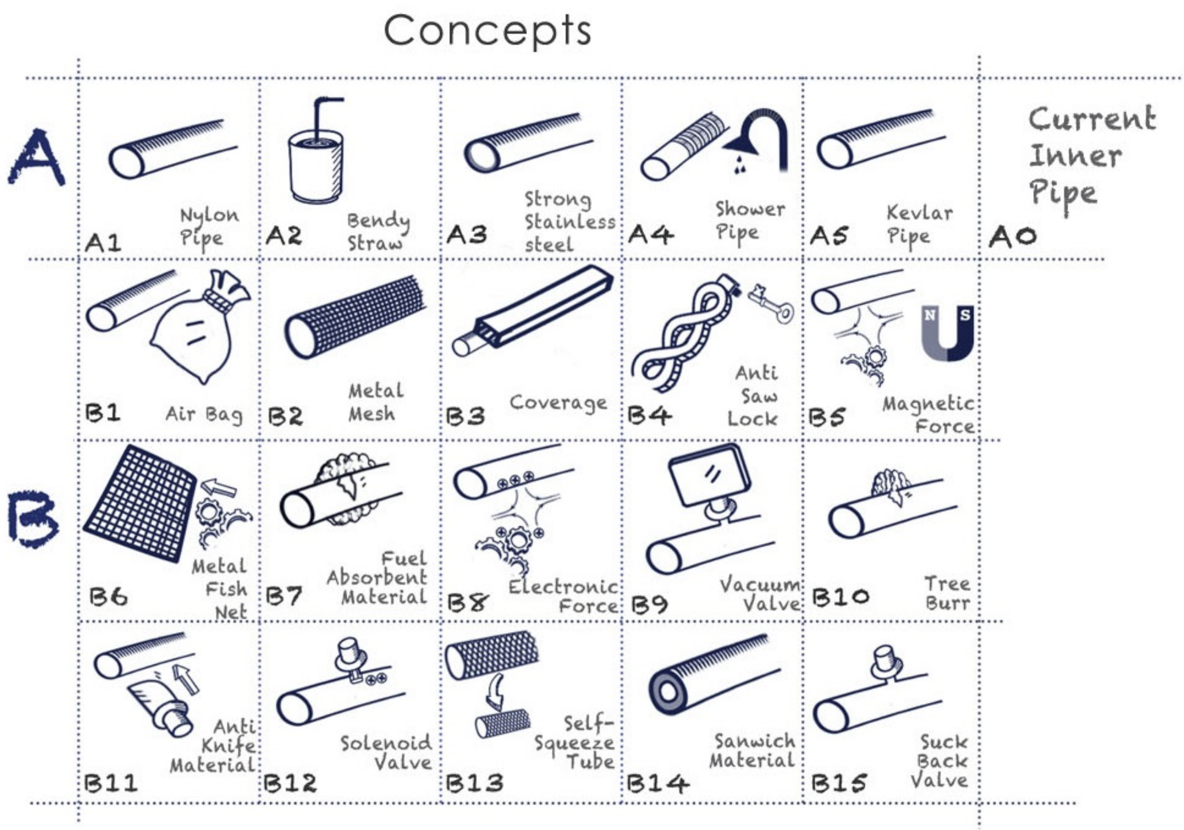


Figure 7. Sketch of concept generation

Following is the explanation of each single concept.

Category A: Concepts of Inner Pipe

A1: Nylon pipe
Nylon pipe is soft and flexible which can sustain squeeze force. With necessary coating, it can prevent from fuel corrosion and dust. The biggest benefit of nylon pipe is its low cost. Besides, its flexibility can stand the vibration from driving to some degree. However, the disadvantage of nylon pipe is its lack of strength and toughness and it is a relatively soft material.

A2: Bendy straw
This idea is inspired by bendy straw that has a concertina-type hinge near the top. The concertina structure helps to resist the squeeze force. Once the force applies, the structure will be stretched and result in deformation which decomposes the coming force.

A3: Strong stainless steel pipe
This idea is to replace normal steel of current inner pipe with strong stainless steel which build the current protection pipes. Thus, the cost, weight and mass of the total fuel pipes can be reduced.

A4: Shower pipe
The idea is inspired by shower pipe. The rings around the pipe reinforce the flexibility and strength compared to plain pipes.

A5: Kevlar pipe

Kevlar is a material invented in the 1960s as a replacement for steel, because it has high tensile strength-to-weight ratio. It can withstand high impact. Nowadays, it has been largely applied to many industrial products.

A0: Current solution
The current solution is a functional solution and still works very well, so it should be kept as a concept of the inner pipe.

Category B: Concepts of Protection Pipe

B1: Air bag
Just like the usual air bag to protect drivers and passengers, this air big is to protect pipes from metal debris. It also consists of a flexible cushion to inflate rapidly during crash happening. It can share the same trigger system with the airbags in steering wheels and inflate quickly when crash signal is detected.

B2: Metal meshes
Metal meshes are a very common material for reinforcement. They offer improved ruggedness, durability, and anti-vandal properties for their incorporated materials. In this case, metal meshes can be laminated under flexible materials to protect inner pipe. Thus, this combination can stand most of the cutting and squeezing forces. Moreover, these two materials can be very cheap if material selection is done appropriately.

B3: Coverage
From the benchmarking analysis, it is known that the coverage solution is commonly used by competitors. Since it has been applied in products for some time, the coverage solution is at least workable. That is the reason that the concept is considered.

B4: Anti-saw lock
Anti-saw lock is a type of lock usually for locking bikes and motorbikes from thieves. An anti-saw lock has PVC coating covering numerous bundles of steel wires twisted together. It also has very flexible shape. This type of lock has been proven effective against drilling and sawing.

B5: Magnetic force
This solution utilizes that the magnets of the same polarity repels. Letting the fuel pipes and broken engine mount obtains the same polarity of magnets, there will be magnet-repelling forces between them to force the broken engine debris away.

B6: Metal fish net
This solution is supposed to be a metal wire knitted net for capturing flying debris of broken engine mounts. The metal net is folded and installed near fuel lines under usual circumstances, and will open if a crash is detected.

B7: Fuel absorbent material
Fuel absorbent material has been used for decades especially for oil leakage accidents on ships. The technology of fuel absorbance is very mature. Some material can soak up liquids 70 times heavier than their own weight, such as polypropylene. However, in order to eliminate possible fire, flame retardant has to be blended into these materials. To apply fuel-absorbent material to fuel lines, they can be laminated between an inner tube and an outer tube to absorb leaked fuel. Besides, these materials are extremely light. Therefore, no mass problems need to be worried about if they are added into pipes.

B8: Electronic force
This idea applied the similar theory as B5. It uses the electronic current forces to make it happen.

B9: Vacuum valve
Vacuum valve is commonly used in industrial dust collection applications. This solution aims to drain the fuel lines with valve devices before any crash happens. The valve devices could be controlled by electronics or physically. A sensor for detecting coming crashes is needed (Cole-Parmer, 2015).

B10: Tree burr
The tree burr solution is to use fuel-involved chemical reaction to stop leakage. The chemical powders are stored between inner pipe and outer pipe. When the fuel pipes break, the powders can have strong chemical reaction with fuel that could form substance like a tree burr to clog the leakage area.

B11: Anti knife material
Anti-knife material has been widely used to make stab vest, butcher gloves and other security products. This material can capture quick knife blades to prevent extensive damage. It is usually produced from very fine knitted metal wires and equipped with the flexibility of fabrics and strength of metal. The squeeze and cutting forces during crash could be captured by anti-knife material.

B12: Solenoid valve
A solenoid valve is controlled electromechanically. They are the most frequently used control elements in the fluidics. The solenoid valves offer safe and high reliable control in the fastest time (ECVV, 2013).

B13: Self-squeeze tube
This idea is inspired by self-inflation stent in vessels for heart surgery. A stent is a tiny wire mesh tube which props open an artery. When an artery is narrowed by a buildup of fatty deposits called plaque, it can reduce blood flow that may result in a heart attack. Stent helps to keep coronary arteries open and reduce the chance of a heart attack (American Heart Association, 2012).

The property of self-inflation of stent enlightens one to come up a self-squeeze structured tube. This tube could squeeze into a much smaller size with more intensive wall formed during crash which can be against squeeze, cutting and piercing forces.

B14: Sandwich material
A sandwich-structured material is a special composite material that is fabricated by attaching two thin but stiff skin materials to a lightweight but thick core. The core material is normally low strength material, but its higher thickness provides the sandwich composite with high bending stiffness and overall low density.

B15: Suck back valve
Suck back valve is currently used to eliminate dripping of dispense media from nozzles in automated dispensing system. It creates a vacuum when switching from open back to closed position to suck back a predetermined amount of liquid. The working theory of suck back valve can be employed to fuel lines. Like the solution of vacuum valve, a sensor to detecting crash is also demanded in order to make sure that valves can suck back all the fuel before any leakage happens (SMC, 2013).

4. Evaluation and Selection of Concepts

In the concepts generation phase, there were 6 concepts of internal pipe and 15 concepts of protection pipe. Before the concept synthesis, the first round evaluation on single concepts was done with a Pugh Selection Matrix (Pugh 1990). After that, 26 synthesized concepts were generated. The second round evaluation was using a Pugh selection Matrix to estimate the 26 concepts and 9 of them were brought to the next round of evaluation. In the final round, "Bubble Sort" was used to select the final winner.

In this section, the color "balloons" which are shown at the right side are to indicate the number of concepts being selected after each round of evaluation.

4.1 Methodology

Pugh Matrix

The Pugh Matrix was addressed in this section. It is a screening method to narrow down the number of concepts. This matrix is to rank each concept regarding the evaluation criteria with "+" or "-". Comparing a concept to current solution against each criteria, if it is considered better, a "+" is signed, if it is worse, a "-" is signed. In the summary, a "+" is counted as "+1" point, and a "-" point is counted as "-1", and calculate all the points to get a total score. Then compare the scores of concepts, and keep the concepts with higher scores to the next evaluation.

4.2 Concept evaluation 1

6 15

In this case, two categories concepts, inner pipe and outer protection, were evaluated separately. 6 inner pipe concepts were narrowed to 5, and 15 protection pipe concepts were narrowed to 9 (See Appendix 3).

The selection criteria in this section was translated from main requirements:

- Material cost
- Cutting prevention
- Squeeze prevention
- Piercing prevention
- Total geometry volume
- Other requirement
- Total mass
- Components amounts
- Assembly/Disassembly time
- Manufacture feasibility
- Fire protection

The ranking system in this case is slightly different from the one in the standard Pugh Matrix. Every concept in each criteria was ranked from three pluses (+ + +) to three minus (- - -) regarding the comparison between new concept and reference concept. In the evaluation, the ranking was done together with packaging engineers and fuel line engineers. See Appendix 3.

Selection criteria	A0	A1	A2	A3	A4	A5		B1	B2	B3	B4
Material cost	0	+++	+	0	+	0		---	+	+	0
Cutting prevence	0	--	0	0	0	+		0	0	0	0
Squeeze prevence	0	+++	0	0	---	+		0	0	0	0
piercing prevence	0	--	0	0	---	+		-	--	0	0
Total Geometry volumn	0	0	-	+	0	0		--	+	---	++
Total mass	0	++	-	++	+	+		--	++	---	++
Components amounts	0	++	-	0	0	0		--	0	-	0
Assembly/disassemble time	0	++	0	0	0	+		--	0	--	0
manufacture feasibility	0	0	-	0	0	0		0	++	+++	0
fire protect	0	---	0	0	-	0		-	0	0	0
other requirement	0	--	0	0	0	0		0	0	0	0
Sum +	0	12	1	3	1	5		0	6	4	4
Sum 0	0	2	6	9	6	6		4	6	5	9
Sum -	0	9	4	0	7	0		13	2	9	0
Net score	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]

5

9

Figure 8. Part of evaluation 1

At last, all the concepts with negative scores were eliminated. 5 solutions of inner line and 9 solutions of protection pipe were left and then synthesized. Theoretically, there would be 5*9 = 45 combinations. But since there are conflicts between concepts in the synthesis, the final number of combined concepts was 26.

4.3 Concept evaluation 2

In the second evaluation, there were 26 candidate concepts. The Pugh Matrix was applied again in this round. However, there were more criteria involved in order to gain a more comprehensive result. According to the "net score", 9 concept with highest scores were left. Figure 9 is part of the result, and the full evaluation is shown in Appendix 4.

