Developing a Resource-Efficient Sensor Cleaning System for Autonomous Heavy Vehicles

A design study and evaluation of different cleaning methods

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Abstract

The global transportation sector is currently shifting towards autonomous vehicles. This shift comes with challenges, such as; identifying obstacles, recognising its surroundings and acting safely based on these perceptions. To accomplish mentioned tasks, the vehicle is equipped with sensors, such as lidars and cameras. A lesser known, yet significant challenge lies in keeping these sensors clean from dirt and debris which tends to accumulate on the lens of the sensors when the vehicle is moving.

This report investigates how lidar- and camera sensors can be cleaned more resource-efficient in comparison to the existing sensor cleaning systems on the market. The goal was to recommend a sensor cleaning system for the range of sensors of an autonomous heavy vehicle. The authors of the study developed and tested several cleaning methods which were evaluated among each other and existing systems, while considering a system perspective.

The developed cleaning systems showed that enabling a low washer fluid consumption had a negative impact on the system’s scalability, durability, compactness and complexity, in comparison to the existing cleaning systems. When utilising a high-pressured fluid, the study found that a sweeping flat spray is more resource-efficient than a static cone spray, where the latter is being commonly used in conventional sensor cleaning systems. The concepts with a sweeping flat spray resulted in a fluid consumption 4-7 times lower than the best reference cleaning system.

In the case of a lidar, when considering a system perspective, it is recommended to use two telescopic flat spray nozzles facing each other and placed in either corner of the lens. It is also recommended that the nozzles are activated one at a time and that fluid I sprayed immediately on activation and kept flowing during the entire stroke to achieve a shaving or ploughing effect on the dirt. This method of cleaning has been observed to be more resource efficient compared to the reference systems. The resource-efficiency of a sweeping flat spray exists for other lens sizes as well, such as cameras and headlamps, however the scaling effects need further investigating. Therefore, additional tests are suggested, such as stress tests to determine the long-term durability of the cleaning system. Additionally, more research is needed to understand the impact of dirt in different environments and how often the sensors need cleaning. This also includes investigating how dirty the sensors can become before losing functionality.

Keywords: Sensor Cleaning, Autonomous vehicles, Cleaning methods, High-Pressure Fluid
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Utvecklingen av ett Resurseffektivt Sensorrengöringssystem för Autonoma Tunga Fordon

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Sammanfattning
Den globala transportsektorn är på väg att skiftra till autonoma fordon. Detta skiftra medför flera utmaningar; som att göra fordonet medveten om dess omgivning, identifiera objekt och agera säkert baserat på dessa intryck. För att kunna utföra dessa uppgifter är fordonen utrustade med sensorer, såsom lidar och kameror. En mindre känd utmaning ligger i att hålla dessa sensorer rena från smuts som ansamlas på sensorernas lins när fordonet framförs.


De utvecklade rengöringssystemen visade att en låg vätskeförbrukning påverkade systemet negativt i aspekter som skalbarhet, hållbarhet, kompakthet och komplexitet, i jämförelse med the befintliga rengöringssystemen. Vid användning av högtrycksvatten fastställde studien att en rörlig platt stråle kan vara mer resurseffektiv än en statisk konisk stråle, där den senare är vanlig bland befintliga rengöringssystem. Koncepten med en platt stråle hade en vätskeförbrukning som var fyra till sju gånger lägre än närmaste referenssystem.


Nyckelord: Sensorrengöring, Autonoma Fordon, Rengöringsmetoder, Högtrycksvatten
This thesis marks the end of our five-year education in Mechanical Engineering and Integrated Product Design at KTH Royal Institute of Technology, Stockholm.

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Stockholm, June 2019

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1 INTRODUCTION

The introduction chapter presents the problem statement along with the reference studies relevant to the research area. Moreover, it describes the purpose and goals for the thesis, as well as the delimitations which were made.

1.1 Problem statement

The global transportation sector is currently shifting towards autonomous vehicles. This shift comes with challenges, such as; identifying obstacles, recognising its surroundings and acting safely based on these perceptions. To accomplish these tasks, the vehicle is equipped with sensors, such as lidars and cameras. A lesser known, yet significant challenge lies in keeping these sensors clean from dirt and debris which tends to accumulate on the lens of the sensors when the vehicle is moving.

If the accumulated dirt is not removed, it will gradually reduce and eventually entirely block the visibility of the sensor. In a fully autonomous vehicle, with no option for a human to take over the control, there is no other choice than stopping the vehicle to avoid safety critical situations (Holmes, 2019). The sudden stop itself not only generates a safety hazard for other road users, but also a financial burden for the owner.

Finding ways of efficiently keeping the sensors clean is currently a prioritized task in the autonomous vehicle sector. Many of the industry leaders are still relying on manual cleaning methods (McFarland, 2018), which somewhat defies the purpose of autonomous vehicles. Yet even suppliers of existing sensor cleaning systems working for the automotive sector today, have not yet solved fundamental uncertainties. An article raises the concern about the increased need of cleaning a system with multiple sensors, pointing out that the combined fluid consumption will become problematic as the number of sensors increase (Linkov, 2018).

1.2 Frame of reference

Sensor cleaning on vehicles is a recent field of technology, which is why there is limited research and studies covering the field. However, there are a few closely related research areas, such as windshield- and headlamp cleaning systems, investigating relevant materials. Moreover, it is difficult to find research that combines and investigates a variation of cleaning methods in one combined report. Most of the discovered research was about a specific way of cleaning, while this thesis work intends to investigate a wider scope of cleaning methods. Appendix A shows a list of the search words that were used to find relevant research papers and patents. The following paragraphs summarise studies that were referenced in this thesis work.

A field study, evaluating the efficiency and benefit of headlamp cleaning systems, shows that the dirt accumulation on automobile headlamps is significantly higher during winter than in summer. Another conclusion was that the moist and soft dirt during the winter was comparable to the standard test dust ECE R-45, however the dry and hard summer dust was not. Even though the dirt accumulation was higher during winter, the cleaning performance of the tested headlamp cleaning systems was better than in summer. However, the low dirt accumulation during summer did not significantly affect the light intensity of the headlamps negatively, which is why a high cleaning performance during winter deemed to be more crucial. The cleaning performance equalled 56% during winter which was considered too low, and lead to the suggestion that headlamp cleaning systems needed technical improvements and optimisations.
This would lead to a higher cleaning performance, thus increasing the field of view of the driver and reducing glaring (Söllner, Polin, Haferkemper, & Khanh, 2012).

Another study evaluating headlamp cleaning systems showed that vehicles with wiper blade mechanisms performed better than vehicles with pressurised washer fluid systems. After cleaning, the wiper blade systems left a remaining 5% dirt on the headlamp lens, while the pressurised washer fluid systems left 12%. In addition, the wiper blade systems used significantly less fluid. Despite these advantages favouring a wiper blade system, most modern vehicles had been converted to high-pressure fluid systems. This change mostly had to do with the poor durability of the wiper cleaning systems (Ytterbom, 1994).

The same study also showed that vehicles with automated headlamp cleaning systems, which were activated together with the windshield cleaning system, had less remaining dirt on the lens after cleaning, compared to headlamp cleaning systems that had to be activated separately. This concluded that cleaning the headlamps more frequently lead to a higher cleaning performance, suggesting that leaving the dirt on the lens for longer leads to the dirt becoming harder and tougher to remove. (Ytterbom, 1994).

Regarding telescopic nozzle cleaning systems, a study pointed out the difficulty to clean the entire surface of the lens. The author points out factors such as the curvature and geometry of the lens, as well as the area covered by the fluid. The fluid spray was achieving good cleaning performance in the centre, where it hit the lens. However, the surface around the centre and towards the edges of the lens were poorly cleaned (Mitkov, 2017).

A report surrounding optimal windshield cleaning performance discussed the usage of windshields coated with a water-repellent coating. The report concluded that coatings cannot replace a wiper blade system, yet, lowers the need to clean. On the other hand, the high cost and relatively low durability make coatings not cost-effective. Therefore, more research is suggested to use surface coatings efficiently (Fagervall & Nyman, 2000).

The report also tested the cleaning performance of wiper blades with integrated fluid lines on the wiper blade. This concept uses the fluid as a dissolver and lubricant but the report does not evaluate the fluid consumption of the cleaning system (Fagervall & Nyman, 2000).

1.3 Purpose
The purpose of the thesis is to investigate how the current sensor cleaning systems on autonomous vehicles can be improved to clean a system of up to 20 sensors. This involves answering the following question,

- How to achieve a resource-efficient cleaning while meeting the desired cleaning performance?

1.4 Goal
The goal is to present a recommendation of a sensor cleaning system for a heavy vehicle’s range of sensors, specifically lidars and cameras. The recommendation should be based upon an evaluation of existing- and developed conceptual systems, while considering a system perspective. This includes considering aspects such as; resource-efficiency, scalability, complexity, modularity, durability and compactness. A sub goal is, based on the findings of the study, to recommend an improved cleaning system for the vehicle’s headlamps.

1.5 Delimitations
A level five autonomous vehicle scenario is presupposed, also known as fully autonomous. This means that no human driver is present inside or around the vehicle while the vehicle is operating. In other words, there is no human assistance available to manually clean any sensors in the case of a blockage.
As dirt can block a sensor instantly it can also build up gradually, the level of dirt accumulation before a sensor is blocked depends on the sensor technology and the application it is used in. Since the needed cleanliness of a sensor can differ considerably, any studies about finding a threshold has been left out.
2 BACKGROUND

This chapter presents the knowledge base upon which the research and product development in this report is based on. This includes sensor technology, state of the art within cleaning systems, a guide to surface cleaning, different types of dirt, as well as more detailed sections within certain areas investigated in the report.

2.1 Surface cleaning

This section presents the most common cleaning principles and the theory behind them. Removing foreign matter, hereon forth referred to as dirt, from a surface requires generally two steps; the first step is to dissolve or break loose the dirt from the surface, and the second step is to transport the dirt away from the surface.

**Solvent**

The role of a liquid, in the context of cleaning a surface, is mainly acting as a solvent. Liquid has the ability dissolving and breaking loose the dirt from the surface. Depending on the dirt, the solvent can include different detergents which increases the capability of dissolving even tougher dirt, such as oils (Techspray, 2019).

**High-pressure fluid**

Cleaning by spraying pressurised fluid on to a surface is also known as high-pressure wash. In such a case, the fluid is sprayed on to the surface in high speed where the kinetic energy of the fluid breaks loose the dirt from the surface, while simultaneously transporting the dirt away from the surface.

The fluid, which is commonly a water and detergent mix, is initially stored in a tank and transported and pressurised by a pump. The impact pressure of the fluid on the surface determines how well the fluid can break loose the dirt. Cleaning with less impact pressure means relying on the fluid’s ability to dissolve the dirt, which in comparison is less resource-efficient (SNP, 2019). Hence, increasing the impact pressure of the fluid leads to a more resource-efficient cleaning.

The lowest impact pressure required to achieve a certain cleaning performance depends on the type of dirt, spray angle of attack and the detergents used in the fluid. In turn, the impact pressure on the surface depends on the kinetic energy of the fluid, as well as the impact angle on the surface. The impact force of the fluid on the surface can be explained through Figure 1, and can be calculated with the following formula,

\[ F = Q \rho V \sin \theta = \rho AV^2 \sin \theta \]

where \( F \) is the impact force, \( Q \) is the mass flow of the fluid, \( \rho \) is the density of the fluid, \( V \) is the change of velocity, \( \theta \) is the impact angle, and \( A \) is the cross-sectional area of the fluid. Thus, the impact force of a constant fluid is the highest when it hits the surface perpendicularly, when \( \theta = 90^\circ \).

![Figure 1. Impact force of fluid jet on surface (Beardmore, 2019)](image)
**Mechanical cleaning**

This type of cleaning refers to using a physical body moving on top of a surface to remove dirt, e.g. wiper blades, brushes or sponges. Mechanical cleaning is very effective in removing dirt, however, it can also be abrasive and requires good control of surface pressure and durable materials. In the case of wiper blades, the pressure of the wiper blade against the surface breaks loose and transports the dirt away from the surface. The additional use of washer fluid helps dissolving the dirt and lowering the friction between the wiper blade and surface. Although wiper blade systems are well-known solutions, e.g. automobile windshield wiper, there are a few drawbacks. Some of the most common problems are explained in Figure 2. These drawbacks are mostly durability-related, which is also described by Ytterbom (1994).