26

	Current Steel +								
	A0B2	A0B4	A0B7	A0B9	A0B10	A0B11	A0B14	A0B15	A1
Selection criteria	meshed metal+coating fireproof paint(prevent piercing)	amti saw lock	fuel absorbing material	vacuum valve	tree burr	anti-knife material	sandwish metal	glass pressure suck back	me e me l
Material cost	+++	+	+	--	++	+	+	+	++
Cutting prevence	0	+	-	-	-	0	+	-	C
Squeeze prevence	0	0	-	-	-	0	+	-	+
piercing prevence	0	-	-	-	-	0	+	-	C
Total Geometry volumn	+	0	0	++	0	+	++	-	+
Total mass	++	+	++	++	+	++	++	++	++
Components amounts	0	0	0	--	0	0	0	0	C
Assembly/disassemble time	0	0	0	0	0	0	0	0	C
manufacture feasibility	++	0	+	-	0	+	0	-	+
fire protect	0	0	++	---	++	0	0	+++	C
Innovative	0	0	+	+	+++	+	++	+++	C
environmental friendly	0	0	+	+	+	0	+	0	+
brand pride(safety)	0	0	0	0	0	0	0	++	C
life cycle	0	0	-	0	-	0	0	-	-
other requirement	0	0	0	-	0	0	0	0	C
Sum +	8	3	8	6	9	6	11	11	1
Sum 0	11	11	5	3	6	10	7	4	8
Sum -	0	1	4	12	4	0	0	6	1
Net score	8	2	4	-6	5	6	11	5	1
Rank							2		2
Continue ?							Yes		Ye

9

Figure 9. Part of the concept evaluation 2 (Find the full table in Appendix 4)

4.4 Concept evaluation 3

In the third round, a new-invented method was applied. The method was inspired by “Bubble Sort” (Sorting-Algorithms, 2015) which is a sorting algorithm. Because of limited information of all concepts, it was difficult to score all the concepts based on the same criteria system. Hence, a one-to-one comparison was invented--- Firstly was to sort all the concepts into two groups X and Y according to the features of concepts. Group X had 7 concepts which share the similarity to use a new protection pipe as solution. The 2 concepts in group Y were both using valves to drain the fuel in fuel line. Second was to choose two concepts which have the same inner pipe from group X, for example, X2 and X3 which both use rubber as inner pipe, and then only compare their protection pipes. The way of scoring was also different from previous methods. There were only “0” or “1”. If the concept is better than the reference/current solution, it got “1”; otherwise it got “0”. The process is shown in Figure 10 below. Finally, there were two concepts left that were X1 --- current inner pipe with sandwich metal protection tube, and Y1 --- using valve with air pressure to drain fuel pipes. [Appendix 5]

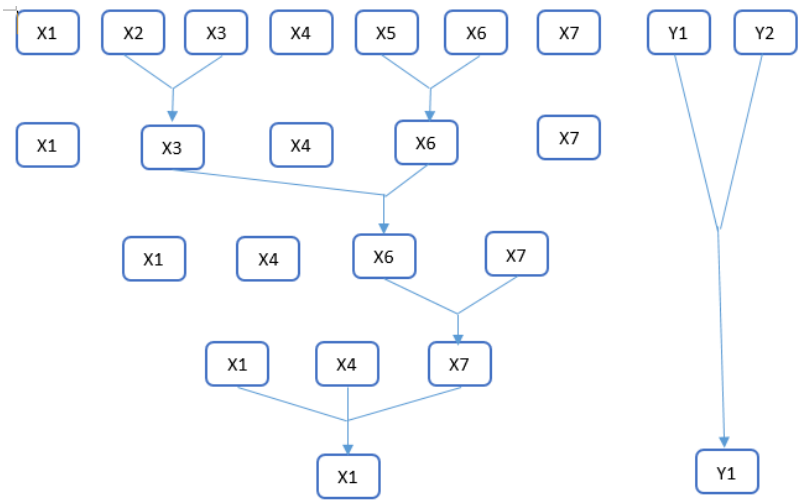


Figure 10. Process of Evaluation 3

1+1

4.5 Final Concept

Finally, two concepts X1 and Y1 were selected. Concept X1 is the current inner pipe with a sandwich metal protection tube which obtained the maximum score in the final evaluation. Therefore, concept X1 is the final solution. On the other hand, Concept Y1 is kept as well. The main reason for this solution not as the final concept was the expensive cost of valves. However, this solution is suggested as a substitute one because it has a huge advantage which overshadows its disadvantages. It can promise zero fuel leakage. Therefore, this concept was considered to be a good potential solution if its problems are solved in the future. In this report, its feasibility will be proved and basic design will be conducted later.

5.Detail Design

5.1 Selection of sandwich material

Sandwich material is a popular material first used in aeronautics and astronautics. Now it has been used in automotive industry because its high strength, high modulus and good performance. The basic structure of the sandwich material is two layers of sheet metal covering a lightweight structure. The skin layers provide high bending and stretching strength, and the core layer is designed to prevent shearing load in the horizontal direction and reinforce the skin layers.

In this report, several varieties of inner structure of sandwich material were studied. They are divided into three categories – fiber, patterns and foam.

5.1.1 Types of sandwich panel

In the world of sandwich materials, both core layers and side layers could use very different material and make very various combinations. In order to join the side layer and core layer, different methods are also applied. For examples, using glue to join the different layers, or using hot treatment to melt the metal layers and join them together. Different join methods are utilized depending on the physical properties of raw materials and their applications. However, sandwich panels differ mostly owing to its structure of the core layer. There are three types of structures: foam, patterns, and fibers.

As shown in Figure 11.a, it is a foamed aluminum panel which is very commonly used in construction industry. It is easy to be manufactured, and the price is relatively low. The core material is light foam structure which can stand the same or even higher force than normal aluminum panel with the same thickness. In Figure 11.b, it is honeycomb sandwich panel. Honeycomb is one of the most stable structures and widely used as reinforce in materials science. Figure 11.c shows a type of fiber sandwich panel from a Swedish company called "Lamera" (Lamera, 2013) who uses metal as skin layers and polymer fiber as inside structure to manufacture this panel. Additionally, the core fiber is not limited to polymer, it can be many different types of fibers.

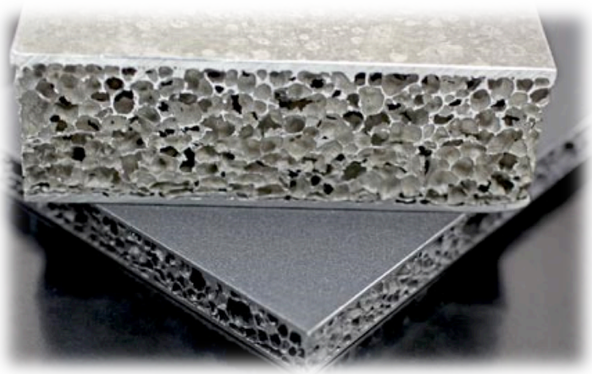


Figure 11.a. Foamed aluminum panel (Raumprobe, 2015)

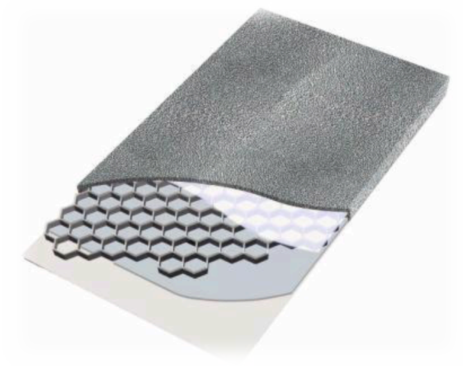


Figure 11.b. Patterns (Honeycomb) sandwich panel (DEC, 2015)

Figure 11.c. Fiber core sandwich panel (Lamera, 2013)

In the current market, most of the sandwich metal products are panels and most of the core materials are pattern stuctures. Figure 12 shows several common pattern structures developed by Zhou, J., Deng, Z., Liu, T., Hou, X (2009). Different types of structures can produce different mechanical properties of sandwich materials.

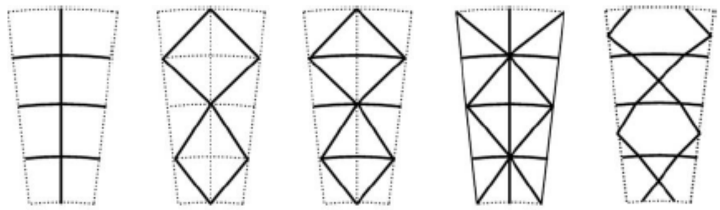


Figure 12. The possible tube patterns in a sandwich tube (Zhou, J., Deng, Z., Liu, T., Hou, X., 2009)

5.1.2 Selection of fiber

Sandwich material has to be able to endure a certain amount of bending forces, thus both the core material and skin material are not intended to have deformation if these forces apply. Under this circumstance, using structure material as core material has a weakness since these structures produce inevitable deformation under forces. Therefore, one has to look for other options core material.

Besides structures, there are several widely used core material, such as polymer foams, balsa wood and tailored fibers. Considering that core materials are demanded to be strong enough against crash, tailored fibers are the optimal choice among all candidate materials.

Tailored fibers also have a variety of types. Three of them are the most common and technologically mature: metallic fiber, carbon fiber and glass fiber.

Metallic fiber
Metallic fiber is the manufactured fibers composed of metal. Compared to organic fiber or other inorganic fibers, metallic fiber has higher abrasion resistance, better ventilation and thermal conductivity. Moreover, its excellent self-lubricating and sintering properties make it used in a wide range of applications. For instance, it has been applied in automotive industry as the friction materials of clutch and brakes. These are mainly metal staple fibers with 20-300 microns in diameter and 2-30mm in length.

Carbon fiber
Carbon fiber, alternatively graphite fiber, is a material consisting of fibers with mostly carbon atoms. The properties of carbon fibers, such as high tensile strength, high stiffness, low weight and high thermal tolerance, make them already very popular in engineering industry. However, due to their manufacture cost, they are more expensive than other inorganic fibers, like glass fibers and metallic fibers.

Glass fiber
Glass fiber is a material composed of numerous tremendously fine fibers of glass. Glass fiber has roughly comparable mechanical properties to carbon fiber. Even though not as rigid or strong as carbon fiber, they are significantly cheaper than carbon fiber. Their heat resistance ability is also favorable. Their biggest drawback is that they are brittle, but they are much less brittle when used in a composite since they can undergo more elongation before they break.

In order to protect the inner pipe from crash, core fiber of sandwich material is required to sustain both static and dynamic forces. The expense of material is also the priority to be taken into consideration. After comparing the properties and cost of the above fiber materials, metallic fiber is selected as the core fiber of sandwich material for protection pipe. Its tensile strength, compressive strength and toughness are adequate against crash impact. Excellent temperature tolerance can make them stand high heat produced during crash. The low density of it helps to reduce weight. Furthermore, its low cost is also a big advantage.

5.2 Product architecture

In the final product, as shown in Figure 13, the inner pipe of a steel pipe which is the same as the current solution. All the joints and fasten clips also remain the same because current routing is working very well and no better routing solution can be developed so far. Meanwhile, using the same clips does not increase the product cost. The improvement of new product is to use the FibreCore™ as protection pipe material. FibreCore™ is a cost effective, lightweight, and crash resistant material which is made by an UK company called Fibre Technology Ltd. They work very closely with Cambriage University (Fibretech, 2014) [http://www.fibretech.com/aboutus.html]

The main advantages of FibreCore™ is high stiffness for low areal density, it is 40% better than titanium and two times better than aluminum; light weight, it has half the density of steel; the thickness has large variance that could change from 1.5mm to 10mm; very good energy absorption ability; no glues used in bonding the material; welding available and recyclable. (Fibretech, 2014)

Figure 13 is a CAD model of fuel lines with protection pipes made from FibreCore™. Figure 14 shows the parameter contradistinctions between FibreCore™ pipe and current stainless steel pipe. The thickness of FibreCore™ pipe is 2mm while the stainless steel pipe is 1.5 mm. They are both 300 mm long. The density of FibreCore™ is almost half of stainless steel. Thus, the mass of a FibreCore™ pipe is slightly less than that of a stainless steel pipe.

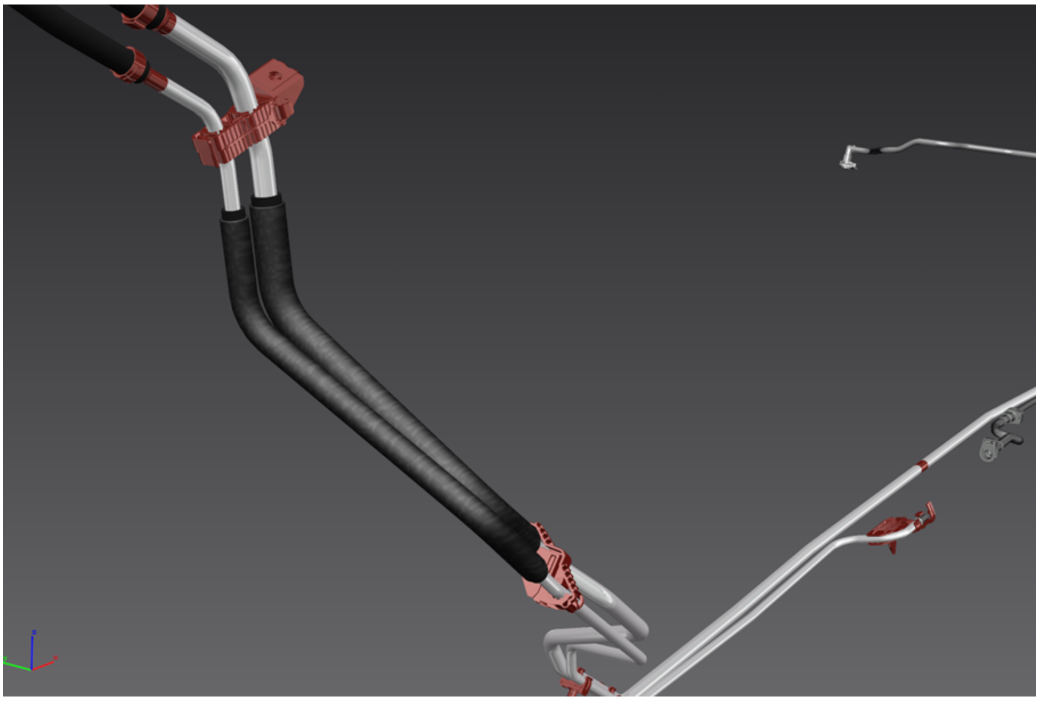


Figure 13. Demonstration of final product

	FibreCore™	Stainless Steel
Mass(kg)	0.19	0.20
Density(kg/m^3)	3616	7860
Thickness(mm)	2.0	1.5
Length(mm)	300	300

Figure 14. Contradistinction of one protection pipe

Figure 15. Core structure of FibreCore™

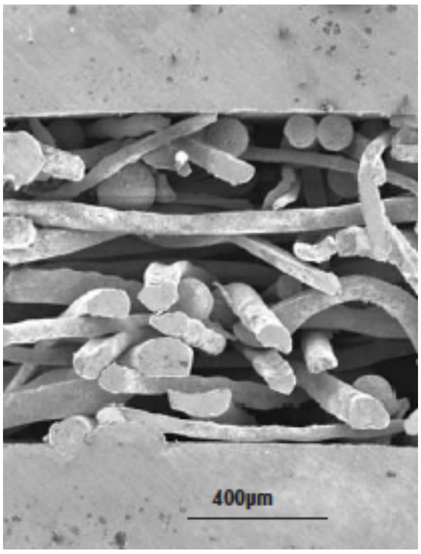


Figure 16. Micro image of cross section of FibreCore™

As shown in Figure 15 and Figure 16, FibreCore™ has three layers. The skin material is 304 stainless steel and thickness is 0.4mm, its core material is melt-spun 304 stainless steel fiber and thickness is 1.2mm. (Stainless Steel Sandwich, 2007) [Appendix 6]

The manufacturing of FibreCore™ have two stages, the first stage is preparation, which is evenly depositing the core layer onto a skin layer, and then place another skin layer onto the core layer. The second stage is assembly in 1150-1250 C° environment for 30 – 90 min, the layers was diffusion bonded in high temperature. The manufacturing size of FibreCore™ is up to 500*1500 mm. (Stainless Steel Sandwich, 2007)

5.3 Calculation and Simulation

5.3.1 Blunt projectile impact calculation

The blunt projectile test is a common method to investigate the impact properties of metal panel materials. Normally researchers use impulse experiments and theoretical calculation together to inspect the material impact properties. In this case, since there is not enough time and budget to get test panel materials, only theoretical calculation is conducted.

The model of calculation is to assume that the test panel is fixed, there is a projectile that starts to fly to the test panel with initial speed v_i until the test plate breaks totally, and the projectile's out speed is v_r.

The thickness of the test panel is h, the density of the test material is ρ. There is a projectile (cylinder) with the radius r_p and mass m_0, that flies to the fixed panel with initial speed v_i.

The energy loss includes two parts: the energy consumed in stretching the test panel and energy consumed in shearing the test panel, the mass of area where it was sheared is m_p. Moreover, the radius of the deformation area is r_1.

According to *conservation of energy*:

$$\frac{1}{2}m_0{v_i}^2 = E + E_f + \frac{1}{2}(m_0 + m_p){v_r}^2$$

E is the energy consumed for stretching the test panel, and E_f is the energy consumed for shearing the test panel.

So the consumed energy for stretching the panel,

$$E = \sigma_f \Delta S h$$

Where σ_f is dynamic yield strength.

According to Zhang(2014), one estimated

$$\Delta S = 0{,}498\pi r_p^2$$

The consumed energy for shearing the panel,

$$E_f = \tau_f 2\pi r_p h^2$$

Which τ_f is dynamic shearing strength.
Therefore the energy consumed for penetrating the panel is:

$$E_p = E + E_f$$

After all, the out speed v_r can be calculated.

According to Tresca Criterion(2015),

$$\tau_f = \frac{\sigma_f}{\sqrt{3}}$$

Dynamic strength is normally 30% higher than static strength. σ_f is the dynamic yield strength.

For calculating stainless steel panel's energy absorbing ability, one input all the data into the matlab script [Appendix 7] and get the results:

v_i is 200m/s, r_p is 4.75mm, m_0 is 0.035kg, h is 1.5mm, and ρ of steel is 7860kg/m^3, static yield strength is 215 Mpa, therefore σ_f is 280 Mpa, and τ_f is 161 Mpa.

In the result, the energy absorbing of the 1.5mm thickness stainless steel panel is 25.6 J, the projectile velocity difference between initial speed and end speed is 56.4m/s.

Comparing with this FibreCore™ sandwich material, it has good energy absorption characteristics, and the panel can withstand a 70 J impact from a 35g projectile with 200m/s speed (showing in Figure X), this means that FibreCore™ have 70 J energy absorbing ability which is better than stainless steel.

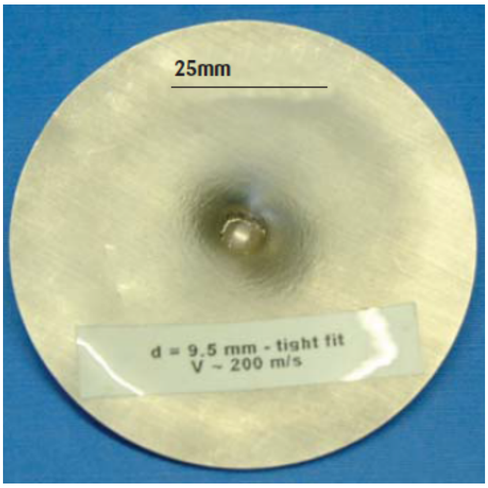


Figure 17. Response of sheet to a 70 joules (a projectile with 35g mass and 200m/s initial speed) impact (Stainless Steel Sandwich, 2007)

5.3.2 Simulation

The above calculation aims to address the excellent property of the FibreCore^{TM} panel. In order to have a more scientific analysis of the tube behavior when impact occurs, one proceeded with Finite Element Simulation in ANSYS, ANSYS is an engineering simulation software which allows engineers to test the situation by simulating in a virtual environment. In this section, two comparison simulation have been done: testing group and the reference group --- testing group is the simulation of the FibreCore^{TM} tube crashed by a stainless block, and reference group is the simulation of the stainless steel tube crashed by the same stainless block.

Modelling

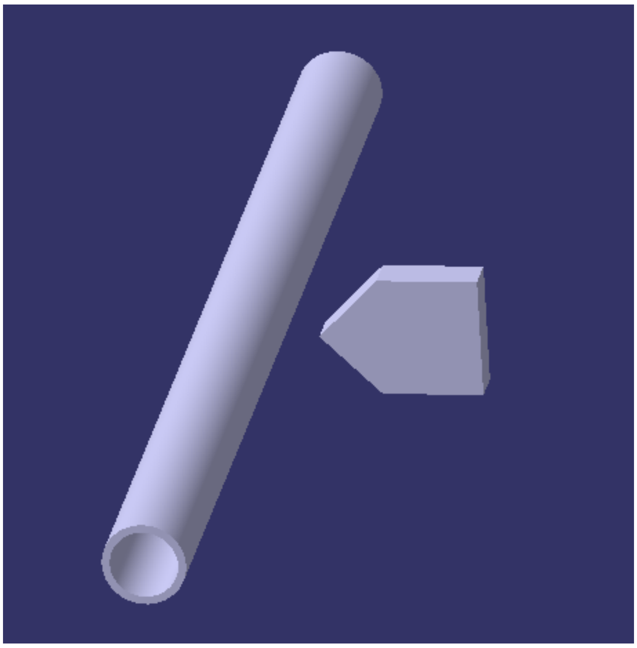


Figure 18. Modeling

The simulation is based on this situation: there is a stainless steel projectile with a sharp edge head and flying with an initial speed of 200m/s because the projectile test's initial speed is 200m/s, choosing the same speed in the simulation is good for comparison.

The projectiles for both simulations are the same, which is a stainless steel block with sharp edge in the front. The mass of the projectile is 0.07kg. The tube is modeled as a straight tube with the same length as the one before bending. There were several differences of parameters between two simulations shown in Table 3, which are mass, density and thickness. The other parameters are the same. Both tube have the same inner radius to fit the assembly size. The end surfaces of the tube were fixed.

		Stainless Steel Tube	FibreCore^{TM} Tube
Projectile	Mass [kg]	0.07	0.07
	Material	Stainless Steel	Stainless Steel
	Initial velocity [m/s]	200	200
Tube	Mass [kg]	0.2	0.19
	Material	Stainless Steel	304 Steel & FibreCore^{TM}
	Density[kg/m^3]	7860	3616
	Length [mm]	300	300

	Thickness [mm]	1.5	2.0
	Inner Radius	17	17

Table 3. Modeling parameters of two simulations

Material

In these two simulations, there are three different material properties that have been applied. In the stainless steel tube simulation, both the projectile and tube are stainless steel. In the FibreCore™ tube simulation, the projectile has the same settings as in the stainless steel tube simulation. The tube material was 304 stainless steel for skin layers and 304 stainless steel fibers for core layer.

Results

Stainless steel tube

The result of the stainless steel tube, as shown in Figure 19, the impact point in the center of tube has manifest deformation, and the strain in the center area was around 0.31-0.37, which does not reach dangerous strain yet. The maximum strain area was close to the fixed tube end that reached the maximum plastic strain. The maximum equivalent plastic strain was 0.48, and the maximum deformation was 69.6 mm.

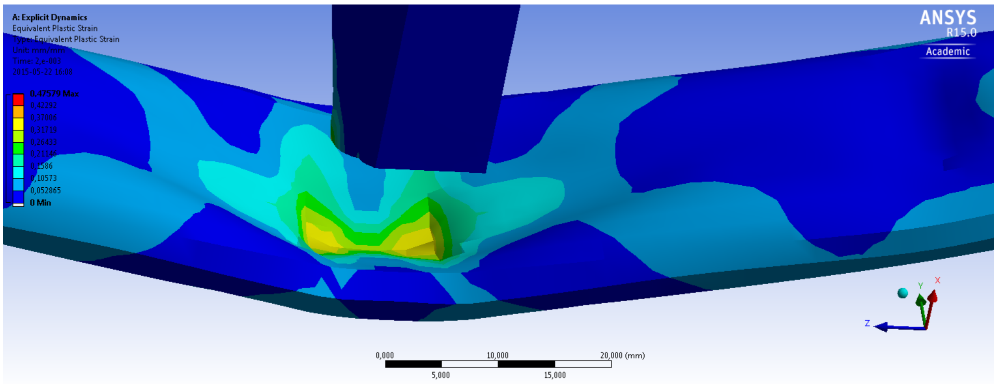


Figure 19. Simulation result of the stainless steel tube

FibreCore™

In the result of FibreCore™, because the core structure is too complicated to model and simulate, the tube was simplified to 3 solid layers. The core layer's properties are sourced from the study of Markaki & Clyne (2005). One of the property data – the tensile testing data of a typical fiber array (446 heat-treated fiber) is shown in figure 20.

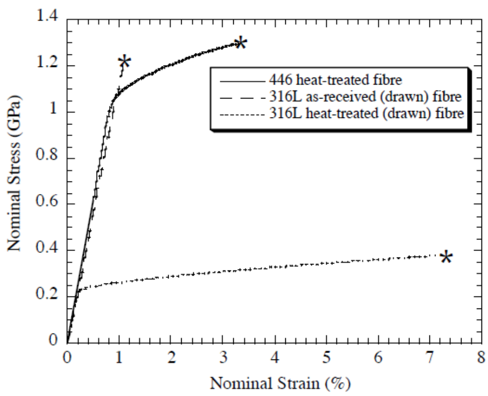


Figure 20. Typical single fiber tensile testing data (Markaki A.E., Clyne T.W. 2005)

In the simulation, the nominal stress of fiber was also signed from the data of the research of Markaki & Clyne (2005), the demonstration of the impact area of FibreCore™ tube is showing in Figure 21.

Table 4 is the comparison of max strain and deformation between stainless steel tube and FibreCore™ tube. The stainless steel tube and FibreCore™ tube have almost the same maximum strain, but FibreCore™ tube has much less deformation than stainless steel when the same crash occurs.

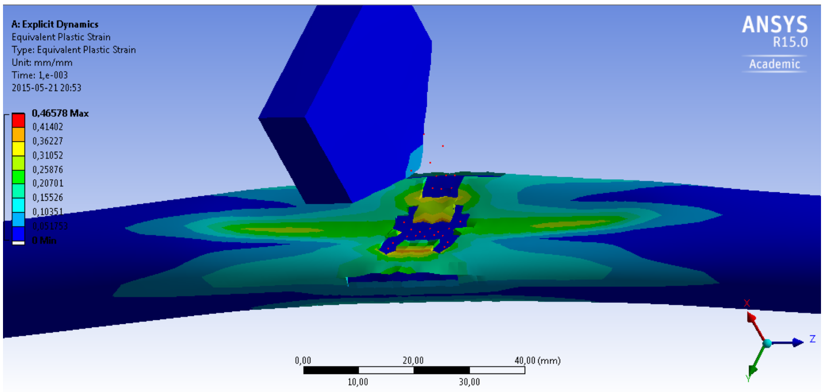


Figure 21. Demo at the impact center of FibreCore™ tube

	Max Strain	Max deformation [mm]
Stainless steel tube	0.48	69.6
FibreCore™ tube	0.46	43.6

Table 4. Comparison of max stain and deformation between stainless steel tube and FibreCore™ tube

6. Cost Estimation

The product in this report will be launched in approximately ten years on a global market. A good product design with lower cost is the most common way to increase its business competitiveness and the one of the main purposes of this project. To fulfill this requirement, cost estimation of new project has to be done. In this project, a new material is suggested. Since there is no supplier to provide information of ready –made FibreCore™ tube, cost will be estimated based on research and calculation.

6.1 Reference product cost

In the current solution, the manufacturing cost of the entire fuel delivery lines is 52€ including feed and return pipes and both their protection pipes, as well as rubber hoses and several fastens (shown in Figure 22).