![Figure 2. Common wiper blade problems (Valeo Group, 2011)](image)

**2.2 Bernoulli’s principle**

Among other achievements, Daniel Bernoulli published *Hydrodynamica* in 1738 (Mikhailov, 2005), which presented a basis for *the kinetic theory of gases*. His work states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure, also known as a decrease in the fluid's potential energy.

The principle of mass continuity mentions that the velocity of an incompressible fluid, when passing a constriction, must increase while the pressure at the same location must decrease according to the principle of conservation of mechanical energy, see Figure 3.
Although Bernoulli explored the relation between speed of flow and pressure, it was Leonard Euler who reasoned Bernoulli’s findings into the equation we are familiar with today (Darrigol & Frisch, 2008) (Anderson, 2016).

### 2.3 Venturi effect

A special case of the Bernoulli principle is the Venturi effect, named after Giovanni Battista Venturi, who published his idea of the Venturi tube in 1797. It came to practical use not earlier than in 1888 with Clemens Herschel’s involvement (Kent, 1912).

Many inventions and applications have later been based on the Venturi effect, some of them are; carburettors, injectors, pumps, automotive diffusers and many more. The fundamental working principle is shown in Figure 4. The medium is sucked inside the chamber by the vacuum created by a stream of air or liquid, also called the motive, and dragged through the nozzle to be mixed and blown out.

The optimal dimensions of a Venturi pump might differ, depending on the application and medium, however, an inlet cone of around thirty degrees opening and an outlet of around five degrees is usual.

### 2.4 Boundary layer effect

Ludwig Prandtl’s findings about boundary layer effects in fluid dynamics was presented in the early 1900’s. Thanks to his contributions, researchers could understand the behaviour of fluid streams running closely along surfaces. This knowledge is used extensively in aero- and hydrodynamic applications. In summary, the boundary layer theory states that the fluid velocity is equal to zero at zero distance to surface (NASA Glenn research Center), also shown in Figure 5.
2.5 Coandă effect

Named after the aerodynamics pioneer Henri Coandă. The Coandă effect is explaining the tendency of a fluid jet staying attached to the surface when passing over a convex surface, see Figure 6. This can either be advantageous or something to avoid, depending on the desired application.

2.6 Road conditions

The type of dirt that a vehicle is exposed to depends on the environment and differs greatly. Common road dirt includes dust, mud, salt, insects, rubber and tar from asphalt. In addition to these, the vehicle is exposed to different weather conditions, such as sun, rain, snow and ice.

The varying weather- and environmental conditions pose different challenges. For example, insects and tar, which contain protein and oil, stick harder to the surface than dirt, mud and salt. As explained in section 2.1, the use of detergents in solvents, such as ethanol, facilitates the removal of tougher dirt and works as an anti-freeze.

Moreover, in dry environments, such as sub-zero winter roads or dusty mines, the use of a liquid solvent can lead to an accelerated dirt accumulation after a cleaning cycle, due to the wet surface allowing dirt particles to stick better. In addition, because of the risk of freezing, liquid solvents cannot be used below a certain temperature, causing ice accumulation on the surface. Figure 7, shows a variety of dirt accumulated on vehicles. The top left image also shows how aerodynamics and distance to ground affects the degree of dirt accumulation, where locations closer to the ground and around wheels have a higher dirt accumulation.
2.6.1 Standard Test Dust

The standard test dust, ECE R45, is a fine particle mixture of silica sand, carbon dust and salt. It is made to resemble the common dirt on roads and is specified by regulations handed by the United Nations Economic Commission for Europe (UNECE), covering regulations about headlamp cleaners on wheeled vehicles (UNECE, 2010). The regulations require the standard test dust to be applied with a spray gun to the headlamp lens, followed by drying the mixture with hot air. Figure 8 shows the Standard Test Dust that was used for the tests in this report.

Figure 8. Standard Test Dust

2.7 Levels of autonomy

Autonomous driving or vehicle autonomy is describing a state when a vehicle can partially or fully control its driving capabilities without any input from a human driver. In Figure 9, the levels of autonomous driving are explained. The cleaning systems in the report have been developed with respect to a fifth level autonomous driving scenario, which means that the vehicle is expected to operate without a driver under all conditions.
2.8 Sensor technology

The autonomous driving technology is made possible by several sensors which record the environment around the vehicle. There are mainly three different sensors being used; camera, lidar and radar. These sensors are placed on several locations on the vehicle and have different functions.

The camera records moving images of the environment, thus recording what it “sees” and is depending on the light from the environment. Ambient daylight or artificial light from a lamp can provide the light a camera needs to generate these images. The camera provides a high resolution 2D representation of the environment, however, is limited when it comes to determining distances to objects.

The lidar, which stands for light detection and ranging, is a sensor that uses infrared light to determine distances to objects. The sensor sends out pulsed light waves which hits objects around the vehicle, and where the time difference for these light wavelengths to return to the sensor is converted into distance. The result is a point-cloud 3D-representation of the environment.

The radar, which stands for radio detection and ranging, is based on the same technology as the lidar, with the difference of using radio waves instead. The radar has a more spatial resolution than a lidar and is used to detect moving objects rather than creating an accurate 3D-representation of the environment.

The collected data of the afore-mentioned sensors is fused together to create an accurate depiction of the environment, which then, via a control unit is used to engage the throttle, brakes or steering, see Figure 10.
Different sensors require different operational environments and are differently affected by potential disturbances. An article points out the complications of the different sensors in different weather conditions (Stock, 2018), which matches with statements gathered from the industry partner regarding the same matter. Table 1 below shows a list of how the sensors function in different environments and how they are affected by different disturbances.

**Table 1. Sensor working environment and disturbances**

<table>
<thead>
<tr>
<th></th>
<th>Camera</th>
<th>Lidar</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working in daylight</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Working at night</td>
<td>Yes, with headlights on</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Disturbance from bad weather</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Disturbance from sensor blocking (dirt, water, etc.)</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 1 shows that the sensor that works best in most situations is the Radar, which is partially why the cleaning of these sensors is not investigated in this report. The lidar and the camera are both sensitive to dirt accumulation and need cleaning systems to function properly. While the lidar transmits and receives light invisible to the eye, the camera needs an external light source. Daylight during the day and light from the headlights during night is necessary, which also requires the headlights to stay clean.

A difficult question to answer was when and how often the sensors need to be cleaned. This depends on many factors. When it comes to how often, Söllner et al. (2012) mentioned that their study on headlamps revealed that dirt accumulation was more severe during the winter months than during the summer. Moreover, the type of dirt was tougher during summer and cleaning less frequently makes the dirt stick more to the lens. Another article states the same issue, where certain dirt needs to be removed within seconds, since it otherwise gets too tough to remove (Holmes, 2019).

When it comes to determining the threshold at which a sensor is too dirty and needs cleaning, there are more software-based considerations involved. To this point, there is no value to when the visibility of the sensor becomes too bad and cleaning needs to be initiated. Hence, there is also no definite value saying what is “clean enough”. This has been confirmed through the expert interviews, as well as an article expressing the same difficulty (Holmes, 2019). This adds some complications in determining the lowest acceptable cleaning performance.

The cleaning of the sensor lens, also called fascia, can temporarily blind the sensor in case the cleaning requires to obstruct the sensor’s field of vision. If the cleaning can be performed out of the field of vision, the sensor could still function during cleaning. However, redundancy can be achieved with multiple sensors overlapping, making it possible for another sensor to temporarily cover for the blinded sensor during a cleaning cycle.
2.9 Sensors on an autonomous vehicle

Approximately twenty sensors, including cameras and lidars, could be needed in a truck to achieve level five autonomous driving. These sensors could be positioned low and high, front and rear, as well as on the sides, see Figure 11. Therefore, the sensors can be differently impacted by dirt accumulation depending on where they are positioned.

Figure 11. Example locations of some of the sensors on a Scania haulage truck (Scania CV AB, 2016)

2.10 Cleaning of camera, lidar and headlamps

The sensors on an autonomous vehicle differ in shape and properties. Consequently, finding an efficient cleaning solution that works for all types of devices will be a challenge. Camera lenses are usually circular and relatively small, while lidars seem to be more rectangular and larger. Headlamps are biggest in size and they come in different shapes.

Figure 12. Left to right; Audi A8 Lidar sensor, Ford F150 park assist camera, Scania truck headlamp

2.11 State of the Art

This chapter covers an analysis of the current market of sensor cleaning systems, including patents, scientific publications and industrialised products.

2.11.1 Market analysis

Camera cleaning systems

There are currently several camera cleaning systems on the automotive market, mostly used for parking-aid cameras, such as the rear-view camera. The majority of these cleaning systems comprise of a fixed high pressure water nozzle sitting close to the edge of the camera lens, aimed at the lens with a low impact angle. This type of cleaning system is durable and cost-efficient, and uses relatively low amount of fluid in comparison to a headlamp cleaning system due to the small camera lens area. Figure 13 shows a static cleaning nozzle spraying washer fluid onto the camera lens. There are many camera cleaning suppliers with static nozzles, such as dlhBowles, Ficosa, Valeo and Continental (Ficosa International S.A., 2019) (Valeo, 2017)
These camera cleaning systems have a fluid consumption range of around 3-12 ml per cleaning cycle.

In addition to these static camera cleaning systems, there are also some solutions which use a telescopic nozzle but also some more unconventional solutions. Mostad Mekaniske is a norwegian supplier which uses a static nozzle together with an elastic string which deems as a wiper and rotates over the top of the lens, see Figure 14. Moreover, Orlaco has an all-time-vision rear-view camera, where the cylindrical lens rotates and gets cleaned with the help of a static nozzle and a wiper blade. (Direct industry, 2019)

Lidar cleaning systems
In comparison to camera cleaning systems, there are fewer suppliers of lidar cleaning systems, however the solutions differ more between them. The use of a static nozzle, as in the camera cleaning systems, provides challenges since the lidar lens is substantially bigger than the camera lens, thus making it harder for a nozzle to cover the whole surface. Valeo has a telescopic nozzle which extends out from the lens to get a larger fluid impact angle as well as cover the whole sensor lens surface, see Figure 15 right. Moreover, Waymo has a lidar cleaning system for their top-mounted lidar comprised of static nozzles together with wiper blades, see Figure 15 left. When the washer fluid has been sprayed onto the lens, the wiper blades flip up against the fascia, followed by a full rotation around the lens cleaning off any dirt. When the cleaning is over, the wiper blades fold down into their default position. In addition to the above-mentioned cleaning systems with movable components, there are also static lidar cleaning systems, similarly to the camera cleaning systems mentioned in the previous section.
Audi has a lidar cleaning system with two telescopic nozzles on each side of the fascia, which extend and spray washer fluid onto the fascia. The telescopic nozzles, similarly to the Valeo telescopic nozzles, extend solely through the fluid pressure which pushes the telescopic arm out. Figure 16 shows the Audi lidar with its telescopic nozzles in retracted position. The Lidar unit is encapsulated by an aluminium case with a plastic front fascia. Aluminium helps with the cooling of the electronics inside and adds robustness as well as protection from moist because of low permeability. On the other hand, the fascia needs to be penetrable for the laser light passing through.

**Headlamp cleaning systems**

The headlamp cleaning systems currently on the market consist mostly of telescopic nozzles with the same functionality as the previous mentioned ones in this report. Due to the headlamp having the largest fascia of all the sensors, the telescopic arms are relatively large in comparison to the ones used for a lidar or camera. In most of the cases the telescopic arm has two nozzles on the tip, which are directed towards different surfaces of the fascia to cover the majority of the fascia.

The Scania headlamp cleaning system can be seen in action in Figure 17 and has the same functionality as the description above. The extended telescopic arm with two nozzles on the end, each of them spraying washer fluid onto the lens of the headlamp. The headlamp cleaning system is required to perform 50 cleaning cycles before the fluid tank needs refilling.
Alternative cleaning systems

In addition to the cleaning systems investigated in the road transportation sector, other industries were analysed as well as and several alternative cleaning systems were found. It was found that boats and CNC cutting machines use a spinning window, where a circular window rotates in high speed and through its centrifugal force makes it impossible for any fluid or dirt to stick onto the surface. Figure 18 shows a spinning window for a CNC cutting machine, where it clearly shows that the portion of the glass which is spinning has a clear view through, while the surrounding window has poor visibility due to the build-up of cutting fluid.