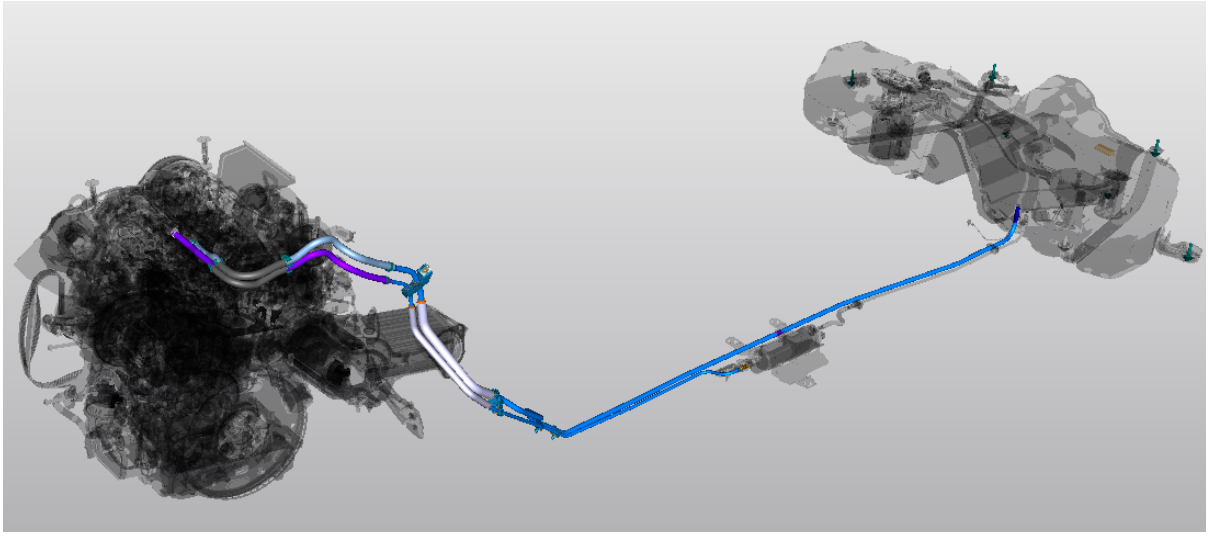


Figure 22. Fuel delivery lines

The cost of manufacturing one protection pipe (shown in Figure 23) is around 3 €/unit. It is a stainless steel tube, whose full length is approximately 300mm, mass is up to 0.2 kg (Here density of stainless steel is 7860kg/m^3).

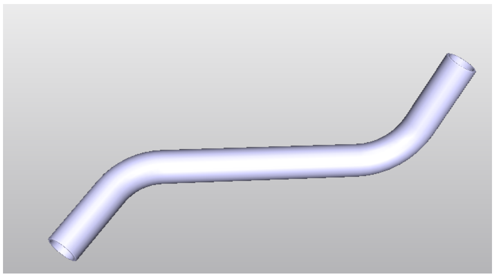


Figure 23. Protection pipe

6.2 Cost estimation of final concept

In general, the total cost of a product usually contains material cost, labor cost and other miscellaneous cost. In this case, the material cost is the price of FibreCore™. Labor cost refers to the manufacture expense to weld the FibreCore™ sheets into tubes. Besides, there are additional fees like management, transportation and maintenance costs etc.

Because the new solution changes nothing other than the material of the protection pipe, only the cost of manufacturing one straight protection pipe is estimated to make a clearer comparison between new and current solutions.

6.2.1 Material cost

The sandwich panel currently provided from the supplier is in dimensions of 200 x 250 x 2mm and costs £ 98.24 (€ 135.16) for each. The supplier can produce the sandwich sheets in any sizes by request. The tube for the feed line has an inner diameter of 13mm, and the tube for the return line has an inner diameter of 17mm. In order to simplify the cost calculation, one takes 15mm as an average diameter for estimation. The length of both tubes is 300mm. The sandwich sheet needed for producing one tubes is approximately 47.1 x 300 x 2mm. Accordingly, the price of each sheet is:

47.1 * 300 *135.16 / (200 * 250) = € 38.20

The unit price looks quite expensive because the sandwich material is still in a prototype stage. If it goes from lab product to mass production, the material cost would be significantly reduced. Additionally, the construction process occurs in two stages that both have no requirements on very fine and expensive machines. From communication with the supplier, one learnt that a study of production process design has been undertaken in anticipation of a notable cost decrease. Meanwhile, the supplier also agrees that there is plenty of room for price reduction if bulk quantity is purchased.

For a further estimation, the concept of "experience learning curve effect" is applied to obtain the cost of the sandwich material as a product in the market. In economy and management, the model of experience learning curve demonstrates the relationship between efficiency and experience. The concept was first introduced to the aircraft industry for gaining cost estimates based on repetitive production of airplane assemblies.

Experience learning curve model is based the premise that individuals and organizations acquire knowledge by doing repetitive work. By gaining experience from repetition, organizations and individuals develop relative improvements in behavior or learning. In manufacturing, as more products are produced by a manufacturer, the per-unit cost often decreases at a decreasing rate.

The direct labor hour model of the learning curve is:

$$Y = KX^{n}$$

where Y = the number of direct labor hours required to produce the X th unit,
K = the number of direct labor hours required to produce the first unit,
X = the cumulative unit number,
n = log ϕ/log 2,
ϕ = the learning percent, and 1 - ϕ = the progress ratio. (Reference for Business, 2015)

As indicated in the model above, there are three concerning parameters in the calculation of "experience learning curve": first unit effort, number of units and learning percent. Unit effort can be considered as unit time and be extended to cost. Although FibreCore™ sheets have been produced in lab for a while, they are limited for research projects. Therefore, the first unit cost of one FibreCore™ sheet as a product equals to the cost of making one FibreCore™ sheet prototype in lab. Thus, the first unit effort in this case is € 38.20. The number of units would be 1,600,000 since the sale target of Volvo cars is 800,000 and each car needs two protection tubes. The learning percent is determined by analysis of cost data for similar products. The construction of the sandwich material is mostly done by machining instead of hand assembly, the learning percent 90% is more appropriate under this circumstance. 90% means that the rate of effort improvement is 10% (100-90=10) each time the production quantity is doubled.

Therefore, in this calculation, the three parameter inputs are 38.20, 1600000 and 90 and they are conducted by the Wright method. The result of Nth unit effort is 3.69 which can also expressed as that the unit price of one tube is €3.69 (Cost Models, 2015) [Appendix 8].

6.2.2 Manufacturing process and cost

The current protection pipes of fuel lines are seamless steel pipes. The other type of steel pipe is welded steel pipe. The technology and process of manufacturing seamless and welded steel pipes are very different. The manufacture method of producing the current seamless steel pipes is extrusion. This technology is employed to produce tubes of small diameters. The extrusion process requires the staring material to be simplex and evenly distributed. Since the sandwich material has three layers, there is no possibility to extrude them from raw material. Hence, the producing process of welded steel pipes is better to be applied to manufacture sandwich panels to tubes (Brensing and Sommer, 2015).

Welding Operation

The welding operation consists of forging individual metal panels over a mandrel to produce an open-seam tube, and heating the mating edges of the open seam and welding them (Brensing and Sommer, 2015). There is a variety of welding methods for constructing metal tubes: pressure welding, electric resistance welding, electric arc welding, gas arc welding and laser beam welding, etc. Based on the requirement of outer diameter and thickness of two fuel pipes, electric arc welding is excluded. The other methods can all accomplish the work of small tube welding with efficiency.

In the welding process, there is one issue needed to be concerned – heat affected zone. This issue on the material surrounding the weld can be detrimental. The material in heat-affected zone loses its strength and even becomes fragile. That is definitely a problem which has to be avoided. With this issue in consideration, laser beam welding is the best option among all the welding methods. It gives a highly concentrated and limited amount of power, which results in a narrower heat-affected zone. In addition, laser welds has more benefits compared to other welds. It provides a full finished tube appearance without any gaps because it is cold worked and annealed to create a tube with a straighter weld and finer grain structure. The narrow weld bead produced by a laser beam has greater strength and ductility, thus outperforming the other welds.

Figure 24. Production line for laser welded stainless steel tubes. (Industrial Laser Solutions, 2013)

A laser-welding production line consists of a set of forming rolls that takes steel from a coil and rolls it into a desired profile. In the middle, a welding system is located for the profile being aligned, welded, pre-heated and annealed precisely. Figure 24 demonstrates a production line for laser welded stainless steel tubes. The input of the steel plate into the forming rolls is shown in the middle, laser source is on the left. With this laser system, production speed can easily reach 10m/min, which is much more efficient than other conventional welding. Sometimes, with improvement on laser power and investment budget, the speed can be over 20m/min. In the welding process, laser beam produces a narrow weld seam with quick energy transfer from beam onto the material. The power input is very low, consuming 15J/cm roughly. Currently, there are more than one type of laser welding, CO_2 laser and fiber or diode laser. There is a substantial cost difference between the former one and the latter two mostly because the latter two do not require "laser gas". Furthermore, the fiber and diode laser beams are more efficiently absorbed by metals. Consequently, lower laser power is demanded for reaching the same productivity with lower service costs.

The running cost of fiber or diode laser beam welding is $0.3/m. For one tube with length of 300mm, the cost is $0.09(€ 0.08). The number covers the costs of energy, but does not include the charges of amortizations, labor and service (Industrial Laser Solutions, 2013).

The labor cost is also a large part in manufacturing cost and has to include all the aspects that involve human work. According to the information from Advanced Laser Applications Workshop (2013), the labor cost in laser welding industry can be tracked by operator burdened wage, handler burdened wage, supervisor burdened wage, maintenance burdened wage, tool maker burdened wage and engineering support staff burdened wage. The labor cost based on given data of all the wages above is :

$$20.75+17.70+38.00+28.00+34.00+60.00 = 198.45\$/hr = 3.31\$/min$$

As mentioned before, the speed of laser welding can be more than 20m/min, thus for producing one 300mm pipe, the labor cost is

$$(3.31/20) * 0.3 = \$0.05 = €0.04$$

Besides energy and labor cost, the fee of equipment purchasing and production line building should be included in manufacturing cost. Setting up a completely new manufacturing line is time-consuming with high investment. One suggestion is to modify the conventional welding system into a laser system, which has been proven feasible. In this way, the early investment on manufacture could be very limited. The advantages of laser welding, like low running costs and outstanding producing quality can be more available in the welding industry.

In addition, there are some other costs involved in manufacture, such as amortizations, service etc. According to statistics, these fees are extremely small compared to energy and labor costs. They are not considered when calculating the manufacturing cost. Thus, the manufacturing cost of producing one FibreCore^{TM} protection pipe is 0.08+0.04 = € 0.12.

6.2.3 Cost estimation summary

In summary, the cost is estimated based on producing one straight protection pipe before it is bended with inner pipe. The total cost of the final concept is 3.69 + 0.12 = €3.81.

Compared to the current solution, the cost of the protection pipe is increased 27%.

7. Substitute concept

7.1 Concept architecture

The substitute concept is based on the valve system and fluid pressure difference to prevent fuel leakage. Valves are able to regulate, direct and control fluid flow by opening, closing or partially obstructing various passageways. In an open valve, fluid flows in a direction from higher pressure to lower pressure (CosmoLearning, 2015)

Fuel delivery systems are complex structures consisting of various elements, each of which plays a specific role in controlling the movements of fuel and decreasing the fire hazards. In this concept, the following elements work together to optimize the performance of crash protection.

- Two valves (valve A, valve B) are placed at the engine side of the two pipes to cut off fuel flows through the pipes to the engine.
- The other valves (valve C, valve D) are installed near the tank side to stop fuel movements through the pipes to the tank.
- Two high-pressure gas capsules are installed at the engine side connected to the two pipes.
- A crash detection sensor is demanded to activate the whole valve system when a car crash is happening.

The two high-pressure gas capsules are the key elements in this concept. Gas capsules are popularly used in air guns as one of the powering methods. In most of the cases, these capsules are pre-filled with pressurized carbon dioxide or nitrogen. Using a gas capsule instead of an industrial gas cylinder is because of their size, weight and expense. Usually, one gas capsule has a height of 100mm, a diameter of 20mm and a weight of around 25 grams with full-filled CO_2 gas. The price of one capsule is approximately €0.2 if massive purchase is made.

The state of CO_2 in the capsule is a pressurized gas above a liquid. CO_2 pressure is determined by temperature, not by mechanical compression. If CO_2 were compressed by mechanical means, it would turn into liquid when it reaches the right pressure. If the gas is released, the remaining liquid in the capsule flashes to gas until the pressure is equalized under that temperature. Therefore, CO_2 guns do not lose velocity as they were shot until all the liquid is gone and they start to run out of gas (Pyramyd Air, 2003).

Valve A and B are designed as normal solenoid valves to switch on and off fluids. A solenoid valve is an electromechanically operated valve, which is the most popularly used control elements in fluidics. In this case, solenoid valves are chosen mostly due to their extremely quick operation controlled by electric current. In addition, their high reliability, long service life and low control power are very advantageous as well. Valve C and D are designed to be check valves also controlled by electric current. It normally allows fluid to flow through it in only one direction and thus it can also be called one-way valve. Generally, check valves are very simple, small and cheap.

All the four valves are open in normal instances. Once a crash happens and the detecting sensor emits a signal, valve A and B will be closed to shut off fuel flow between engine and pipes. At the same time, valve C and D will be closed which only allow fuel fluid to move from pipes to the tank side. Then outlet of gas capsules will be opened to let the high-pressure gas enter into two pipes to blow the fuel back to the fuel tank.

7.2 Concept analysis

Usually, a car crash happens in 0.1s. This part is to analyze the feasibility of the substitute concept. One needs to prove that gas capsules can blow fuel back to the other side of the one-way valves in less than 0.1s.

To calculate the time needed to blow fuel back, both the feed pipe and return pipe have to be taken as the calculate target since their different diameters and opposite flow directions. Because of the complicated flowing condition in pipes, the following calculation will be conducted under an ideal circumstance. One assumes:

1) The pipes are full of flowing fuel. In another word, the flow is considered as pipe flow instead of open channel flow. In this circumstance, the effect of atmospheric pressure is ignored.

2) The pipes are deemed as a straight pipe at the same horizontal level. The influence of their actual curved routings does not make a big difference to the result due to the extremely rapid flow rate.

3) The viscosity of diesel and friction between tube and diesel are not taken in account.