Another investigated sector was the surveillance camera sector. There are many outdoor surveillance cameras, situated on buildings, train stations, highway roads and many more. However, many of these cameras do not have an active cleaning system and instead use build geometry, such as a round lens facing down, as well as placement, i.e. protected under a building, to prevent dirt from accumulating. If cleaning should be necessary, these cameras are cleaned manually. The surveillance cameras also have the advantage of not being in an equally dirty operating environment than a vehicle-based camera which is placed closer to the ground where dirt is stirred-up from the movement of the vehicle. Despite this, some cameras with a wiper cleaning system were found as well as a camera with a wiper- and fluid system. Figure 19 shows this camera which has a nozzle that sprays washer fluid onto the fascia which then rotates and gets cleaned by a static wiper placed in the back portion of the fascia, out of way of the camera image.
2.11.2 Patents

Twenty patents have been investigated with a selection of search terms (PatentList). Currently, the topic of sensor cleaning is hot, the number of patents introduced is rising and reputable companies are involved, such as Robert Bosch, Valeo, Continental, Uber, Ford, and others. The types of cleaning solution can be categorised in a few different groups; water, air, water and air, water and wiper, as well as dirt prevention. The majority of the patents are using washer fluid in some innovative way rather than finding alternative methods to clean without water. Some inventions claim that air can be used to keep the surface clean. A list of found patents can be seen in Figure 20.

<table>
<thead>
<tr>
<th>Patents</th>
<th>Public date</th>
<th>Applicant</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>US2017/0313286</td>
<td>2017</td>
<td>Fico Transpar</td>
<td>water &amp; air</td>
<td>2-in-1 water + air</td>
</tr>
<tr>
<td>US2018/0015908</td>
<td>2018</td>
<td>Uber Tech.</td>
<td>water &amp; air</td>
<td>2-in-1 water + air</td>
</tr>
<tr>
<td>WO2014/010579</td>
<td>2014</td>
<td>Hidekazu Miyoshi</td>
<td>water &amp; air</td>
<td>2-in-1 water + air</td>
</tr>
<tr>
<td>US20160339875</td>
<td>2016</td>
<td>Asmo</td>
<td>water &amp; air</td>
<td>telescopic 2-in-1 water + air</td>
</tr>
<tr>
<td>WO201859771</td>
<td>2018</td>
<td>Valeo</td>
<td>water &amp; air</td>
<td>telescopic 2-in-1 water + air</td>
</tr>
<tr>
<td>US20180339313</td>
<td>2018</td>
<td>dlhBowles</td>
<td>water</td>
<td>pressurized water system</td>
</tr>
<tr>
<td>US2013/0146577</td>
<td>2013</td>
<td>Continental</td>
<td>water</td>
<td>pressurized water system</td>
</tr>
<tr>
<td>WO2017202562</td>
<td>2017</td>
<td>Valeo</td>
<td>water</td>
<td>water system with &quot;unlimited&quot; water</td>
</tr>
<tr>
<td>WO2018188822</td>
<td>2018</td>
<td>Continental</td>
<td>water</td>
<td>water system with &quot;unlimited&quot; water</td>
</tr>
<tr>
<td>US20170313287</td>
<td>2017</td>
<td>Kautex</td>
<td>water</td>
<td>flipping arm with water spray</td>
</tr>
<tr>
<td>US2018/009418</td>
<td>2018</td>
<td>NextEV</td>
<td>water &amp; wiper</td>
<td>exposed/non-exposed state sensor</td>
</tr>
<tr>
<td>GB2560639</td>
<td>2018</td>
<td>Ford</td>
<td>water &amp; wiper</td>
<td>contactless (air+water) and wiper</td>
</tr>
<tr>
<td>US2002/139394</td>
<td>2002</td>
<td>HP</td>
<td>water &amp; wiper</td>
<td>wipers on lens rotating</td>
</tr>
<tr>
<td>US 2018/0170319</td>
<td>2018</td>
<td>Ford</td>
<td>water &amp; wiper</td>
<td>similar to above</td>
</tr>
<tr>
<td>US2016/0121855</td>
<td>2016</td>
<td>Waymo</td>
<td>water &amp; wiper</td>
<td>water and foldable wipers</td>
</tr>
<tr>
<td>US20170210351</td>
<td>2017</td>
<td>Ford</td>
<td>water &amp; wiper</td>
<td>swirling elastic membrane and water</td>
</tr>
<tr>
<td>DE10012004</td>
<td>2001</td>
<td>Robert Bosch</td>
<td>air</td>
<td>dirt prevention through pressurized air</td>
</tr>
<tr>
<td>WO2018130610</td>
<td>2018</td>
<td>Connaught</td>
<td>air</td>
<td>continuous cleaning through air stream</td>
</tr>
<tr>
<td>WO2016/045828</td>
<td>2016</td>
<td>Valeo</td>
<td>prevention</td>
<td>air pillow</td>
</tr>
</tbody>
</table>

Figure 20. Patent search list

2.12 Nozzles

A nozzle is used to control the direction and characteristics of a fluid flow when the fluid exits a closed path. The opening of the nozzle, also referred to as orifice, increases the fluid speed and breaks it into drops. Depending on the geometry of the orifice, various spray patterns can be achieved such as; conical spray, flat spray and mist spray, see Figure 21.
2.13 Durability
Life expectancy of mechanical joints is depending on the design. Robustness and durability is measured subjectively by the number of systems and parts that need to interact. Large translational movements is considered prone to get stuck compared to than short rotational motions.

2.14 Sealing and ingress protection
Gaps, pockets and slots are common places for dirt accumulation. This can be prevented by adequate sealing, especially if an electronic device is expected to be operated in harsh environments. Ingress Protection, also known as IP classifications, determine how well an object is protected against solids in different sizes and liquids in various amounts, pressures and temperatures, see Figure 22.
Seals are malleable materials such as polymers or soft metals placed between parts, lids and covers to keep tight. Static seals can come in many different shapes and sizes as well as O-rings. Dynamic seals can be radial seals around shafts used e.g. in electric motors or bearing units, see Figure 23. In addition, axial seals are typically used in hydraulic cylinders, to prevent hydraulic fluid from escaping, as well as keeping dust and debris out. In general, we could say that static seals are under less strain than dynamic ones since there is no major friction to deal with.

*Figure 23. Radial shaft seal (Flowup, 2017) (Khoshaba & Haralanova, 2016)*
This chapter describes the process and methods that were used in the research.

### 3.1 Double diamond

A design process is highly personal, complex and iterative. There are a multitude of popular process models, which are based on research and experience. The double diamond method represents a rough idea of how this process usually works out. Consisting of four different steps, the steps can be either diverging or converging. (Design Council, u.d.)

*Discover* – Gather information and learn about the field you are designated to work within.

*Define* – Condense and crystallize the challenge, make a problem statement and prioritise any product properties. What is possible? what is desired? In other words, create the project briefing.

*Develop* – Ideas and concepts generated, prototyped and tested in several iterations. Trial-and-error is natural and helps designers to refine ideas.

*Delivery* – Finalise and deliver a result, present the product with its details.

Figure 24 shows an illustration of the Double Diamond method with the different stages marked.

![Double Diamond Method](image)

*Figure 24. Double Diamond (Design Council, u.d.)*

### 3.2 Basic Design Cycle

An iterative process consisting of five stages which yields an intermediate outcome upon the consecutive stage builds on. The stages are: Analyse, Synthesise, Simulate, Evaluation, Decision. One cycle is complete after finishing all five stages, Figure 25. There is room for trial-and-error and the cycles can be repeated until a desired level of “ripeness” have been achieved (van Boeijen, Daalhuizen, Zijlstra, & van der Schoor, 2013, ss. 18-19).
3.3 Expert interviews
Interviewing individuals with knowledge in their respective field of expertise is a quick and simple way of accessing concentrated information. Although any such information needs to be methodically verified with tests or research, it is an effective way to find which path to go after in your research.

3.4 Internet search
Undoubtedly, the internet is an effective tool in the search for information. However, quicker and easier access does not always mean better results. Examining sources critically and sticking to reliable institutes, scholarly databases and reputable industry partners as much as possible increases the quality of the work.

3.5 Literature study
Academic publications such as thesis reports and journal articles, among other formats, were used. Research papers as well as technical writings from industry leaders lays a foundation to build the study on.

Peer-reviewing is when members of a related research community evaluates the quality of a scholarly publishing. This is a widely accepted method of formal communication between science workers. The history goes back to Henry Oldenburg (1618-1677) and the first peer-review of his publication “Philosophical Transactions of the Royal Society” in 1665 (Elsevier, u.d.).

3.6 Collage
A collage is a collection of images often presented physically on a board. The choice of content is up to its user and can be anything representing, colours, shapes, textures and functions. The purpose with a collage is to present the current state of the situation or setting a mood which inspires the designer. The method is preferably used in the early stages of concept generation (van Boeijen et al., 2013, ss. 92-93).
3.7 How-Tos
How-Tos are the challenging questions any concept and designer need to answer. In other words, how-tos are problem statements created by various stakeholders or product life phases. An example is “How do I keep vegetable fresh during transport the store location?” The way of formulating questions like this challenge the mind to reflect and reason more accurately. (van Boeijen et al., 2013, ss. 126-127)

3.8 Brain drawing/-writing
This method is comparable to brainstorming. A fundamental difference in the process is the “6-5-3 method”, a way of extracting ideas, and it proceeds as follows.

First, a problem is defined and each member of the group of six, sitting around a table, is handed a pen and a paper. They are asked to write down or draw three ideas in five minutes of time. After one cycle of idea generation members are asked to pass their papers to someone sitting next to them. The cycle is repeated as many times as the number of members in the group. Finally, an evaluation stage is performed. Ideas can be categorised as wanted and overlapping ones may be combined. The result is an inventory of ideas (van Boeijen et al., 2013, ss. 118-119).

3.9 C-box
A design process can many times get fuzzy and difficult to follow. It is certainly important to organise and visualise your work at times when decisions need to be made. The C-box is a way of evaluating ideas visually through ordering them in degree of innovation and feasibility (van Boeijen et al., 2013, ss. 142-143). Figure 26 shows an example of the C-box.

![Figure 26. Illustration of C-box](image)

3.10 Datum method (Pugh’s decision matrix)
This evaluation method breaks down the properties of an idea into smaller elements, namely design criteria, and makes it possible to rate them at the partial level. One concept in the group of concepts is chosen as reference, which can be changed as you the design criteria is up to the designers to choose, some of them can be as follows: feasibility, modularity, scalability, durability etcetera.
After going through all criteria, the result for each idea is summed up and compared with other ideas in the matrix. This method is typically used after a brainstorming session (Pugh, 1981) (van Boeijen et al., 2013, ss. 146-147). Figure 27 shows an example of a Pugh’s evaluation matrix.

![Figure 27. Pugh's evaluation matrix](image)

### 3.11 Design drawing

Whether you are used to or not, at some point in a design project explaining requires paper and pen, which is also called sketching, see Figure 28. Design drawing is a powerful way of communicating ideas quick and easy with little resources spent, in contrast to CAD and computer renderings. Therefore, this method is very well suited whenever a basis for discussions and decisions is needed. Of course, the level of detail is can be kept low or high depending on the need. The efficiency of the method is highly relying on the skill of the sketcher. Higher drawing skills makes the process run more efficiently and minimises misconceptions.

If a design is too intricate or better explained in the three-dimensional space, usually design drawing requires too much effort. Defining your purpose before sketching and knowing when not to choose design drawing is important. (van Boeijen et al., ss. 158-159)

![Figure 28. Design Drawing](image)
3.12 Weighted objectives
Knowing which concept to choose can be a difficult task. The Weighted evaluation matrix is aiming to make this decision process less complicated and biased. By defining design criteria, just as in the Pugh’s matrix explained in section 3.10, we can evaluate the concepts step by step and answer one question at a time. The difference with this method is that the importance of a criteria is taken into consideration by assigning a value, a higher value equals more importance. The concepts are then evaluated and given a performance value within a specific criterion. When all concepts have been individually evaluated the performance, value is multiplied by the weight value and noted as a sub score. Finally, all sub scores per each concept are summed and compared against each other, see Figure 29.

The tricky part is picking a winner, not only by looking at the score but making a holistic judgement about the result. This could mean examining the trustworthiness, quality and quantity of your information given at the time you set your values. This method suits a stage in your project where you only have a few selected concepts to deal with (van Boeijen et al., 2013, ss. 150-151).

![Figure 29. Weighted objectives matrix (van Boeijen et al., 2013, ss. 150-151)](image)

3.13 Agile processes
In 2001 a constellation of software developers announced a manifesto (Beck, o.a., 2001). A new working principle, which is considered as the opposite alternative to the “Waterfall model”, a more classic view of project. The Waterfall model means a step by step process on the project planning level which suggests finishing a life cycle step in its entirety before proceeding with the next. In agile processes, the various activities are processed in a more integrated manner, e.g. testing is done iteratively. On the contrary, the waterfall model requires the design phase to be finished before moving over to the testing phase.

3.13.1 Scrum
While Agile is a set of values and principles, scrum is a framework for teams to work and reach their goals together. It comes with a set of rules, roles and terminology. The name comes from “scrummage”, a terminology used in the Rugby sport. Scrummage or scrum happens when the
The game has to restart after an event and the players of the opposite teams take position around the ball to execute a team effort to gain possession of the ball. Commonly, the scrum repeats a few times and the stronger team advances.

The inspiration from the sport sets the philosophy of Scrum in project work, breaking down a project into manageable pieces and solving one problem at a time. The word Scrum in product development context was initially introduced by a Professor of management Practice and a professor in organisational theorist (Takeuchi & Nonaka, 1986) and has since then been developed by numerous people into what it is today (Krishnamurthy, 2012).

Although not fully adopted, Scrum tools have partially been used in this project, more exactly, activities such as backlog, sprints, demos and retrospective.

### 3.14 The project processes

The overall project process is based on the Double Diamond process, see 3.1. Figure 30 shows the adapted Double Diamond process that was used in this thesis, along with the timeline shown in Figure 31.

**Figure 30. Double diamond and basic design cycle combination**

**Figure 31. Timeline of thesis**
This chapter presents the results of the pre-study, followed by the results from the three design cycles. The three design cycles contain a development phase, as well as an evaluation phase, along with the conclusion from each design cycle.

4.1 Pre-study
This section presents the results of the pre-study, as well as the findings from the background research, which together formed the conclusion of the pre-study.

4.1.1 Audi sensor benchmarking
As a way of establishing a reference the cleaning performance of the LiDAR cleaning system an Audi automobile with autonomous driving capabilities was benchmarked, see Figure 32.

![Figure 32. Audi A8L 2018 automobile (Raynal, 2018)](image)

The LiDAR is forward-looking and positioned approximately at bumper level. The level three autonomous driving function is activated by the driver, but the cleaning itself runs regardless of the autonomous driving being active or inactive.

Two relatively small telescopic nozzles, on each side, moves in a forward linear motion and sprays the fascia with washer fluid, see Figure 33. The second function of the washer fluid is to drive the telescopic mechanism which essentially is a hydraulic cylinder. The cleaning cycle is divided into two bursts, pre-wash and wash. The total cycle duration is approximately two seconds.
**Lab tests**
Dirt application and cleaning tests were performed using a standard test dust, see section 2.6.1. The dust was applied by first wetting the surface and subsequently blowing the dust onto the surface, trying to replicate the conditions and dirt accumulation caused by driving on roads. Although the system uses 50 ml/cycle, the cleaning performance is low. As seen in Figure 34, only a small sector of the fascia is cleaned by the spray.

![Figure 34. Audi A8 autonomous LiDAR cleaning system in action](image)

**Field test**
The system was tested on the road as well and the LiDAR unit was examined several times while driving on the roads, see Figure 35.
The cleaning system could keep the fascia clean, see Figure 36. However, the autonomous system was never used during the testing, instead, an ocular inspection of the fascia was done.

In conclusion, the Audi LiDAR does not have enough performance for a level five autonomous driving scenario. Although, good results were achieved in field tests, the consumption is too high. During the one-hour long testing, the washer fluid reservoir needed to be refilled once. Also, the kind of dirt accumulation encountered in the field test was not as difficult to remove as the standard test dust, used in the lab tests.

4.1.2 Air cleaning test
To evaluate the cleaning performance of compressed air, an air cleaning test was performed. Two tests were performed with a surface covered in the standard test dust; one test where the
dirt mixture was dried, and one where it was kept wet. The compressed air was sprayed at the surface with an air gun. Figure 37 shows the result of the test with the wet surface. The air managed to transport the dirt diluted water away from the surface, however, leaving small dirt particles behind.

![Figure 37. Air cleaning performance on wet surface](image)

In the test with the dried surface, the air was not able to efficiently break lose the dirt from the surface and transport it away, resulting in an even worse cleaning performance compared to the first test, see Figure 38.

![Figure 38. Air cleaning performance on dry surface](image)

In conclusion, cleaning with solely air will not be able to prevent dirt accumulation and is not able to obtain an adequate cleaning performance.

4.1.3 Conclusion of pre-study

A central conclusion from the background research was that cleaning systems which do not use cleaning solvents, for example air cleaning systems and hydrophobic surfaces, were not able to achieve a clean and unobstructed sensor fascia on their own. In other words, the need of a solvent during cleaning was found necessary.
The benchmarking of Audi’s lidar cleaning system revealed that the fluid consumption is 50 ml per cleaning cycle. Another leading supplier of high-pressure fluid cleaning systems was contacted, which have a static nozzle lidar cleaning system with a fluid consumption of 42 ml/cleaning cycle. These reference systems, when scaled up to 20 sensors, would require a tank of 50 litres if the previous mentioned 50 cleaning cycles before refill are required. This is not considered plausible. To this, the cleaning performance of the Audi system is insufficient on the test performed with the test dust. Although the test drive environment showed sufficient cleaning performance, harsher environments can be expected. The use of the standard test dust as a reference, also facilitates test comparison when performing tests later in the project, as well as goes in line with the UN regulations for approval of headlamp cleaners.

The development of camera cleaning systems has come further than the cleaning systems for the lidars. This is not unexpected, since the use of cameras on vehicles, such as rear-view cameras for park assist, is nothing new, whereas the use of lidars still is uncommon in comparison. In addition, the camera has an advantage of having a smaller fascia, which means that the fluid consumption, when scaled up to multiple sensors, does not consume as much as a lidar cleaning system.

Therefore, it was decided to focus more on improving and evaluating the lidar cleaning systems in this thesis. However, during development and evaluation, camera and headlamp cleaning systems will be included in the reflections.

### 4.2 Design parameters

As expressed in section 2.8, there is no definite value for how clean a sensor must be, nor is it possible to say how often it needs to be cleaned. Thus, to be certain that the cleaning will be enough, a fully clean fascia was requested. However, a 100% clean fascia is difficult to obtain and measure, which is why a margin of 10% was accepted, resulting in a requirement of a 90% clean fascia after one cleaning cycle.

Determining the fluid consumption limit of the cleaning system was a challenging task since, as explained in section 2.8 Sensor technology, there is no definite value of cleanliness. However, the industry partner has a requirement for their headlamp cleaning system which states a minimum cleaning capacity of 50 times before needing to refill the reservoir. In addition, the industry partner has agreed on the possibility of having a second reservoir, on top of the existing one which is used for the headlamp and windshield, which means an additional tank of 12 litres dedicated to sensor cleaning, see Figure 39.
According to section 2.9 Sensors on autonomous vehicles, a system of 20 sensors is required, divided in lidars and cameras. To leave some margin, a worst-case consumption was considered. Thus, regardless of a lidar or camera, it was decided that a 12-litre tank should last for 50 cleaning cycles for each sensor of the set of 20 sensors. According to the calculation, this results in a fluid consumption limit of 12 ml per cleaning cycle.

In conclusion, the cleaning system must achieve a 90% clean fascia after one cleaning cycle, and not using more than 12 ml of washer fluid while doing so.

Fluid consumption is not the only issue when scaling a system of 20 sensors on a heavy vehicle. Additional parameters regarding a system perspective, more qualitative than quantitative, are considered during the evaluation of the cleaning systems. Table 2 presents the definition of each evaluation criteria used in the Pugh’s and the weighted evaluation matrix and shows on what terms the ideas were evaluated.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning performance</td>
<td>The presumed cleaning performance of the cleaning system</td>
</tr>
<tr>
<td>Durability</td>
<td>The ability to withstand failure in the system over time. The need of maintenance is penalized. Risk of failure rises with the number of components, moving components, friction interfaces.</td>
</tr>
<tr>
<td>Low sensor disturbance</td>
<td>The ability of the cleaning system to be out of the field of vision of the sensor at all times. Cleaning media or component in field of vision is penalized.</td>
</tr>
<tr>
<td>Low complexity</td>
<td>The state or quality of not being intricate or complicated. Low number of parts and conventional technique/mechanisms are rewarded.</td>
</tr>
<tr>
<td>Low use of limited resources</td>
<td>Limited resources are washer fluid, pressurized air and electricity, where the severity decreases in said order. Low use of these resources is rewarded. For example, the ability to use as little washer fluid as possible, to achieve a 90% clean fascia.</td>
</tr>
<tr>
<td>Highly scalable</td>
<td>The possibility to be changed in size or scale and keep function performance.</td>
</tr>
<tr>
<td>Highly modular</td>
<td>Part flexibility, possibility to be separated and recombine components. Large area free for mounting = better. Number of locations possible to mount on truck.</td>
</tr>
<tr>
<td>Highly compact</td>
<td>The smaller space occupied by the cleaning system the better. Bulkiness is also penalized.</td>
</tr>
</tbody>
</table>

4.3 **Design Cycle 1**

This chapter follows the ideation and evaluation of the ideas generated based on the previous research above.

4.3.1 **Ideation**

This section presents all the ideas which were generated with the help of brainstorming, brain drawing, the 6-3-5 method and How-tos.
Idea 1 with rotary bars, see Figure 40 left. Two bars, rotating around a vertically mounted shaft. The bars sweep over the fascia when the cleaning cycle is activated. A number of small nozzles integrated along the rotating bars and facing the fascia perpendicularly, sprays washer fluid while the arms rotate.

Idea 2, the rotary arm, has an arm connected to a shaft which rotates and allows the arm to swing back and forth when activated, see Figure 40 middle. The arm is positioned near the surface and has multiple nozzles on the inside, facing the surface of the fascia perpendicularly. Idea 3, the rotary fascia idea is shown in Figure 40 right. The sensor package sits on a stationary platform and a cylindrical fascia sits on top which can rotate around a vertical axis. A set of nozzles spray washer fluid on the facia while it rotates and rubs against a wiper blade.

Figure 40. From left; ideas 1, 2 and 3

Idea 4 with an air pillow is a preventative solution, see Figure 41 left. A continuous stream of air is directed inside a cavity which the lidar sits in. The air can i.e. be supplied by a pneumatic compressor of the vehicle.

Idea 5, the telescopic bar, has a bar with nozzles positioned perpendicularly near the surface, see Figure 41 middle. The bar is joined with two hydraulic pistons which are moving vertically along the sides of the fascia.

Idea 5, the rotary cover is shown in Figure 41 right. It is like the Rotary arm, but with a large rotating cover, which adds extra protection. Inside the rotary cover, there is a wiper blade and nozzles facing the fascia perpendicularly.

Figure 41. From left; ideas 4, 5 and 6

Idea 7, the fluid cascade is made of a cylindrical fascia rotating around a horizontal axis, see Figure 42 left. A small cavity below and near the fascia is filled with washer fluid. An air nozzle stays submerged in the liquid and, when activated, pushes liquid up on to the surface to clean while the fascia turns.

Idea 8, the fluid diversion ring consists of multiple nozzles located close to the periphery of a round fascia and facing forwards, see Figure 42 middle. The nozzle spray is redirected by a J-profile ring on the outskirt of the facia.

Idea 9, the telescopic ring is a socket, with nozzles embedded inside, which extends by moving in a linear forwards motion, see Figure 42 right. This provides the spray a bigger angle of attack and a good impact protection at the same time.
Figure 42. From left; ideas 7, 8 and 9

Idea 10, the moving sensor has the same working principle as in the Telescopic ring, but the sensor moves inwards instead, and the outer ring is stationary, see Figure 43 left.

Idea 11, the linear spray bar and wiper idea, has a bar running in a vertical linear motion, see Figure 43 middle. The bar has nozzles and wipers facing the fascia surface and moves along with the bar.

Idea 12, the linear spray bar, is similar to the previous idea but without the wiper blade, see Figure 43 right. The nozzles are positioned perpendicularly.

Figure 43. From left; ideas 10, 11 and 12

Idea 13, the rotary fascia and fluid catchment, is shown in Figure 44 left. A cylindrical fascia rotating around a horizontal axis, inside a housing with an opening forward. Inside the housing, nozzles are placed perpendicularly and facing the fascia. A wiper blade is included too.

Idea 14, the tilting fascia idea, is shown in Figure 44 right. The sensor unit and fascia is joined and rotates together to wipe clean against wiper blade. Nozzles are positioned in the periphery of the front side.