The calculation is based on the theory of momentum conservation principle. When crash happens, valve A, B, C and D are all closed which makes the gas capsules and fuel flows an isolated system. Thus, the amount of momentum the gas capsule lost is equal to the momentum gained by fuel flows.

$$M_{gas} = M_{fuel}$$

It is difficult to obtain the momentum one gas capsule can produce since there is no data of the initial speed of gas released from the capsule. However, the capsules are mostly used in air pistols, the momentum of gas can be detected from the kinetic movement of bullets.

$$M_{bullet} = M_{gas}$$

Thus, there is

$$M_{bullet} = M_{fuel}$$

The .177(4.5mm) caliber air pistol is chosen as the example because it is one of the most commonly used caliber in CO_2 powered air pistols. One gas capsule can support at least 18 full shots before starting to lose velocity and each bullet can reach 400 fps (feet per second) of initial velocity. The average mass of one bullet for .177 caliber is 5.5g.

The kinetic data of one bullet

Velocity change of bullet:

$$\Delta v_b = v_b - 0 = 400fps = 122m/s$$

Mass of bullet:

$$m_b = 5.5g = 5.5*10^{-3}kg$$

The maximum flow rate in a diesel engine can reach 200 l/h, and average density of diesel is 0.84ton/m^3. The pipe length from valve A to C (B to D) is 1560mm.

Density of fuel:

$$\rho_f = 0.84\ ton/m^3 = 0.84*10^3 kg/m^3$$

Length of pipe from A to C:

$$l = 1560mm = 1.56m$$

To calculate the volume rate fuel flow more conveniently, one defines that the flow direction from A to C (B to D) is the positive direction.

(1) For a feed pipe (inner diameter of inner pipe =7mm)

Volume rate of fuel flow:

$$V_f = -200\ l/h = -0.056*10^{-3} m^3/s$$

Cross-sectional area of feed pipe:

$$A_f = \pi r^2 = 38.5*10^{-6}\ m^2$$

The mass of fuel in pipe from A to C:

$$m_f = \rho_f * l * A_f$$

Based on that the momentum of bullet equals to the momentum of fuel flow, there is

$$m_b * \Delta v_b * 18 = (v_f' - V_f/A_f) * m_f$$

The end velocity of the fuel flow is

$$v_f' = 237.9\ m/s$$

The time to drain the fuel in pipe A to C

$$t = l/\bar{v} = 2l/(v_f' + V_f/A_f) = 0.013s$$

(2) For a return pipe (inner diameter of inner pipe = 11mm)

Volume rate of fuel flow:

$$V_f = 200\ l/h = 0.056*10^{-3} m^3/s$$

Cross-sectional area of feed pipe:

$$A_f = \pi r^2 = 95.0*10^{-6}\ m^2$$

The mass of fuel in pipe from B to D:

$$m_f = \rho_f * l * A_f$$

Based on that the momentum of bullet equals to the momentum of fuel flow, there is

$$m_b * \Delta v_b * 18 = (v_f' - V_f/A_f) * m_f$$

The end velocity of fuel flow is

$$v_f' = 97.6 m/s$$

The time to drain fuel in pipe from B to D

$$t = l/\bar{v} = 2l/(v_f' + V_f/A_f) = 0.032s$$

In conclusion, to both feed pipe and return pipe, the high-pressure gas from capsules are capable to blow the fuel inside pipes to the other side of the check valves(C, D) in less than 0.1s. There will be no fuel leakage if the crash happens and pipes break. Therefore, the substitute concept is feasible.

7.3 CAD model

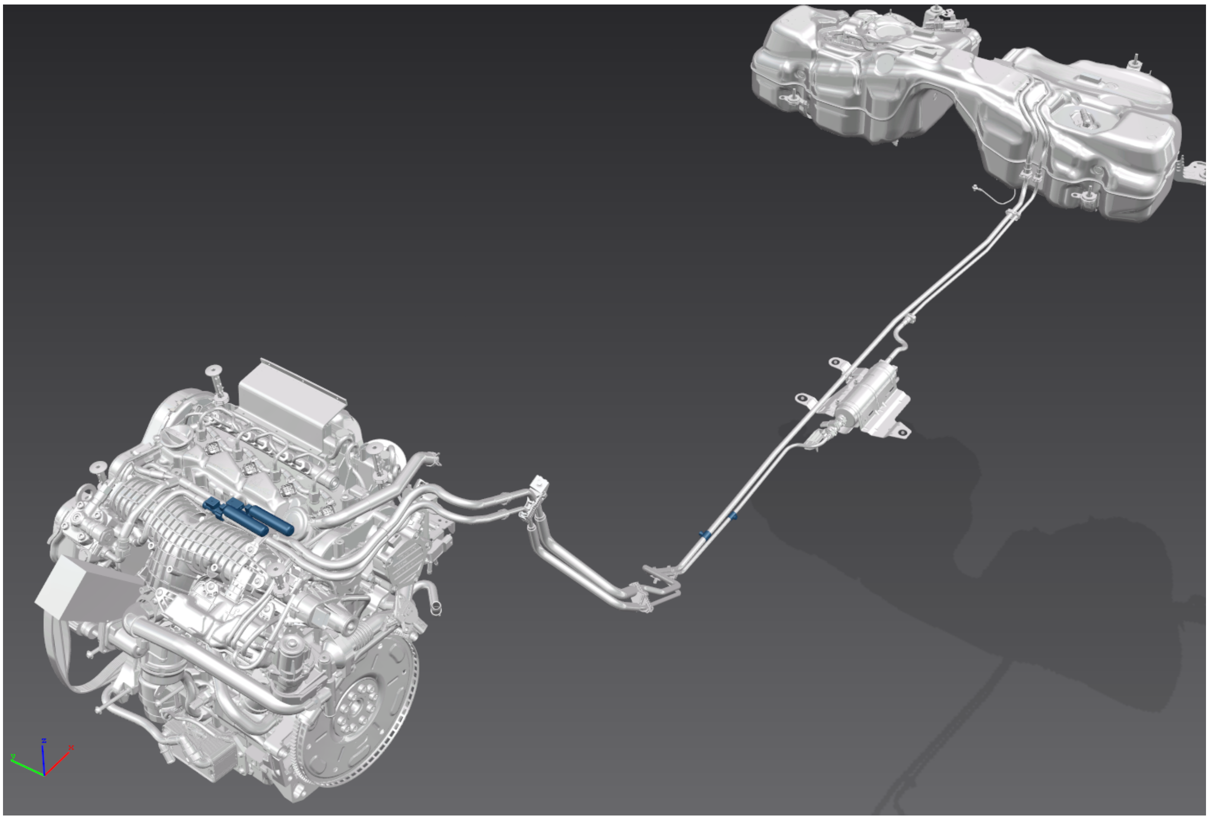


Figure 25. An overview of the substitute concept

Figure 25 illustrates an overview of the substitute concept. This figure shows the rough locations of each element in order to give a vision about the work principle of substitute concept. The dark blue parts are the valves and gas capsules.

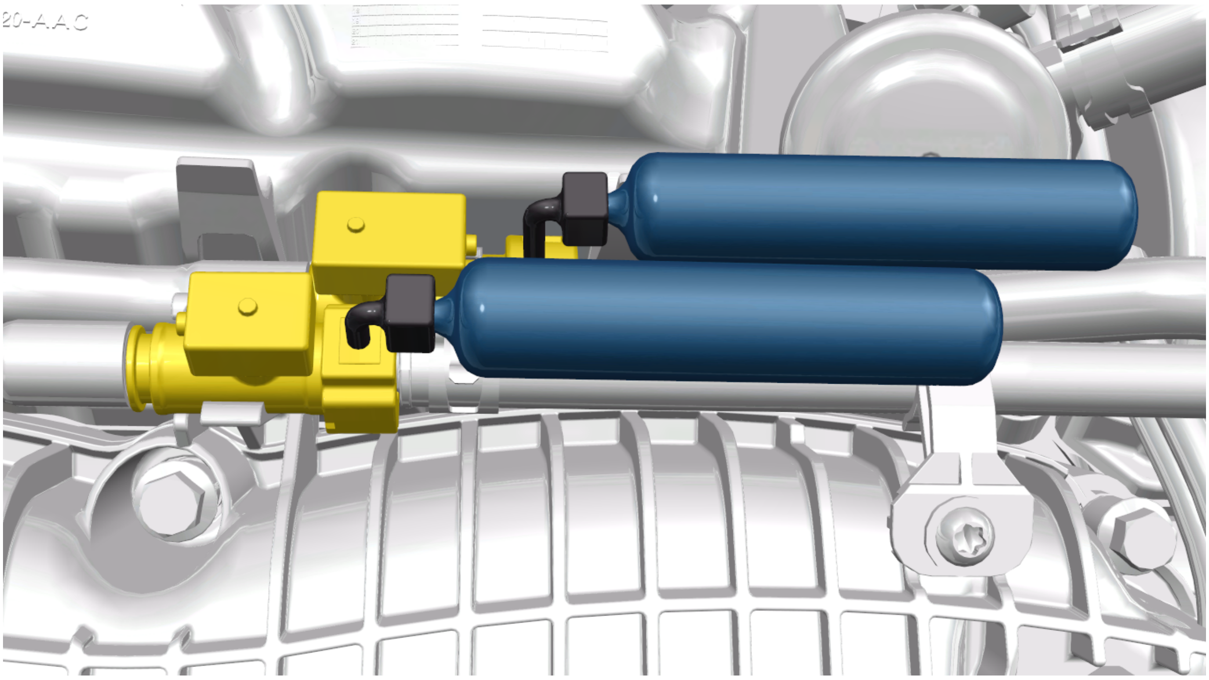


Figure 26. Solenoid valves A,B and two gas capsules

Figure 26 shows the zoom- in picture of solenoid valves A,B and two gas capsules. It does not show the real connecting method but only their relative locations on the engine.

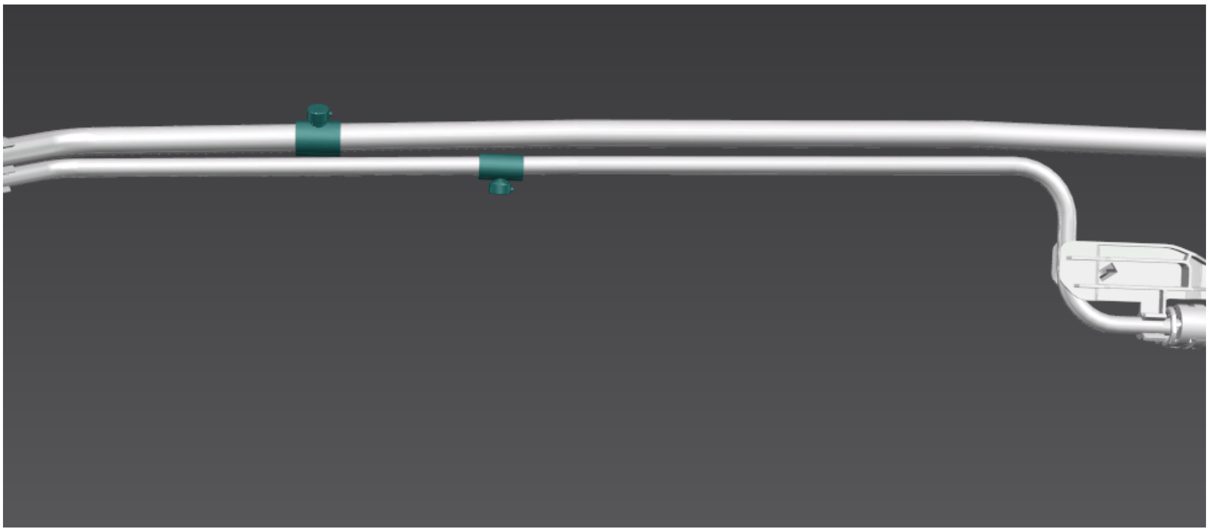


Figure 27 Solenoid check valves

Figure 27 demonstrates the two solenoid check valves installed in feed and return pipes.

8. Discussion

8.1 Discussion of the Concept Generation

Concept generation is the most iterative part of the entire development process. In this project, a function tree is outlined as the base of generating ideas. It breaks a complex function of target object into simpler sub functions and new concepts are then identified based on the sub-functions.

Technically, function tree analysis is not a part of concept generation. Function decomposition is a method used to analyze the main function of a system for several purposes. One of the most common purposes is to support design and synthesize a system under development (Almefelt, 2013).

In this project, function tree is necessary in concept generation because it seems too abrupt to start idea generation just according to requirement specifications. The application of function analysis can make these two parts connected more smoothly and allow idea generation to be more structured and comprehended.

Even though one agrees that function decomposition is the most reasonable way to start concept generation, the establishment of function tree still turns out to be the most controversial part. In the first version of function tree, the initial step – defining the system's main function – was challenging to be carried out precisely. When it comes to the fuel delivery system, it is natural to define its major function as "deliver fuel". Hereafter, the decomposed functions could be "avoid pressure drop", "prevent crash" and "avoid corrosion" and so on. These sub functions looked fine and followed the guidelines of building function tree. But actually, they are difficult to generate single ideas from and too much like alternative expressions of requirements. After researching the function decomposition of other projects and discussion, one found out the reason of the resulting problems. The main function is meant to be set with boundaries. Hence, one decided to define the main function more targeted on the project per se instead of giving a vague and general function of fuel lines. The sub functions were also defined on critical and promising aspects.

In concept generation, two methods – brainstorming and 6-3-5 were chosen to process this part. They were selected by Shah's classification theory. Shah divided idea generation methods into two groups: intuitive ones and logical ones. Intuitive methods aims to remove perceived barriers to divergent thinking and increase the chances for conditions perceived to be promoters of creativity. Logical methods involve step-by-step problem analysis and direct use of catalogued solutions (Almefelt, 2013). Considering the project expected to be an "out of the box" and innovative conceptual design, it is more appropriate to use intuitive methods. Thus, two intuitive methods brainstorming and 6-3-5 were utilized.