Figure 44. From left; ideas 13 and 14

Idea 15, the fluid vacuum ring idea, is shown in Figure 45 left. Same as the fluid diversion ring idea, but with a waste liquid catchment system using vacuum. The nozzles are also embedded inside the J-profile of the outer ring.

Idea 16, the fluid vacuum strip, is shown in Figure 45 right. The nozzles are positioned along a horizontal line under a cap above the fascia. Nozzles are facing the fascia with a small angle of attack. At the bottom there a waste liquid catchment system, using vacuum.
4.3.2 Resource-efficient fluid consumption

Three different ways have been identified to use less washer fluid than the reference systems. The first one is based on the technical aspects of spraying the washer fluid. This refers to the spray angle, the velocity of the washer fluid and the distance between the nozzle and the fascia. The second way is based on reusing the washer fluid for several cleaning cycles until it is too dirty, upon which the dirty fluid is discarded. The third way is grounded in a recycling system which collects the dirty fluid after a cleaning cycle, as well as a filter system which cleans the fluid and puts it back into the washer fluid tank.

Another way of using limited resources more resourceful, would be to have several cleaning modes. The first cleaning mode uses, as an example, only air. If cleaning with air does not improve visibility, cleaning mode two is activated, which uses washer fluid.

4.3.3 Evaluation

The C-box arranged the ideas in a line ranging from not innovative- and easy solutions to very innovative- and difficult solutions, see Figure 46. None of the ideas resulted in the top left corner, very innovative and easy, which coheres with the conclusion made in Table 4, which showed that the solutions generally become more complex as functionality increases. On the bottom right corner, not innovative and difficult, the two last-mentioned ideas are found due to the difficulty of integrating a water catchment and filtration system.

The level of innovation was determined by the novelty of the technology as a whole or if the technology is already implemented in the same or other markets. The feasibility was determined based on the complexity of the idea, compactness, number of systems, and more.
The 16 ideas were also evaluated with three Pugh’s evaluation matrixes, each matrix referencing one of the following cleaning system: the Audi Lidar cleaning system, a static nozzle lidar cleaning system, and finally the Scania headlamp cleaning system. The static nozzle lidar cleaning system is similar to the system shown in section 2.11.1 in Figure 13, which is why this illustration was used when referencing this system henceforth. Table 3 shows a shortened version of the evaluation matrix referencing the Audi Lidar cleaning system, while all three full-length matrixes can be found in APPENDIX B. As a reminder, the definition of the different evaluation criteria can be found in Table 2 in section 4.2.

### Table 3. Pugh’s evaluation referencing the Audi Lidar cleaning system

<table>
<thead>
<tr>
<th>Reference: Audi Lidar cleaning</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning performance</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Durability</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Low sensor disturbance</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Low complexity</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Low use of limited resources</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Highly scalable/modular</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Highly compact</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$\Sigma (1) = 2, 3, 4, 2, 4, 5, 2, 3, 3, 3, 2, 0, 0, 0, 0, 0$

In all three matrixes, idea 5 scored a positive result due to the simplicity of the solution. However, the compressed air cleaning test above concluded that any idea based on solely air as cleaning media does not result in sufficient cleaning. Nonetheless, this does not rule out the idea completely, since it potentially can be combined with other ideas. Idea 8 also scored a positive result in two of the matrixes, due to its advantage of having solely static components.

The reference system which lead to the most minuses on the ideas was the static nozzle cleaning system. This was mostly due to the ideas being more complex and less durable, scalable and compact. The ideas which came out on top in that matrix were the ones that are assumed to be better in terms of dirt removal, low sensor disturbance and low use of limited resources, namely idea 13 and 14, which also happen to be the most complex ideas.

A common denominator for all three matrixes, on top of being better at dirt removal than the reference, is the different ideas’ potential of diminishing the usage of limited resources. Table 4 shows where the strengths and weaknesses of the ideas are, by adding the number of pluses and minuses received for each criterion. For example, 14 out of 16 developed ideas scored better in cleaning performance than the Audi lidar cleaning system. The table shows that an improved cleaning performance and low use of limited resources for most ideas result in a more complex and less durable-, scalable- and compact solution.

### Table 4. Overall strengths of the ideas

<table>
<thead>
<tr>
<th>Strengths of ideas</th>
<th>14/16</th>
<th>11/16</th>
<th>15/16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td>2/16</td>
<td>1/16</td>
<td>2/16</td>
</tr>
<tr>
<td>Low sensor disturbance</td>
<td>5/16</td>
<td>4/16</td>
<td>4/16</td>
</tr>
<tr>
<td>Low complexity</td>
<td>2/16</td>
<td>1/16</td>
<td>1/16</td>
</tr>
<tr>
<td>Low use of limited resources</td>
<td>15/16</td>
<td>11/16</td>
<td>15/16</td>
</tr>
</tbody>
</table>
4.3.4 Conclusion

To summarize, the findings from the different evaluation methods in loop 1, the concluding statement for each idea is shown in Table 5 below. The conclusion states the idea’s positives and negatives, as well as potential improvements and combinations with other ideas.

Table 5. Conclusion from the evaluation of the ideas

<table>
<thead>
<tr>
<th>Idea</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Idea has potential when combining mode-thinking of idea 6, wiper system of idea 11, as well as an air system. Thus, several modes can be applied: static air system, static fluid, and lastly rotating bar fluid system with added wiper on bar.</td>
</tr>
<tr>
<td>2</td>
<td>Fair cleaning performance; inline high-pressure nozzles positioned closely against the fascia is efficient, but the rotational motion does not cover the full surface = dirt residue build-up. No wiper blade = less abrasion on fascia. Fairly robust; needs an electric motor to drive the arm but rotational motion is good.</td>
</tr>
<tr>
<td>3</td>
<td>High cleaning performance due to wiper cleaning and potential to spray fluid without blocking the sensor field by moving nozzles to the side. Some question marks on how to seal between sensor package inside and the rotating fascia.</td>
</tr>
<tr>
<td>4</td>
<td>The spray angle and surface coverage ensure a fair cleaning performance. However, the direction of the telescopic arm (vertical) would lead to a fairly high space-occupation above the sensor, if compared with similar solutions using a rotational arm. Hence, this concept was discarded.</td>
</tr>
<tr>
<td>5</td>
<td>The compressed air cleaning test showed that solely air systems do not meet the requirements. However, using comp. air alongside a fluid system has advantages in terms of resource-efficiency. Thus, it has potential to be combined with other ideas.</td>
</tr>
<tr>
<td>6</td>
<td>The disadvantages of the cover (bulkiness, sensor blocking and durability/safety) overweight the advantages of the cover. The advantages of having several modes has potential, which is why a combination of idea 1 and 11 could be favourable.</td>
</tr>
<tr>
<td>7</td>
<td>Advantages of low fluid consumption, as well as never blocking the sensors. Similar to idea 13, however, due to concerns in terms of functionality and cleaning performance, this idea was discarded.</td>
</tr>
<tr>
<td>8</td>
<td>Advantages related to static components, such as simplicity, durability and scalability, made this idea favourable. Some question marks on cleaning performance and resource-efficiency on bigger surfaces. Potential combination with idea 5 and 15.</td>
</tr>
<tr>
<td></td>
<td>Description</td>
</tr>
<tr>
<td>---</td>
<td>-------------</td>
</tr>
<tr>
<td>9</td>
<td>The extending ring surrounding the sensor came with durability concerns due to dirt accumulation between the sensor and the ring. This could be avoided by having free-standing telescopic nozzles around the sensor, which would result in the same solution which exists on the market today. Hence, this idea was discarded.</td>
</tr>
<tr>
<td>10</td>
<td>Linear movement of the whole sensor package was deemed unnecessary complex, and durability concerns due to dirt accumulation between moving parts, are reasons to why this idea was discarded.</td>
</tr>
<tr>
<td>11</td>
<td>High cleaning performance due to fluid, wiper cleaning and surface coverage. Disadvantage of having a linear motion and sensor blocking with every cleaning cycle. Potential if multiple cleaning modes can be used and rotational movement can be implemented.</td>
</tr>
<tr>
<td>12</td>
<td>Disadvantage of having a linear motion and sensor blocking with every cleaning cycle. Due to the similarity to idea 11, which has an additional advantage through the wiper, this idea was discarded.</td>
</tr>
<tr>
<td>13</td>
<td>Advantages in terms of fluid consumption, no sensor blockage and cleaning performance have potential to outweigh the disadvantages in terms of the complexity of the idea. Question marks on sealing, cleaning inside or outside, and rotation.</td>
</tr>
<tr>
<td>14</td>
<td>Disadvantages, such as bulkiness and occupied space were reasons to why this idea was discarded.</td>
</tr>
<tr>
<td>15</td>
<td>Water catchment and central filtration has several disadvantages (complexity, maintenance, space limitation, etc.) which is why this idea was discarded. However, the nozzle configuration has potential, thus a combination with idea 8 could be interesting.</td>
</tr>
<tr>
<td>16</td>
<td>Water catchment and central filtration has several disadvantages (complexity, maintenance, space limitation, etc.) which is why this idea was discarded.</td>
</tr>
</tbody>
</table>

Together with the conclusions presented above, the ideas were combined and boiled down into three concepts, which is visually presented in Figure 47 below. Concept A is a combination between ideas 1 and 11, whereas concept B is a combination of ideas 3 and 13, and finally concept C is a combination of ideas 8 and 15.
4.4 **Design Cycle 2**

This chapter presents the further development of the three concepts that resulted from Design Cycle 1, namely Concept A, B and C. The further development includes defining and testing the concepts, and in the end evaluating the concepts against each other.

4.4.1 **Concept A**

Concept A consists of a rotating arm which navigates from the top down to the bottom of the fascia, see Figure 48. The arm has high pressure fluid nozzles arranged in a line, which spray the fluid with a small distance perpendicular to the fascia.

![Figure 48. Sketch of Concept A](image)

The testing phase also evaluates the use of a fluid- and wiper solution as an option to the high-pressure fluid nozzles. The arm is positioned above the fascia in default mode. This concept is based on the fluid impact force theory described in section 2.1, which states that the highest impact force is achieved when the fluid hits perpendicularly to the surface, thus using the fluid more efficiently.

**Testing concept A**

The testing phase of concept A consists of verifying that a 90% clean fascia can be achieved within the fluid consumption limit of 12 ml/cleaning cycle, as described in section 4.2. The full test report can be found in APPENDIX C.

The hypothesis was that the high-pressure fluid arm solution would use more washer fluid than the wiper arm solution, since the high-pressure fluid needs to dissolve, break-up and transport...
the dirt. The wiper arm solution, however, only needs the fluid to dissolve the dirt, while the wiper blade breaks up and transports the dirt.

**High pressured fluid arm**

The fluid consumption depends on the type of nozzle, the quantity of nozzles next to each other on the arm, the spray angle, the system pressure and the distance of the nozzle to the fascia. To find the nozzle configurations with a fluid consumption within 12 ml/cleaning cycle, a MATLAB-script was created which resulted in three different nozzle configurations.

Table 6 shows the cleaning results of the tests performed with the three different nozzles on a fascia covered in ECE-R45 standard test dust. The first row shows the tests performed with one 0200 nozzle which resulted in a 90% clean fascia strip at a cleaning cycle of 1 second. The same test with a cleaning cycle of half a second resulted in a fascia strip which was less than 90% clean, thus not successful. The following tests with the 0100- and 0060 nozzle and with a cleaning cycle of 1 second also resulted in a 90% clean fascia strip, and at the same time with a lower fluid consumption.

*Table 6. Cleaning performance of high pressured fluid*

<table>
<thead>
<tr>
<th>Nozzle configuration</th>
<th>Cleaning cycle: 1s</th>
<th>Cleaning cycle: 0.5s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle 0200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to fascia:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption: 12,0 ml/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s @ 2.0 Bar @ 4 Nozzles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid consumption:</td>
<td>12 ml</td>
<td>6 ml</td>
</tr>
<tr>
<td>Cleaning performance:</td>
<td>OK</td>
<td>Not OK</td>
</tr>
</tbody>
</table>

| Nozzle 0100          |                    |                      |
| Distance to fascia:  |                    |                      |
| 10mm                 |                    |                      |
| Consumption: 10,3 ml/|                    |                      |
| s @ 2.0 Bar @ 7 Nozzles |               |                      |
| Fluid consumption:   | 10.3 ml           |                      |
| Cleaning performance:| OK                 |                      |
Nozzle 0060  
Distance to fascia: 10mm  
Consumption: 6,5 ml/s @ 2,0 Bar @ 7 Nozzles

Fluid consumption: 6,5 ml  
Cleaning performance: OK

Fluid consumption: 3,3 ml  
Cleaning performance: Not OK

This concluded that the lowest fluid consumption with the high-pressured fluid arm is equal to 6,5 ml/cleaning cycle. This can be achieved with seven 0060 nozzles next to each other, at 10 mm from the fascia, at a system pressure of 2 bar, and a cleaning cycle of 1 second.

**Fluid- and wiper arm**

The minimum fluid consumption when using a fluid- and wiper arm is derived from the results of the tests performed for concept B, which also uses a fluid- and wiper system. It is recommended to read the test results of concept B to fully understand the conclusions made here.

The tests in concept B concluded that the fluid consumption can be as low as 5 ml per cleaning cycle to obtain a 90% clean fascia. However due to issues concerning dirt accumulation within the geometry of concept B, the conclusion was that more fluid was needed to have a self-cleaning system. Nevertheless, this is not an issue for the fluid- and wiper arm in concept A. Dirt accumulation surrounding the fascia does not affect the functionality or durability of the system and is dealt with like any other dirt accumulating on the outside of the vehicle, namely either washed away in rainy weather or in a car wash. Therefore, an open system like Concept A, does not need extra fluid to self-clean the system like concept B, which is why the minimum fluid consumption is equal to the previously mentioned 5 ml per cleaning cycle, which is the amount needed to obtain a 90% clean fascia.

**Conclusion concept A**

The tests to verify the cleaning performance and fluid consumption of concept A revealed that either cleaning option, high pressured fluid or fluid- and wiper, show successful results. Thus, it was decided to go forward with both concepts. Hence, concept A was divided into concept A1, with a high pressured fluid arm, as well as concept A2, with a fluid- and wiper arm. Concept A1 has a minimum fluid consumption of 6,5 ml, while concept A2 has a minimum fluid consumption of 5 ml per cleaning cycle.

**4.4.2 Concept B**

The concept consists of a stationary sensor encapsulated by a rotating cylindrical fascia which is sustained by a housing, see Figure 49. The fascia can rotate around its axis and rubs against a wiper blade located at the highest point of the fascia. A nozzle in the vicinity of the wiper blade delivers washer fluid to the wiper blade when cleaning is activated.
As the fascia rotates the liquid spray is applied and the dirt wiped off by the wiper blade. Waste liquid is disposed downwards with the help of the gravity. The fascia is motorized by an electric motor and activated by a control unit when needed, the washer fluid is delivered by a central pump at low pressure, ideally atomised and distributed evenly over the fascia surface in the axial direction.

**Testing concept B**

The testing phase of concept B included elaborating the minimum fluid consumption of the system. The hypothesis is that a fluid- and wiper system requires the least amount of fluid from the different cleaning principles, since the wiper blade breaks up and transports the dirt, rather than the fluid doing that.

The test was performed using a camera found in Scania’s accessories library, which similarly to concept B has a rotating fascia and wiper blade, however with a fascia half the size of the previously specified 90 mm. Figure 50 shows how the test was performed.

The wiper blade is very effective and wiped off the dirt with the slightest use of liquid. Even with no liquid applied the wiper managed to clean successfully, however it was found that the wiper blade was still wet from previous tests upon further examination. After a few test cycles the dirt started accumulating at the wiper blade, see Figure 51. Over time, this can clog the system, cause premature wear on the wiper blade and lens, thus lowering the cleaning performance.
Consequently, it is important that dirt accumulation is prevented, which can be solved by distributing the spray partially over the wiper blade, which not only cleans the fascia but also keeps the wiper blade and its surroundings clean.

The tested ATVC camera has a width of 45 mm, while the design parameters were set for a fascia with a width of 90 mm. Thus, two mist nozzles are required for the use in concept B, which would result in twice the fluid consumption. However, the test concluded that the minimum fluid consumption was not driven by the amount needed to obtain a 90% clean fascia, it was rather driven by the necessary amounts of liquid needed for preventing the dirt accumulation within the enclosure of concept B.

**Conclusion Concept B**

Thus, the minimum fluid consumption is equal to the fluid needed to have a self-cleaning system, which is difficult to determine. However, it can be solved by turning the nozzles partially towards the wiper blade and optimizing flow will theoretically help. Other factors such as, position of wiper blade, avoiding pockets and optimizing the geometry around the wiper is advised. These factors need to be further elaborated and tested. In comparison with the other tests performed, it is however considered possible to use a maximum of 10 ml/cleaning cycle, to, on top of cleaning the fascia, achieving a self-cleaning system.

**4.4.3 Concept C**

Static liquid- and air nozzles located around the edge of the fascia, distributed in a certain configuration. Two sets of nozzles, aimed against each other shoots out the washing fluid and creates a wave front located on the surface of the fascia, see Figure 52. The wave front is in a turbulent state and hypothetically helps with cleaning of the surface more effectively.

The timing and pressure is governed by a control unit in such a way that the position of the wave front can be moved in a controlled fashion, hence establishing a sweeping effect allowing the wave front to theoretically travel over the full fascia. Ideally, the pressure of one side is decreased as the opposite side is increased, consequently allowing the wave front to be moved, much like the behaviour of a tug of war.
Figure 52. Sketch of concept C

Testing concept C
The testing phase of concept C included more than solely verifying the fluid consumption. Firstly, tests had to be performed to verify if the wave front has a cleaning effect, as well as tests to how the wave front can be moved up and down the fascia.

The hypothesis was that the turbulent zone where the two fluids collide result in a friction zone on the surface which removes the dirt. The other hypothesis was that the wave front can be moved up and down by increasing the pump power output of the top nozzles while lowering the bottom ones, and vice versa.

Moving the wave front up and down
Moving the wave front was possible by changing the pump power output. However, with increasing power, the distortion of the shape of the wave font increased as well. Therefore, controlling the wave movement was not successful. Also, the range of movement is limited, meaning that the wave front could not reach the perimeter of the nozzle, which means that the fascia can only get partially cleaned. Figure 53 left shows the position of the wave in the center of the fascia. The centre and right image shows the distorted wave front above and below the fascia, as a result of changing the pump power output.

Figure 53. Moving the wave front by changing pump power output

An alternative way to move the wave front was achieved by keeping the pump power output constant and changing the impact point of the nozzles instead. This would require e.g. a well-coordinated rotational movement of the nozzles, so that the incident angle of the nozzles meet at different locations over the fascia, see Figure 54.
Does the wave front have a cleaning effect?

This test was performed by creating a wave front in the centre of the fascia and evaluate the cleaning efficiency of the area on the fascia right behind the wave front, see Figure 55.

Figure 55 shows that the fascia is only partially cleaned and that the zone where the opposing sprays are colliding is left uncleaned. In summary, the wave front does not have a cleaning effect. Another observation was that the liquid, after colliding, was splashing and separating perpendicular out from the surface or sideways direction across the side of the fascia.

Further development concept C

The results of the tests showed that the wave front did not have a cleaning effect, which is why this cleaning principle was discarded. However, the tests showed that rotating the nozzles ensures the fluid to hit the entire fascia. With the nozzles being on the side of the fascia, this had an advantage toward concept A, which is why concept C was updated, see Figure 56.
The revised concept consists of two opposed nozzles in either corners of the fascia, which spray fluid sequentially to prevent a wave front forming. The nozzles hit the centre of the fascia and then rotate inwards, thus changing the impact area on the fascia. To verify the fluid consumption, a test was performed. Figure 57 shows the result of the respective nozzle spraying into the centre of the fascia from the side. It showed that a 90% clean fascia could be achieved with the 0390 nozzle at fluid consumption of 12 ml/cleaning cycle.

**Conclusion concept C**

The revised concept C with two rotating nozzles opposed to each other in either corner can achieve the cleaning performance requirements while having a fluid consumption within the limit of 12 ml/cleaning cycle. Small rotations will make it possible for the fluid to hit the entire area of the fascia, thus cleaning efficiently with high pressure along the entire area of the fascia. Due to the low impact angle on the surface and the long distance to the impact point, in comparison to concept A1, it will however not be able to clean as efficiently as concept A1. This is clearly shown by the doubled fluid consumption, but nonetheless still is within the fluid consumption limit.
4.4.4 Evaluation

This chapter presents the results of the evaluation of the concepts in loop 2. Table 7 shows the weighted evaluation matrix which includes the four revised concepts from the testing phase, as well as Audi’s telescopic lidar cleaning system and the previously referenced static nozzle lidar cleaning system. The weighted evaluation matrix includes the qualitative criteria, upon which the cleaning concepts have been assessed based on the criteria’s definition as previously described in section 4.2.

Table 7. Results of the weighted evaluation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>3</td>
<td>The application and use of the trucks mean a higher quality demand. Thus, durability is considered a central criterion, which is why it is weighted the highest amongst the qualitative criteria.</td>
</tr>
<tr>
<td>Low sensor disturbance</td>
<td>1</td>
<td>Due to the overlap between multiple sensor’s field of vision, the temporary blind spot caused by cleaning a sensor, can be covered by a neighbouring sensor. Therefore, temporary sensor disturbance during cleaning is weighted low.</td>
</tr>
<tr>
<td>Low complexity</td>
<td>3</td>
<td>Achieving the desired cleaning performance with the simplest system is favoured, which is why complexity is weighted the highest.</td>
</tr>
<tr>
<td>Highly scalable</td>
<td>2</td>
<td>Having the same cleaning system for different sizes of fascia is favoured, however, not crucial.</td>
</tr>
<tr>
<td>Highly modular</td>
<td>2</td>
<td>Placing the sensors on multiple locations around the truck and adapting the cleaning system to a specific location, makes modularity to a medium weight.</td>
</tr>
</tbody>
</table>
Due to the conceptual definition of the concepts, it is difficult to estimate the occupied space of the concepts, which is why compactness was not weighted higher than two.

On top of the qualitative criteria evaluated above, there is one criterion left to evaluate, namely the fluid consumption of each cleaning concept per cleaning cycle. This is visualized in a staple diagram shown in Figure 58.

The grey staples show the score received in the weighted evaluation matrix, while the blue staples show the fluid consumption of each cleaning system derived from the testing phase. The dotted line represents the fluid consumption limit. It shows that the reference systems are well above the fluid consumption limit, while the developed concepts are within the accepted limit. The diagram shows a correlation between the weighted scores and the fluid consumption. A low fluid consumption comes at a cost of a lower score when it comes to the criteria in the weighted evaluation matrix. Achieving the lowest fluid consumption, as in concept A2, resulted in the biggest drop in the total weighted score. In contrast, the highest weighted score, achieved by the reference system, corresponded to the highest fluid consumption.

**4.4.5 Conclusion**

As previously mentioned, one reason for the high fluid consumption of the reference systems is due to the fluid being spread over a bigger area, thus achieving a lower fluid impact force, which as previously mentioned affects the cleaning efficiency. Concept C is like the reference systems in the aspect that the nozzles are placed on the side of the fascia and does not have any part of the system moving in front of the fascia. The difference is that the fluid is more concentrated, thus achieving a higher fluid impact force, while covering the entire fascia by rotating the nozzles. This added functionality lowers the total weighted score by 10 points in comparison to the reference systems, however, lowers the fluid consumption by 30 ml, which is a reduction of 68%. Although the fluid consumption was even lower for the other developed concepts, it was not considered enough to motivate for the loss of compactness, scalability, modularity and durability in comparison to concept C. Due to these conclusions, concept C was considered the most favourable concept.

**4.5 Design cycle 3**

This section presents the further development of concept C, the concept adaptation to other fascia sizes, and finally a comparison between a sweeping flat spray and a static cone spray.
4.5.1 Final concept C

What needs to be defined further in this last design cycle is how the nozzle should be rotated or moved for the flat spray to hit the entire fascia. The added complexity of making the nozzles rotate, for example with the integration of an electric motor, was not considered optimal, which is why other mechanisms were discussed. It was found that the same cleaning method, namely moving the flat spray across the area of the fascia, can be achieved by having a telescopic arm that sprays the water continuously during the extension of the telescopic arm. This resulted in an updated revision of concept C, see Figure 59.