In general, the process of using the two methods in idea generation went well although some iterations happened inevitably. There is one regret that 6-3-5 was not made full use of. 6-3-5 is a more structured and efficient version of brainstorming. With more people involved, this method can play a bigger role in structuring participants' ideas and inspiring more creativity. During idea generation, the team thought about looking for more people participating. However, due to the confidentiality issue, no people outside Volvo is allowed to join. The people within Volvo were at that time considered as "inside box" people, which do not meet the purpose of idea generation in this project. In the end, the 6-3-5 was done only by two persons in the team and turned out to be 2-3-5.

8.2 Discussion of the Concept Selection

The first concept evaluation was done before concept combination. It is comparatively easy because it is to evaluate against sub-functions. This is not the commonly used process in the most of product development projects. One has discussed the evaluation methods with the experienced engineers. They agreed that it is beneficial to change the traditional development process to make it more adapted to the product. One more different evaluation method is about concept synthesis. In this project, selection and synthesis were done at the same time, the unpromising combinations were eliminated during the synthesis.

Another change of methods is the Pugh matrix. However, instead of giving single "1"or " -1", some extra weights were added from "3" to "-3" depending how much difference there was between the concept and reference. Normally Pugh Matrix is a qualitative method that is not a precise evaluation. By changing the evaluation scale, the result became more obvious.

Within the whole selection process, evaluations have to be done with experience and reliable inferences because of the lack of information. Hence, there could be inaccuracy in the evaluation. Especially, the cost comparison was based on the references from internet, because it was not a statistical data, the evaluation result could be different from the reality. For example, the price of sandwich material was considered relatively lower than steel, because some samples prices that can be found on internet were lower than the real market price. Showing the lower price is a part of advertise strategy. Actually, most of the sandwich material are under development, the average price could be higher. In the late stage, when the final sandwich material was decided, we realized the price was much higher than normal steel. Anyway, we continually worked with the sandwich material, because the material has very good properties, and also it is too late to redo the evaluation.

However, product development is to develop or improve products for the future, so lack of information is quite common. As a product developer, experience is valuable knowledge, and inference ability based on professional experience is also necessary. Even if there is no certain proof to support every single evaluation, decisions still have to be made. For example, this project was aiming to lower the product cost, but current cost and supplier information usually are very confidential information to a company. One has contacted many companies and asked about their product price. Only a few companies replied and sometimes it took a long time to finally obtain their information. This is also the reason that the concept evaluation was more time-consuming than it was planned.

At last, the final concept was chosen. It is going to change the material of the protection pipes. Material revolution is going on all the time, sandwich metal as a new material has been proved to have better properties than normal metal. Meanwhile, its price is higher. But as long as the manufacturing technology continues to be improved, the price will decrease in the future. The substitute concept was selected because of its good potential. As it has been mentioned at the beginning, this thesis is giving a suggestive proposal to the company. The substitute concepts meet this purpose, it has its significance as a suggestive concept. However, due to the limited time, one did not go deep on this concept.

8.3 Discussion of the Simulation

The calculation methods of sandwich structure material apparently have its limitation. Most of the studies focused on the experiment and mathematical simulation, and very little on theoretical research. Besides, the modeling structures were very simple and overlooked some small effects, for example, the specific change of microstructure of the inner structure. Therefore, in the calculation, one considered the sandwich metal is one layer of the metal panel, and applied its properties to the calculation theories. Meanwhile, the theories also have limitation, for instance, the law of conservation of energy is idealized, and the method of modeling sandwich panel is not very exact etc. All of these limitations will make a difference to the real product.

In most of the studies, the simulation models are repeated pattern structure or simplified realistic structure. The problem in this project is that the structure of the core layer is fiber. It is very difficult to model them, so one has to simplify the core layer. One tried to model one type of the supplier's fiber based on their provided information. However, the data is still too limited to model a fiber precisely.

In order to reduce the distance between the simulation and reality, one considers it is better to have a physical test of the FibreCore™ in the future.

8.4 Discussion of Cost Estimation

The cost of the entire fuel lines was 52€ when the project started. One of the main target was to reduce product cost as one had been informed by fuel engineers that the protection pipe was quite expensive. But at that time, both fuel engineers and the team has no knowledge about the exact price of each component of the fuel lines. Later, one was told by the product buyer that the price has been decreased to 37€ owing to the process modification. The protection pipe of the fuel lines remained the same price, which was much cheaper than the team thought. However, because those expensive components are very necessary to the system and designing them is not the priority task to perform, one still put the concentration on the redesigning of protection pipes. Henceforth, the detailed design part including cost estimation is only regarding the protection pipes. Even if the cost of the protection pipes are not as high as one expected, there is still room to reduce, and reducing them is the still the main task for the team to put effort on.

The cost estimation of FibreCore™ sheets is a theoretical value based on the assumption that this material can be mass-produced. FibreCore™ has shown its excellent properties and commercial potential according their supplier. While calculating with "experience learning curve", one took 1.6 million as the number of units which is only the number of protection pipes. Since FibreCore™ sheets are on their way to be appreciated more in industry, the manufacture amounts will be larger in the future. Thus, the cost of FibreCore™ sheets will travel more on the "experience learning curve" and reach a more decreased one.

The estimated cost of energy use is based on an information resource from the laser welding industry in the Czech Republic while the labor cost is sourced from the US laser welding industry. If the welding process is located in Sweden, there may be variation on several expenses due to the different charges.

The total estimated cost of one FibreCore™ tube is higher than the current cost of one stainless steel tube. As one mentioned in discussion of concept selection, there are plenty of sandwich material with lower prices than metal. However, in this project, fulfilling the requirement of high strength against the car crash is the top priority, which led one to select metal sandwich material for protection pipe. The cost of metal sandwich material is hardly lower than normal metal material due to the higher complexity of construction process of sandwich material.

Therefore, the estimated cost of it is difficult to be lowered further to compete with the cost of current stainless steel tubes for the moment. But the remarkable properties of FibreCore™ tubes overshadow the cost problems and still make them the most promising option for producing protection pipes.

8.5 Discussion of Substitute Concept

The substitute concept is kept after the evaluation due to its potential as an excellent solution in the future. Its excellence mostly is embodied in the consequence that it assures zero fuel leakage if crash happens. Among all the ideas from the concept generation, this solution is the only one can make zero leakage happen. In addition, the innovation, uniqueness and "out of the box" thinking of this concept is meaningful to fuel lines design.

Certainly, one of the reasons of this concept being a substitute solution is that it did not score high in evaluation. Currently, this concept has several disadvantages in cost and mass. It contains seven elements, two solenoid valves, two solenoid check valves, two high-pressure gas capsules and a crash detection sensor. The existence of these elements increases both costs and mass of the fuel lines. In the earlier development phase of the substitute concept, one intended to cut down the numbers of elements to decrease the effect of its disadvantages. Initially, one preferred to control the fuel flows by two valves, one for each pipe. However, it turned out that having four valves is necessary if this concept has to keep its biggest advantage – zero fuel leakage. Thus, the design of the substitute concept has been carefully thought and the optimal one is presented at last.

Since it is not the final concept, the team did not go deep in its detail design. In the detail design part, concept architecture design, feasibility analysis and CAD are conducted. The result of feasibility proof is a theoretical one under an ideal circumstance. It is based on the momentum conservation principle, the amount of momentum of bullet equals to the momentum of fuel flow. In reality, the energy or momentum loss definitely exists during conversation process. Nevertheless, the amount of loss would be extremely small, so that can be overlooked. Generally speaking, the results of concept analysis may not be accurate, but it is capable to prove the feasibility of the concept.

9.Conclusions

During this thesis work, the situation of the frontal crash protection has been studied. The biggest risk is fuel leakage and sparks which can make crash fire and explosion. In this report, the focus is to prevent the fuel leakage during crash. To solve this problem, the authors have focused on two different angles: reinforcement of the protection material and using an innovative solution to achieve zero leakage.

In the result of this project, there are two solutions proposed. The final concept is changing the protection pipe material to an enhanced sandwich metal, and the substitute concept is using vacuum valve to drain the fuel lines before they get crashed. The final solution took most of the time of the project, and numerous materials have been considered and analyzed. Balancing the cost and performance makes the material selection very difficult to do. After sandwich material was chosen in selection, one type of sandwich metal --- FibreCore^{TM} ---was selected out of sandwich metal. FibreCore^{TM} has more advanced properties than steel in various areas. From calculation and simulation, it is seen that the new material has good crash resist ability. The manufacturing feasibility analysis and cost estimation were also conducted.

For the substitute concept, the feasibility was proved and CAD models were shown. The CAD pictures only indicate the conceptual design and do not show the accurate location and routing. This substitute concept also requires sensor technology to detect the crash and give signals before any damages. If this system could apply in future cars, the fuel leakage of frontal crash will be annihilated totally.

The authors hope that these proposals and studies which have been done in this project is beneficial to develop safer cars in Volvo Car Corporation.

10. Future Work

During the conducted work, some themes was excluded or overlooked for the purpose to keep the content within the framework of the thesis. This section describes the work of the project which can be explored further in the future.

To the final concept, the entire concept feasibility analysis including calculation and simulation is based on the statistics from the supplier. The result of concept analysis is very positive that the FibreCore^{TM} material has very outstanding mechanical properties to protect fuel lines from leakage. However, most of the data and information from the supplier is about the stainless steel fiber – the core material of FibreCore^{TM}. There is little record about the material FibreCore^{TM} per se. The input parameters for calculation and simulation are also sourced from both the information of stainless steel and supplier reference of the fibre.

During the time while one has finished the project and been completing the report, the supplier promised to deliver several FibreCore^{TM} samples. If one is provided extra time, the physical testing of the sample material is likely to be conducted. Hence, the practical properties of the material can be obtained to see if the theoretical calculation and simulation can be confirmed. Moreover, a prototyping of a FibreCore^{TM} protection tube is much expected to be developed.

In this project, the routing design of fuel lines was decided to remain unchanged. This decision was made mostly due to the large amount of expense and work for the routing alternation. There is always conflicting for balancing a lower cost as a requirement and a desired technical change which could rise the cost. However, seeing this conflict in a bigger picture, the increase of cost is probably necessary for improving the product to the next level and satisfying user needs more. To the fuel lines, if a new design can significantly upgrade vehicle safety and reduce driving hazardousness, a higher cost is sometimes acceptable. In this project, since a lower cost is the priority requirement, the research did not go in that direction and thus a redesign of routing is skipped. In the future, if no absolute cost requirement is given, the routing design of fuel lines deserves putting effort to.

The substitute concept can be developed more comprehensively. A more detailed design of two solenoid valves and check valves can be covered including the exact valve types and locations. The connection fashion and related components can also be developed with factors of cost and mass taken into consideration. The gas capsules used for blowing fuel back was used in air guns. Since there are no high-pressure gas cylinders small enough to fit in the limited space in engine, gas capsules become a suitable solution. If the substitute concept is realized in the future and large quantities of all parts is needed, specialized gas capsules can be manufactured particularly for this concept.

11. Reference

Advanced Laser Applications Workshop, 2013. *The real cost of laser welding.* [pdf] Available at: <http://www.autosteel.org/~/media/Files/Autosteel/Great%20Designs%20in%20Steel/GDIS%202013/Laser%20Welding%20101%20%20Case%20Studies%20%20Part%20I.pdf> [Accessed: 15 Oct 2015]

Almefelt, L., 2013. *Introduction to design methodology*, PPU140. Chalmers University of Technology, unpublished.

American Heart Association, 2012. *What is a stent*. [pdf] Available at: <http://www.heart.org/idc/groups/heartpublic/@wcm/@hcm/documents/downloadable/ucm_300452.pdf> [Accessed: 15 Mar 2015]

AZO material, 2015. *Properties: stainless steel - Grade 304 (UNS S30400).* [online] Available at: <http://www.azom.com/properties.aspx?ArticleID=965> [Accessed: 25 Mar 2015]

Automotive Benchmarking, 2015. *Auto Reverse*. [online] Available at: <http://www.a2mac1.net/home/home.asp> [Accessed: 6 Feb 2015]

Brensing, K and Sommer B., 2015, *Steel tube and pipe manufacturing process.* [pdf] Available at: < http://www.smrw.de/files/steel_tube_and_pipe.pdf> [Accessed: 10 May 2015]

Cole-Parmer, 2015. *Vaccum Valve.* [online] Available at: <http://www.coleparmer.com/Product/Accessory_Vacuum_Valve/EW-15954-87> [Accessed: 20 Mar 2015]

Core value of Volvo cars. 2015. [online] Available at: < http://www.volvocars.com/intl/about/our-company/core-values>. [Accessed: 25 January 2015].

CosmoLearning, 2015. *Topics: chemical engineering – valves.* Available at: <http://cosmolearning.org/topics/valves-484>[Accessed: 22 May 2015].

Cost models, 2015. *Learning Curve Calculator.* [online] Available at: <http://fas.org/news/reference/calc/learn.htm> [Accessed: 19 Mar 2015]

DEC, 2015. *DEC Engineering Corperation – Stainless Honeycomb Panel*. [online] Available at : <http://www.deceng.co.kr/site1/product/product_1_04.asp> [Accessed: 26 Apr 2015]

Denso Group, 2009. *Common Rail System.* [online] Available at: <http://www.denso.co.th/denso/en/technology_1.jsp?lang=en> [Accessed: 20 Feb 2015]

ECVV, 2013. *Fuel Gas Solenoid Valve*. [online] Available at: <http://www.ecvv.com/product/1000071043.html> [Accessed: 30 Jan 2015]

Fibretech, 2014. *Fibrecore*. [online] Available at : <http://www.fibretech.com/fibrecore.html> [Accessed: 14 May 2015]

Hull, E., Jackson, K and Dick, J., 2002. *Requirements Engineering*. London: Springer.