![Figure 59. Rendering of the updated and final concept C](image)

Hence, the cleaning system consists of two telescopic nozzles placed in either corner of the fascia. When the telescopic arm starts extending, the flat fan nozzle hits the fascia close to the corner. As the arm extends, the nozzle impact area moves closer to the middle of the fascia, which can be seen in Figure 60. The red line illustrates that the impact area of the flat spray moves as the telescopic arm extends. When the arm is fully extended, the nozzle impact area is positioned past the middle of the fascia, making sure that the whole area of the fascia is covered by the two nozzles.

![Figure 60. Sequential illustration of the extension of one telescopic arm](image)

When the arm is fully extended, the position of the flat fan nozzle is the same as during testing of concept C in Figure 57. This way, it can be assured that the cleaning performance of the revised functionality is met. For this concept to work as intended, several questions needed to be answered. The sections below present the answers to these.

**How to spray while in motion?**

In concept C, the pressurised washer fluid has a multi role; to set the telescopic mechanism in linear motion and washing away dirt. Conventional telescopic nozzles spray the fluid when the telescopic arm has fully extended, where the arm is extended by the system pressure created by the pump. Even though concept C has a nozzle that sprays continuously, the system pressure is enough to extend the telescopic arm simultaneously. Figure 61 below shows an example of a telescopic arm with a continuous spray as the arm extends.
How to control cylinder motion?
To meet the fluid consumption limit with the tested flat fan nozzle, see Figure 57, the cleaning cycle cannot exceed 1 second. Thus, the duration of the telescopic extension needs to be controlled, which can be achieved by a damper. To this, the telescopic arm needs to retract after cleaning, which can be achieved by a return spring. In other words, the telescopic arm needs a return spring and a damper.

There are many ways of damping the motion, such as friction between piston and cylinder, as well as hydraulic damping. Another way would be to change the system pressure and hence controlling the compression of the return spring. The least complex damper would be the frictional damper, however, the durability and functionality in different temperatures needs further investigating.

How can wave front be prevented?
The tests showed that the cleaning performance is low behind the wave front created from the intersection point of two opposing nozzles. This can be prevented by having sequential cleaning, meaning that only one nozzle extends and sprays at a time. This can be achieved in many ways, for example by having an electromagnetic valve at the T-connection from where the fluid flows to the two nozzles.

Nozzles and spray angle of attack
To make sure that the cleaning performance can be met, the nozzles were, as previously mentioned, placed in the same position as in Figure 57 shown in the previous testing section. This meant a minimum fluid impact angle of 12 degrees and a maximum spray distance of 50 mm. Figure 62 below shows the impact of the fluid when the telescopic arms are fully extended. It also shows that the two-spray overlap in the centre of the fascia, in order to achieve full coverage. The telescopic arms are slightly tilted to meet the spray distance of maximum 50 mm.

Moreover, to make sure that the whole fascia is covered, the two sprays must overlap in the centre. Consequently, some fluid will be wasted which can be seen in the top right- and bottom left corner. This depends on the shape of the fascia; a quadratic fascia would lead to no wasted fluid, while the more rectangular the fascia gets, the more fluid will be wasted with this configuration.
4.5.2 Resource-efficiency of a sweeping flat spray
The tested sweeping flat spray has shown to be more resource-efficient than the static cone sprays used by the reference systems. This section explains why. Figure 63 shows an illustration of a sweeping flat spray, left, and a conical spray, right.

![Figure 63. Left to right; illustration of a sweeping flat spray and a static conical spray.](image)

If the cleaning systems is set to use the same fixed amount of washer fluid per second, a system with a cone spray would have less impact force than a flat spray, since the fluid is distributed onto a bigger surface area. Thus, the cone spray has a smaller impact force but instant coverage, while the flat spray has a higher impact force but needs to be moved to reach all spots of the fascia. As presented in section 2.1 on surface cleaning and as shown in the test results, a higher impact force means a more resource-efficient cleaning, leading to a better cleaning performance for the sweeping flat spray, when considering the same fluid consumption. In order to reach the same cleaning performance of the flat spray, the spray duration of the cone spray needs to be prolonged, resulting in a higher total fluid consumption.

If the same impact force is desired, the cone spray needs to have a higher fluid consumption per second. This would require a higher system pressure, with a higher capacity than the tested pumps. Due to the higher fluid consumption per second, the cleaning duration needs to be kept to a split of a second to keep the same total fluid consumption per cleaning cycle, when comparing with a flat spray with a spray duration of one second.

In summary, increasing the system pressure and reducing the cleaning time would result in a high-pressured burst which would require additional pressure accumulators to reach high pressures. This means that a sweeping flat spray could achieve a resource-efficient cleaning with simpler equipment.

4.5.3 Adaptation of concept to other fascia sizes
Concept C was initially developed for the size of a lidar fascia. This section presents how the cleaning method in concept C could be used on other fascia sizes, such as camera and headlamps.

Two studies suggested that the cleaning performance of the telescopic headlamp cleaning systems are insufficient (Söllner et al., 2012) (Mitkov, 2017). Both refer to a cleaning system with a telescopic nozzle which, upon full telescopic extension, sprays a conical spray on to the headlamp lens. This system can be optimized by using the same cleaning principle as presented in the final concept C, namely a sweeping flat spray. Since the existing headlamp cleaning systems use a cone spray, the same arguments can be used as explained in the previous section.

However, if the same design as suggested for the final concept C can be applied on a headlamp needs further investigating. The size difference between the fascia of the headlamp and the lidar, would require that the lidar nozzles would have to be scaled up to match the bigger fascia
of the headlamp. However, scaling up components does not always work as expected. According to the theoretical physicist Richard Feynman, a physical phenomenon does not always work as expected when scaled up or down (Feynman, 1960). These potential scalability effects need to be investigated further.

On the contrary, in the case of a smaller fascia than the lidar, i.e. a camera unit, the fluid consumption advantage of the sweeping motion, as described in the previous section, is not believed to be as apparent because of the lens being so small. Due to the small camera surface, the cone spray is distributed on a smaller area, thus not losing as much impact force as it does when distributed on a bigger area. Hence the difference in impact force of the fluid between a flat spray and a cone spray is not as significant as for a lidar surface, meaning that the resource-efficiency will be closer to equal. However, no tests have been performed to verify this argument, which is why further investigations are needed.

Figure 64 shows an illustration of how the final concept theoretically could be adjusted for different fascia sizes, in this case camera, lidar and headlamp. The top row show different configurations of a conventional cone spray, while the bottom row show the same surfaces with a sweeping flat spray.
The discussion presents the reflections around the findings and results of the thesis. The first section discusses the methodology, followed by a discussion around the performed tests and the analysed cleaning methods.

**Methodology**

As explained in the Delft Design Guide (van Boeijen et al., 2013, ss. 146-147), the Pugh’s decision matrix, has some strengths and limitations. Being able to evaluate and compare multiple concepts simultaneously is powerful, still, the decision matrix alone is not enough to present the ultimate answer. Instead, it establishes a confident base of discussions to build your decision on. Also, making sure that all concepts are equally developed before running through any decision matrix is important for better precision. When looking at the evaluation results, a correlation was detected; the most complex ideas scored best when referencing the least complex system. In other words, cleaning ideas which were relatively complex were not affected as much by the negative aspects that came from making it complex.

The C-box worked as a visual board where the ideas could be collected and grouped, while discussing them. This helped in forming opinions about the concepts, exposing the designer to the entire collection concepts initiated spontaneous cross breeding of ideas, hence boosting creativity. At the same time, displaying the previous concept work together with the axis gave a desired structure and clear direction to further work. Forcing the designer to decide about which concept elements should be further developed to achieve a simplistic and innovative concept. Another strength of this method is the capability of simultaneously handling a big number of ideas, making it suitable in an early stage concept development phase.

The evaluation in the first two design cycles both showed that the better the concepts scoured on resource-efficiency, the worse they performed on the more system-related qualitative criteria. Everything comes to a price of something else. This is not an uncommon phenomenon in product development. Changing one aspect of the system, results in a change of another aspect of the system. In this case, lowering the fluid consumption lead to a higher complexity and a lower scalability, modularity and compactness.

**Testing**

Söllner et al. (2012) states that the standard test dust corresponds well to the road dirt during the winter months. Moreover, the accumulated dirt during the summer months, contains more insects which makes the dirt stick harder to the lens, consequentially making it harder to remove. Hence, in future testing it would be advised to use different types of dirt during testing, to verify that the cleaning system is able to remove a wider range of dirt. Nonetheless, the use of the standard test dust has been valuable, since it facilitated the comparison between the developed concept in this report with the existing cleaning system on the market today. In addition, as previously mentioned, the standard test dust is regulated by the UN to be used to approve the cleaning performance of headlamp cleaning systems, which is another confirmation that the standard test dust is suited to be used during testing.

It is difficult to say if the dirt application on the fascia in the lab tests represents how dirty the sensors would become out on the roads. As observed in the Audi field test, see section 4.1.1, the lidar is being cleaned at low dirt levels even when autonomous driving is inactivated, meaning that the sensor is never allowed to become dirtier than shown in the images of the field test. Thus, it can be reasoned that the sensors would not allow the fascia to get covered anywhere close to the dirt accumulation in the lab tests. Defining the threshold on how dirty the sensors can become before cleaning, is therefore a key element in making sure that lab tests are comparable to the user scenario.
Polyvinyl chloride (PVC) plastic was used in the cleaning tests. The material properties regarding dirt adhesion was never investigated, for example is it easier or more difficult to remove dirt from a surface made of a different material. To this, some of the reference systems have a different material on their fascia. This could lead to some measurement uncertainty when comparing the tests to the reference cleaning systems.

Smaller canals mean that fluid can freeze easily, as well as get clogged by contaminants. The smaller nozzle orifices of the flat spray nozzles in comparison to the reference system, can possibly become problematic. To determine the durability of the recommended flat spray nozzles, stress tests in different environments are suggested.

At some point, autonomous vehicles are expected to need maintenance and service work. Except work requiring a mechanical workshop, refuelling and refilling the washer fluid reservoir is needed. The question is, how long is a vehicle expected to run before the need of a refill? These considerations lay the basis of how much washer fluid can be used in one cycle of cleaning. More exactly, how far must a vehicle run without attention to be reckoned as an autonomous vehicle?

An upper fluid consumption limit of 12 ml/cycle, see section 4.2, is a value based on a maximum tank capacity for the heavy vehicles specific to the industry partner. This limitation can change for other vehicle applications. Another way of determining the maximum consumption value could be achieved if data could be collected from a field test including various weather conditions, e.g. muddy off-road, dusty dirt road, winter tarmac road, summer tarmac road. Other types of dirt accumulation are interesting too, such as insects and ice.

In summary, an uptime-based consumption analysis based on a user scenario and field test data could give a more realistic picture of how much fluid consumption is acceptable. See Table 9 as an example.

Table 9. Consumption scenario calculation

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<tr>
<td>Set up a measuring system e.g. transmission loss.</td>
<td>Set a required uptime before washer fluid refill is needed</td>
<td>Measure time until significant dirt accumulation happens, per sensor</td>
<td>Divide uptime with the time when dirt accumulation happens, per sensors. Yields num. of cleaning cycles.</td>
<td>Add up num. of cleaning cycles from all sensors.</td>
<td>Multiply by the lowest measured fluid consumption possible</td>
<td>Yields the required reservoir capacity and volume.</td>
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Cleaning methods

In the early stages of the project, non-liquid cleaning methods, such as air and hydrophobic coatings, as well as various liquid-based methods, were investigated. Finding an effective cleaning principle has been a multi-faceted probing process. However, cleaning efficiency and resource consumption has been central requirements in the choosing of a cleaning principle.

Making the surface unattractive to dirt by treating it with different coatings has been disregarded because of low durability reasons, as mentioned by Fagervall & Nyman (2000). The user conditions of a heavy vehicle require resisting harsh environments such as abrasive debris, chemicals and scuffing. Therefore, coatings can be a supportive technology but is not believed to work without an additional cleaning system. More research is expected in this area, and a durable and cost-effective coating in combination with a cleaning system can increase the interval between the cleaning cycles, thus reducing the fluid consumption.
Cleaning with air is an interesting idea. Using the pneumatic system available in trucks instead of carrying around an extra reservoir of liquid sounds attractive and could save weight and space. However, the air cleaning tests presented in section 4.1.2, showed that compressed air is not an effective cleaner on its own, but it has certain advantages. As air is not as limited on a truck as washer fluid, a cleaning system with different cleaning modes could be one potential advantage. Firstly, the cleaning system could try cleaning the sensor fascia with solely air. If that does not result in the desired cleaning performance, a second cleaning cycle with washer fluid could be initiated. This way, the fluid consumption can be lowered.