Industrial Laser Solutions, 2013. *Laser welding replaces TIG*. [online] Available at:< http://www.industrial-lasers.com/articles/print/volume-28/issue-1/features/laser-welding-replaces-tig.html> [Accessed: 20 May 2015]

Lamera, 2013. *Lamera AB Sweden – Home of Hybrix™*. [online] Available at: <http://www.lamera.se/eng/index.php?option=com_content&task=view&id=12&Itemid=29> [Accessed: 4 May 2015]

Markaki A.E., Clyne T.W., 2005. *Mechanical and Electrical Properties of Stainless Steel Sandwich Sheets with Fibrous Metal Cores*, Designed for Automotive Applications. Pp.24

Mollenhauer, K and Tschoeke, H., 2009. *Handbook of Diesel Engines*. Berlin: Springer.

Pugh, S., 1990. *Total Design*, Addison-Esley, Reading MA

Pyramyd Air, 2003. *What about CO2*. [online] Available at: <http://www.pyramydair.com/article/What_About_CO2_December_2003/6> [Accessed: 20 May 2015]

Raumprobe, 2015. *AFS – Platte (Aluminium Foam Sandwich).* [online] Available at: <http://www.raumprobe.de/material/pohltec-metalfoam-gmbh/afs-platte-aluminium-foam-sandwich/datenblatt/> [Accessed: 9 May 2015]

Reference for Business, 2015. *Experience and learning curve.* [online] Available at: <http://www.referenceforbusiness.com/management/Em-Exp/Experience-and-Learning-Curves.html>[Accessed: 12 Oct 2015]

SMC, 2013. *High Purity Suck Back Valve*. [online] Available at: <http://www.smcusa.com/top-navigation/cad-models.aspx/23492/LVC23-High-Purity-Suck-Back-Valve Single-or-Unit-Type> [Accessed: 5 Apr 2015]

Sorting-Algorithms, 2015. *Bubble Sort - Sorting-Algorithms Animations*. [online] Available at: <http://www.sorting-algorithms.com/bubble-sort> [Accessed: 20 Apr 2015]

Stainless Steel Sandwich, 2007. *Stainless Steel Sandwich – CUED Publication database*. [online] Available at : <http://www.eng.ox.ac.uk/tan/pdf-publications/brown_ss_sandwich_matworld_2007.pdf> [Accessed: 3 May 2015]

Tresca Criterion, 2015. *Mises Criterion and Tresca Criterion*. [online] Available at : <http://www.failurecriteria.com/misescriteriontr.html> [Accessed: 20 May 2015]

Ulrich, K.T., and Eppinger, S.D., 2012. *Product Design and Development*, Fifth edition, New York: McGraw Hill

Zhang, Qingnan., 2014. *Study on the Ballistic Impact Effect of Sandwich Panels with Aluminium Honeycomb Cores*, Master Thesis. Beijing Institute of Technology, unpublished.

Zhou, J., Deng, Z., Liu, T., Hou, X., 2009 *Elastic structural response of prismatic metal sandwich tubes to internal moving pressure loading*. International Journal of Solids and Structures, Volume 46, Pp. 2354–2371

12. Appendix

Appendix 1: Interview
Appendix 2: Picture of simulation scenario
Appendix 3: Concept Evaluation 1
Appendix 4: Concept Evaluation 2
Appendix 5: Concept Evaluation 3
Appendix 6: Pictures of FibreCore^{TM} Sheets
Appendix 7: Matlab script of current material energy absorbing
Appendix 8: Experience learning curve

Appendix 1: Interviews

With *Erik Fredholm: Designer of Bränsle & Evap-system*

1. For diesel engines, why has the return pipe of the fuel system bigger diameter than the feed pipe?
   The return pipe carries fuel from high pressure to low pressure while the feed pipe carries fuel from low pressure to high pressure. Enlarging the return pipe diameter is preventing too much pressure in the fuel pump.

2. Should the effect of static electricity be taken into consideration when the material is designed?
   Yes, it should. Conductive material should be used with static electricity led to ground.

3. What is the physical state of fuel in the return pipe of diesel engine and gasoline engine?
   Diesel engine: liquid fuel
   Gasoline engine: fuel evaporation

4. Is the material same for the pipes of gasoline engine?
   Since there is evaporation flowing in the purge pipe while liquid fuel in the feed pipe of gasoline engine, the material of the two pipes can be different.

5. Are the diameters of the pipes calculated results?
   The diameters are affected by many parameters of the fuel system, such as the pressure in the fuel pump, fluid volume, turbo accelerating timing, connector diameters and seal capability.

6. Is fuel corrosive to some materials?
   Yes, it is. Fuel has both corrosion and solvent effect to some materials.

7. What is the cost of the current solution of fuel pipes for a diesel engine?
   The current solution of fuel pipes in one diesel engine costs 51.480 €.
   There are three parts of pipe lines: ①plastic pipe, ②steel pipe and ③plastic pipe covered by fire protection. The prices for the three parts are ③>②>①

8. How about the working temperature of the fuel pipe?
   There are two parts of fuel pipe:
   The pipe under the lower body part: For diesel engine, the temperature is from room temperature to 60 degrees, and for petrol engine, the temperature is generally room temperature.
   The pipe near by the engine: both petrol and diesel engine are from 100 to 130 degrees.

With *Anders Sandahls: Engineer of Frontal Crash Simulation*

Intro: The expert showed us the scenario simulation that is the easiest case to result in fuel pipe leakage when crash happens. The vehicle hits obstacles with the left front side since fuel pipes place on the left of engine to the rear parts.

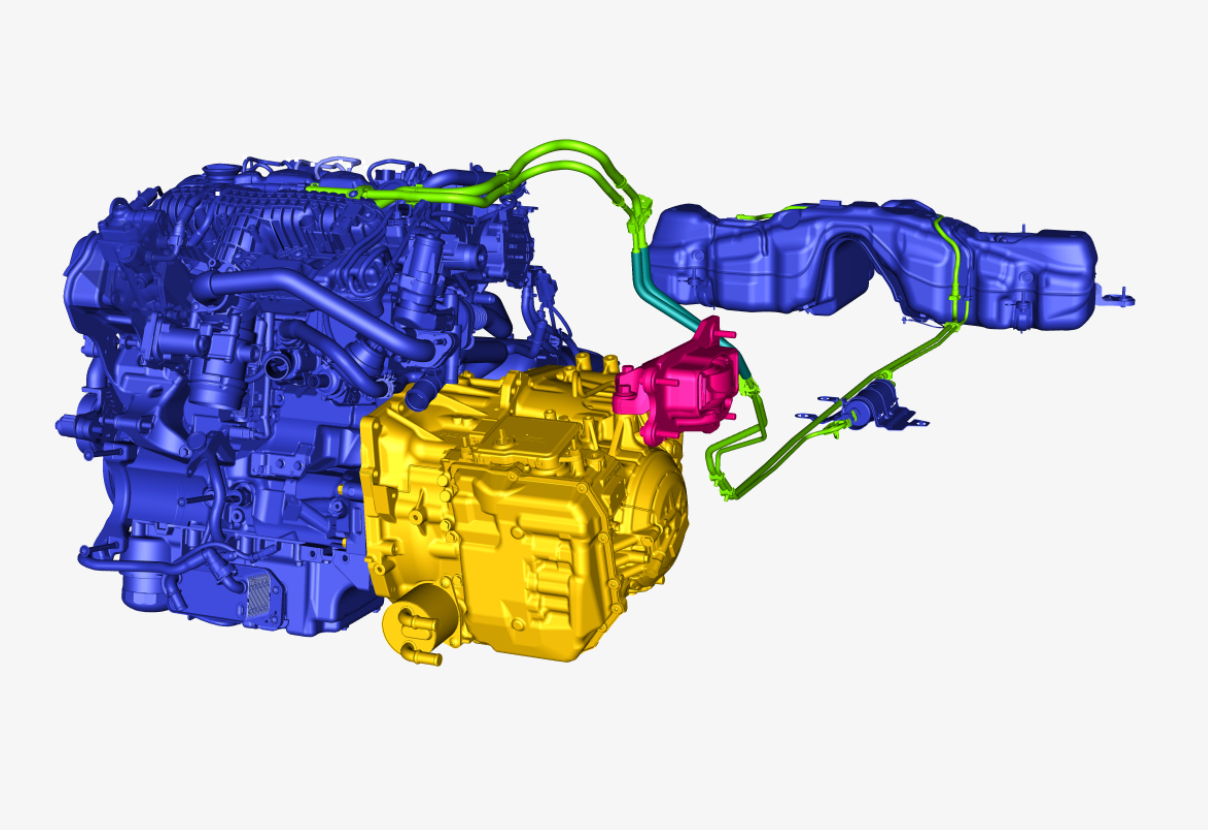
1. What are the exact causes of fuel pipe leakage?
   When the crash happens, the engine mounts would be broken to let gearbox and engine move backwards which would punch the pipes behind. Under this circumstance, all the parts of the engine compartment could be squeezed including fuel pipes or the broken mounts or metal chips could have sharp edges and cut the fuel pipe.

2. How long is the usual time for crash happening?
   In most of the cases, the happening time is 0.1s.

3. What is the risk of crash?
   There is legal requirement for fuel leakage amount during crash. Furthermore, the leakage of fuel often causes fire since there are always heat and sparks generated in a car crash, especially the electrical cables are closely located to fuel pipes.

4. How many times of simulations have to be done before production?
   There are hundreds of situations to be simulated before the physical production.

Appendix 2: Picture of Simulation Scenario



Blue parts: Engine, filter and fuel tank
Yellow part: Transmission
Red part: Engine mount
Green parts: Fuel lines

Appendix 3: Concept Evaluation 1

Selection craiteria	A0	A1	A2	A3	A4	A5		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
Material cost	0	+++	+	0	+	0		---	+	+	0	-	-	0	-	+	0	+	0	---	--	0
Cutting prevence	0	--	0	0	0	+		0	0	0	0	-	0	0	-	-	0	0	-	0	0	0
Squeeze prevence	0	+++	0	0	---	+		0	0	0	0	-	0	0	-	-	0	0	-	0	0	0
piercing prevence	0	--	0	0	---	+		-	--	0	0	0	-	0	0	-	0	--	-	--	0	0
Total Geometry volumn	0	0	-	+	0	0		--	+	---	++	+	-	0	+	++	0	+	++	0	0	0
Total mass	0	++	-	++	+	+		--	++	---	++	+	0	++	+	++	+	++	++	++	+	+
Components amounts	0	++	-	0	0	0		--	0	-	0	+	--	0	+	--	0	0	--	0	0	-
Assembly/disassemble time	0	++	0	0	0	+		--	0	--	0	---	-	0	---	0	0	0	0	0	0	-
manufacture feasibility	0	0	-	0	0	0		0	++	+++	0	---	-	0	---	0	-	++	0	--	-	-
fire protect	0	---	0	0	-	0		-	0	0	0	0	0	-	0	---	+	0	---	0	0	-
other requirement	0	--	0	0	0	0		0	0	0	0	0	0	0	0	-	0	0	-	0	0	-
Sum +	0	12	1	3	1	5		0	6	4	4	3	0	2	3	5	2	6	4	2	1	1
Sum 0	0	2	6	9	6	6		4	6	5	9	3	5	9	3	3	8	6	3	7	8	5
Sum -	0	9	4	0	7	0		13	2	9	0	9	7	1	9	9	1	2	9	7	3	5
Net score	0	3	-3	3	-6	5		-13	4	-5	4	-6	-7	1	-6	-4	1	4	-5	-5	-2	-4
Rank																						
Continue ?					No			No		No		No	No		No				No	No		

Appendix 4: Concept Evaluation 2

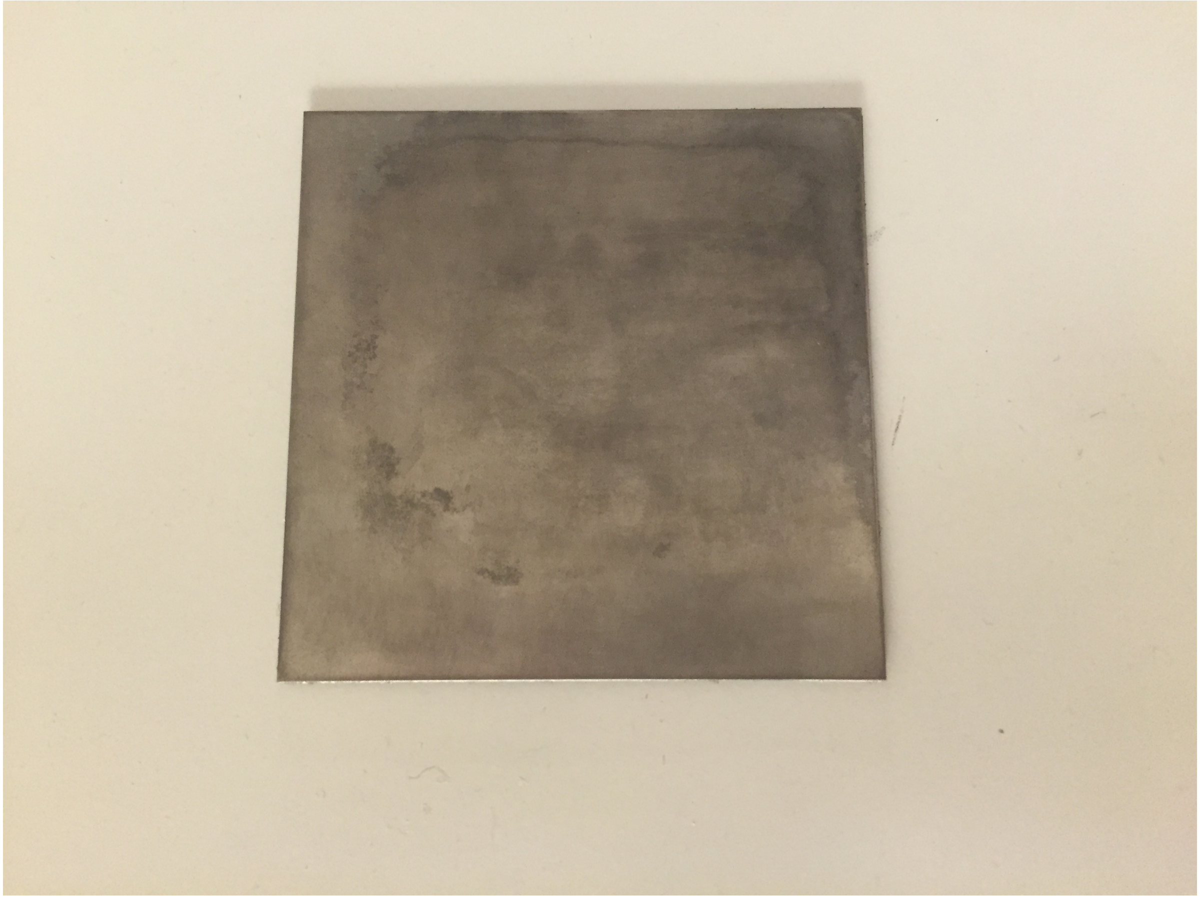
	Current Steel +								Nylon +							
	A0B2	A0B4	A0B7	A0B9	A0B10	A0B11	A0B14	A0B15	A1B2	A1B4	A1B7	A1B9	A1B10	A1B11	A1B14	A1B15
Selection craiteria	meshed metal+coating fireproof paint(prevent piercing)	amti saw lock	fuel absorbing material	vacuum valve	tree burr	anti-knife material	sandwish metal	glass pressure suck back	meshed metal	amti saw material	fuel absorbing material	vacuum valve	tree burr	anti-knife material	sandwish metal	glass pressure suck in
Material cost	+++	+	+	--	++	+	+	+	+++	++	++	-	+++	++	++	++
Cutting prevence	0	+	-	-	-	0	+	-	0	+	--	--	--	0	0	--
Squeeze prevence	0	0	-	-	-	0	+	-	+	+	0	0	++	+	+	++
piercing prevence	0	-	-	-	-	0	+	-	0	--	--	--	--	0	0	-
Total Geometry volumn	+	0	0	++	0	+	++	-	+	0	0	++	0	+	++	-
Total mass	++	+	++	++	+	++	++	++	+++	++	+++	+++	++	+++	+++	+++
Components amounts	0	0	0	--	0	0	0	0	0	0	0	--	0	0	0	0
Assembly/disassemble time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
manufacture feasibility	++	0	+	-	0	+	0	-	++	0	+	-	0	+	0	-
fire protect	0	0	++	---	++	0	0	+++	0	0	++	---	++	0	0	+++
Innovative	0	0	+	+	+++	+	++	+++	0	0	+	+	+++	+	++	+++
environmental friendly	0	0	+	+	+	0	+	0	+	+	++	++	++	+	++	+
brand pride(safety)	0	0	0	0	0	0	0	++	0	0	0	0	0	0	0	++
life cycle	0	0	-	0	-	0	0	-	-	-	--	-	--	-	-	--
other requirement	0	0	0	-	0	0	0	0	0	0	0	-	0	0	0	0
Sum +	8	3	8	6	9	6	11	11	11	7	11	8	14	10	12	16
Sum 0	11	11	5	3	6	10	7	4	8	8	6	3	6	7	8	3
Sum -	0	1	4	12	4	0	0	6	1	3	6	13	6	1	1	7
Net score	8	2	4	-6	5	6	11	5	10	4	5	-5	8	9	11	9
Rank							2		3					4	2	4
Continue ?							Yes		Yes					Yes	Yes	Yes

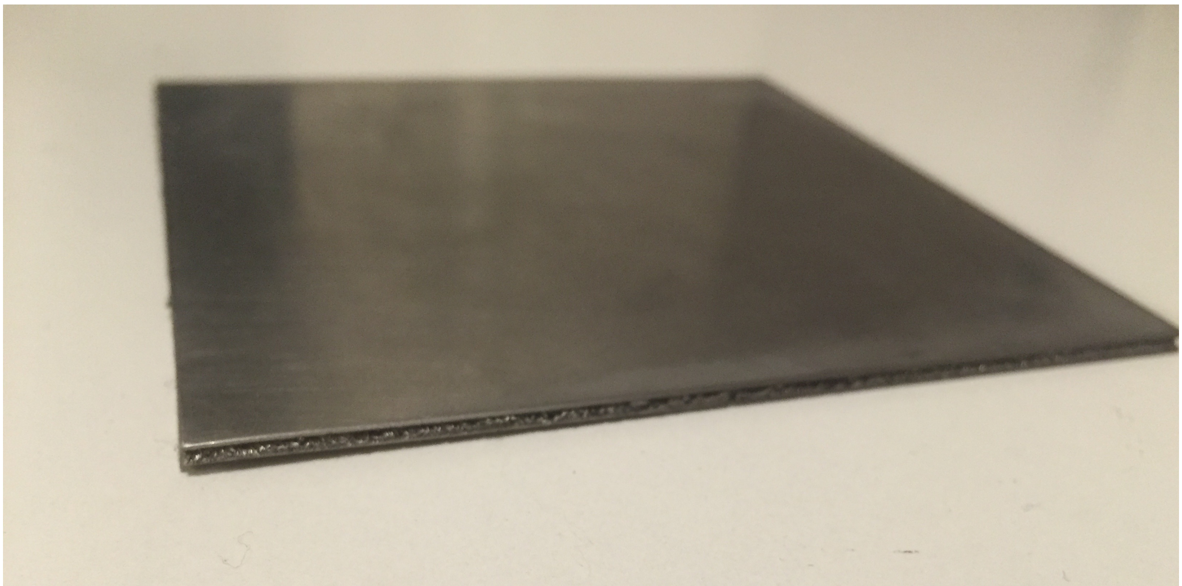
	straw pipe +	-	Kevlar+							
	A2B11	A3	A5B2	A5B4	A5B7	A5B9	A5B10	A5B11	A5B14	A5B15
Selection craiteria	anti knife material	cutting and replace inter pipe	mesh metal	amti saw lock	fuel absorbing material	vacuum valve	tree burr	anti-knife material	sandwish metal	glass pressure suck back
Material cost	+	0	-	-	-	-	-	-	-	-
Cutting prevence	0	0	++	+++	+	+	+	++	+++	+
Squeeze prevence	0	0	++	++	+	+	+	++	+++	++
piercing prevence	0	0	0	-	-	-	-	0	+	-
Total Geometry volumn	-	+	+	0	0	++	0	+	++	0
Total mass	+	++	++	+	++	++	+	++	++	+++
Components amounts	-	-	0	0	0	--	0	0	0	0
Assembly/disassemble time	-	-	0	0	0	0	0	0	0	0
manufacture feasibility	0	0	++	0	+	-	0	+	0	-
fire protect	0	0	0	0	++	---	++	0	0	+++
Innovative	+	0	0	0	+	+	+++	+	++	+++
environmental friendly	0	0	0	0	+	+	+	0	+	0
brand pride(safety)	0	0	0	0	0	0	0	0	0	++
life cycle	0	0	0	0	-	0	-	0	0	-
other requirement	0	0	0	0	0	-	0	0	0	0
Sum +	3	3	9	6	9	8	9	9	14	14
Sum 0	9	11	9	10	5	3	6	8	7	5
Sum -	3	2	1	2	3	9	3	1	1	4
Net score	0	1	8	4	6	-1	6	8	13	10
Rank			5					5	1	3
Continue ?			Yes					Yes	Yes	Yes

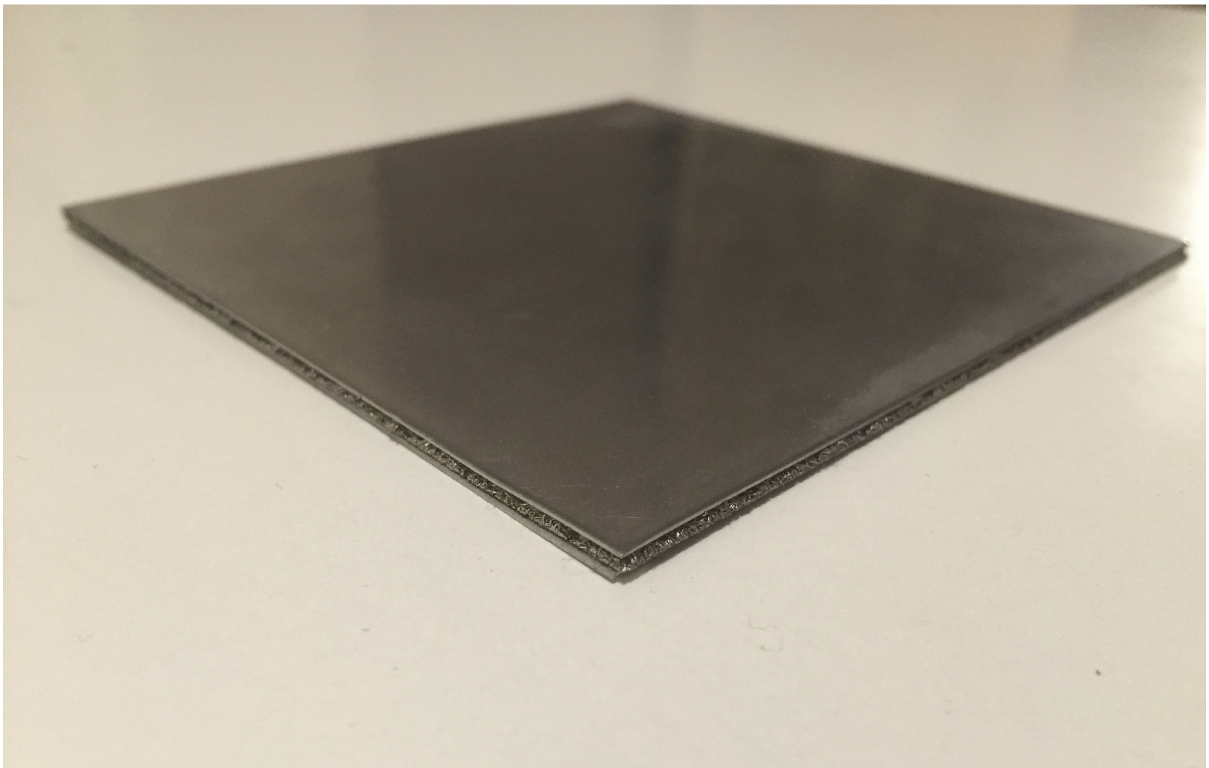
Appendix 5: Concept Evaluation 3

Bubble Sort																					
			A0B14		A1B2		A1B11			A1B14			A5B2		A5B11				A5B14		
			X1		X2		X3			X4			X5		X6				X7		
Selection craiteria	**parameter**		current steel+sandwish metal		current Rubber+meshed metal		current Rubber+anti-knife material			current Rubber+sandwish metal			Kevlar+mesh metal		Kevlar+anti-knife material coating				Kevlar+sandwish metal		
		unit		Vs. X4		Vs. X3		Vs. X2	Vs. X6		Vs. X7	Vs.X1		Vs. X6		Vs. X3	Vs. X5	Vs. X7		Vs. X6	Vs. X4
Material cost	raw material price	€	63	0	7	1	17	0	1		1	1		1		0	0	1		0	0
Cutting prevence	feacture toughtness	$MPa.m^{1/2}$		1		0		1	0		0	0		0		1	0	0		1	1
Squeeze prevence	tensile strength	Mpa		0	200-360	0	200-360	1	0	200-360	0	0	2000-3000	0	2000-300(	0	0	0	2000-300(	0	0
piercing prevence	Shear Modulus	Mpa		1		0		1	0		0	0		0		1	0	0		1	0
Total Geometry volumn		m3		0		0		1	0		0	0		0		0	1	0		0	0
Total mass	density	g		0		0		1	0		1	1		0		0	1	0		0	0
Components amounts		ps	24	0	24	0	24	0	0	24	0	0	<24	0	<24	0	0	0	<24	0	0
Assembly feasibility		/		0		0		0	0		0	0		0		0	0	0		0	0
manufacture feasibility		/		0		0		0	0		0	0		0		0	0	0		0	0
fire protect		/		1		0		0	0		0	0		0		1	0	0		0	1
legal				0		0		0	0		0	0		0		0	0	0		0	0
Sum				3		1		5	1		2	2		1		3	2	1		2	2

Appendix 6: Pictures of FibreCore^{TM} Sheets







Appendix 7: Matlab script of current material energy absorbing

```
%% current materila

clc; clear;

r_p = 0.0095/2;
rho_st = 7860;
m0 = rho_st*4/3*pi*(0.0095/2)^3;
v_i = 200;
h = 1.5*10^-3;

sigma_f = 1.3*215*10^6;

m_p =h*pi*r_p^2*rho_st ;


%pahse1

tau_f = sigma_f/sqrt(3);

E = sigma_f*0.498*pi*r_p^2*h;

E_f = tau_f*2*pi*r_p*h^2;

v_r = sqrt( (0.5*m0*v_i^2-E-E_f)/(0.5*(m0+m_p)) );

diff_v=v_i-v_r

E_p = E + E_f
```

Appendix 8: Experience learning curve

Input Data

Method:	(●) Wright ( ) Crawford	
First Unit Effort:	38.20	
Number of Units:	1600000	
Learning Percent:	90	0 to 100

Recalc

Results

Nth Unit Effort:	3.693279895931	
Cumulative Average:	4.355298577707	
Cumulative Total:	6968477.724331	

(Cost Models)