In addition, as expressed in section 2.4, some environments suggest the use of air rather than fluid, which is another potential advantage. The use of washer fluid in dry environments, such as dusty mines or snowy ice roads, could result in even quicker dirt accumulation. In these environments, it could be beneficial to have the option to use air for cleaning. However, the cleaning performance of air in these environments need further testing. In summary, the use of air for cleaning has several potential advantages, such as increased resource-efficiency and use in dry environments. However, this study did not find a way to solely use air as a cleaning media and rather sees the possibility to improve the fluid-based system by combining it with an air cleaning system.

Mechanical cleaning, such as a wiper blade, is a highly potent method of cleaning and is always combined with a fluid delivery system. The wiper requires washer fluid to lower friction and function properly, but in return the existence of a wiper blade lowers the use of washer fluid. Therefore, a wiper blade system has a relatively high cleaning performance. This coincides with the research from Ytterbom (1994), pointing out that the residual dirt after a cleaning cycle was cut in half when having a fluid- and wiper system, in comparison to having a high-pressure fluid system. Ytterbom (1994) also points out the durability issues that comes with having a wiper blade, such as scratches on the windshield and the degradation of the wiper blades. If an increased robustness and service life can be achieved, the wiper blade solution could be attractive with its record low washer fluid consumption.

Being a non-contact cleaning method, high-pressure fluid systems have several benefits to fluid- and wiper systems. Less friction means less maintenance and wear related issues. This could also mean a cheaper fascia, because the fascia does not need to be hard coated or be made from glass. Setting up the optimal high-pressure fluid system is about balancing performance and consumption. Ideally, the fluid spray must be potent enough to remove dirt but use as little washer fluid as possible. Parameters, such as spray density, system pressure, duration and spray angle of attack plays a role. With the main goal of keeping consumption as low as possible, the challenge has been to find the sweet spot of nozzle size, distance to fascia and cleaning performance. In the configurations which were tested in this thesis, the use of a flat spray nozzle was able to be optimized.

As stated in 2.1, the impact angle of the fluid to the surface affects the impact force on the surface, thus affecting the cleaning efficiency. This was confirmed during testing, when comparing the results of the tests in concept A and concept C. The impact angle in the last test of concept C was 12 degrees, in comparison to 90 degrees in concept A. To achieve the same cleaning performance, the last test in concept C needed twice as much fluid than the most resource-efficient test in concept A. Upon further research on the cleaning efficiency with different fluid impact angles, a study was found after completion of the tests, which investigated this issue (Scott, 1981). It showed that the cleaning-efficiency of flat fan nozzles are the highest at 90 degree, while the cleaning efficiency is halved when coming down to around 15 degrees. This coincides well with the tests performed in the thesis. Moreover, Scott (1981) presented that the cleaning-efficiency declined exponentially when going below 10 degrees. Thus, it is not suggested to have a fluid impact angle below 10 degrees.
The use of a sweeping flat spray, instead of a static cone spray, allows for an increased impact force on the surface while at the same time allowing for the whole surface to be cleaned. The slightly increased complexity of the system, which comes from making the flat spray move, is considered a favourable compromise which allows a considerably higher resource-efficiency than a static cone spray. Moreover, the increased durability in comparison to the fluid- and wiper system, as well as the more favourable scalability aspects, resulted in the sweeping flat spray ending up as the best suited sensor cleaning system.
A wide range of sensor cleaning systems have been considered, including cleaning systems based on air, fluid and wiper blades. The study concluded that cleaning systems which do not use solvents, for example air cleaning systems and hydrophobic surfaces, were not able to achieve a clean and unobstructed sensor fascia. In other words, the need of a solvent during cleaning was found necessary. Therefore, for a system of 20 sensors, the resource-efficiency is a central aspect. The fluid consumption limit per cleaning cycle and sensor was set to 12 ml, which is approximately four times lower than the best referenced lidar cleaning system.

The purpose of the thesis was to investigate how a more resource-efficient cleaning can be achieved, while meeting the desired cleaning performance. The tests in the report reveal several conceptual cleaning concepts which have a fluid consumption of less than 12 ml, thus considered resource-efficient. Among these are high-pressured fluid and fluid- and wiper cleaning systems, which both showed a potential to use between 5-12 ml per cleaning cycle. However, the lower the fluid consumption, the more system-related drawbacks were identified, such as decreased durability and increased complexity of the system.

When it comes to high-pressured fluid systems, the study found that the use of a sweeping flat spray is more resource-efficient than a static cone spray, with the latter being commonly used in conventional sensor cleaning systems. A sweeping flat spray achieves a higher fluid impact pressure, which correlates to a higher cleaning efficiency.

When evaluating the concepts from a system perspective, the sweeping flat spray system with an impact angle of 12 degrees scored the highest among the conceptual cleaning systems. The concept uses less packaging volume, contains fewer moving parts, has the potential to be used for different fascia sizes, and the mounting location around the sensor can be more easily adjusted. The further development of this concept resulted in the final recommendation for a lidar cleaning system in an autonomous heavy vehicle application. The final concept consists of two telescopic flat spray nozzles placed in either corners of the fascia. Upon cleaning, the arms extend while simultaneously spraying fluid with an impact angle of 12 degrees onto the fascia. This function enables the flat spray to move over the surface from the corner into the centre of the fascia, ensuring resource-efficient cleaning.

When considering the use of a sweeping flat spray for a smaller fascia, such as a camera, the fluid consumption benefits are less prominent, and there is not believed to be a significant difference between the fluid consumption of existing camera cleaning systems. This has however not been verified, which is why further investigating and testing is needed. Due to the larger surface of a headlamp, the use of a sweeping flat spray is promising. How the sweeping flat spray is achieved, needs further investigating and testing. Due to the substantially bigger surface of a headlamp in comparison to a lidar, it is unknown if the cleaning performance can be maintained when the telescopic nozzles are scaled up.

Hence, the goal of recommending a cleaning system for lidars has been met. The recommendation of a cleaning system for cameras and headlamps has been discussed and a more definite answer would require further investigations. The conceptual cleaning systems developed in the thesis demonstrate an evident possibility on how to achieve a more resource-efficient sensor cleaning system for a system of up to 20 sensors.
7 References


Smith, L. J. (2018, 12 02). *How getting ice, snow or dirt on your headlights could land you a £1,000 fine*. Retrieved from https://www.express.co.uk/life-style/cars/1052605/car-headlight-fine-snow-ice-dirt


Valeo Group. (2011, 06 24). *Valeo - make it simple to detect wiper defects!* Retrieved from Youtube: https://www.youtube.com/watch?v=trVdsEmPrCc


APPENDIX A: Literature Search Terms

The following list shows the search terms which were used to find relevant research which was used as a frame of reference for the thesis.

- wet and dry cleaning
- dry cleaning
- cleaning efficiency
- efficient cleaning
- cleaning techniques
- cleaning techniques surfaces
- lidar cleaning system
- car lidar cleaning system
- camera cleaning system
- car camera cleaning system
- physical cleaning methods
- mechanical cleaning methods
- surface cleaning
- dirt removal
- dirt removal surface
- mechanical surface cleaning
- mechanical surface cleaning efficiency dirt
- mechanical wiper brush surface cleaning efficiency dirt
- review different windshield cleaning
- mechanical windshield cleaning
- headlamp washing
- headlamp cleaning
- headlamp wiper cleaning
- window cleaning
- windshield cleaning
- windshield washing
APPENDIX B: Pugh’s evaluation

### Pugh’s evaluation referencing the Audi Lidar cleaning system

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### Pugh’s evaluation referencing the static nozzle lidar cleaning system

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### Pugh’s evaluation referencing the Scania headlamp cleaning system

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<td>Durability/Cost</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Laser sensor disturbance</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Ease of use of limited resources</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Scalability/Mobility</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Compactness</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>
**Test rig**
The tests have been performed in the facilities of the industry partner, with necessary measuring equipment. The rig itself was designed and built with tools and elements available in a thrift shop or the company part libraries. The rig is designed to be as dust proof as possible so that dirt application and cleaning tests can be performed without polluting the surroundings. The main constituents of the rig are shown in Figure 65.

*Figure 65. The various parts of the test rig*
**Fascia mounting**
A piece of PVC plastic which, ninety by fifty big is representing the front surface of a Lidar sensor. The fascia can easily be attached and detached from the mounting rail as well as a group of spray nozzles can be configured flexibly around the fascia, see Figure 66.

![Figure 66. Fascia mounting](image)

**Preparation of dirt**
A batch of slurry made of Standard test dust, see section 2.6.1, and water was prepared before the tests. The spray gun propels the slurry by compressed air and the viscosity of the slurry is important to control. If too dry; the slurry could not pass through the canals of the spray gun, if too wet; the dirt could not hold on to the fascia due to big drops of water accumulating and washing away the dirt. Figure 67 shows the different tools used to prepare the dirt mixture.

![Figure 67. Tools used to prepare and apply the standard test dirt](image)

**Application of dirt**
Dirt application is important for a quick and precise testing. At its best, a test run was ready to go every five minutes, including preparing, applying and drying the test dirt, as seen in the
sequence in Figure 68. This method of application is representing the accumulation of dirt caused by driving on a road with conditions according to chapter 2.6.

Calibration
A pressure gauge was connected to one of the fluid lines which helped to calibrate the nozzle flow rates, see Figure 69. By using a variable laboratory bench power supply and altering the power output of the pumps, it was possible to test that the theoretical nozzle flow rates were equal to the actual flow rates.

General test parameters
The general test parameters include all parameters that have been kept constant during the testing phase. Table 10 shows the values along with a description behind the chosen value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of fascia (height x width)</td>
<td>50 x 90 mm</td>
<td>According to size request by partner</td>
</tr>
<tr>
<td>Test dirt</td>
<td>ECE-R45</td>
<td>Standard Test Dust as used in industry</td>
</tr>
<tr>
<td>Dirt mixture</td>
<td>50/50 dirt and water</td>
<td>Composition suited for spray gun use</td>
</tr>
<tr>
<td>Fluid consumption limit of cleaning concept</td>
<td>12 ml/cleaning cycle</td>
<td>As described in section 4.2 in the main report</td>
</tr>
</tbody>
</table>
Test Concept A – Tilt arm

Proof of Concept:
Investigate the total fluid consumption. Acceptable consumption, less than 12 ml/cycle.

- What is the minimum fluid consumption when using solely high-pressure fluid?
- What is the minimum fluid consumption when using a fluid and wiper solution?

Answering these two questions would give us a reason to proceed or cancel the concept.

Hypothesis
The wiper blade is going to help reducing the washer fluid consumption. Washer fluid is used to mainly dissolve the dirt, the wiper blade brakes up and transports the dirt away from the surface. Also, the washer fluid lubricates the blade and makes it run smoother and more efficiently.

On the other hand, a system without the wiper blade would require a more potent spray. The high-pressure jet is used to dissolve, break-up and transport the dirt. This system would use more washer fluid.

Methodology:
A fixture was built to replicate the movement of the rotating arm which runs along the fascia surface, Figure 70. Nozzles are placed along the fixture and fixed at a constant distance, pointed towards the fascia perpendicularly.

Figure 70. Sliding fixture holding a nozzle, Concept A

Three different flat fan nozzles were used, ranging from low to high fluid consumption, see Figure 72. The nozzles were of convex distribution type, Figure 71.

Figure 71. Nozzle types, (PNR Nordic, 2018)
The three nozzles, JBR-0060, JBR-0100 and JBV-0200 according to Figure 72.

<table>
<thead>
<tr>
<th>25°</th>
<th>40°</th>
<th>50°</th>
<th>65°</th>
<th>80°</th>
<th>95°</th>
<th>Capacity Code</th>
<th>D mm</th>
<th>Capacity (l/min) at different pressure values (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JBD</td>
<td>JAL</td>
<td>JAN</td>
<td>JAR</td>
<td>JAT</td>
<td>JAV</td>
<td>JAJ</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0060</td>
<td>0.28</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0100</td>
<td>0.34</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0150</td>
<td>0.28</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0200</td>
<td>0.46</td>
<td>0.096</td>
</tr>
<tr>
<td>JBD</td>
<td>JBL</td>
<td>JBN</td>
<td>JBR</td>
<td>JBT</td>
<td>JBV</td>
<td>JBJ</td>
<td></td>
<td>0260</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0350</td>
<td>0.66</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0550</td>
<td>0.79</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 72. PNR Nordic nozzle diagram (PNR Nordic, 2018)

The table gives valuable information, however, we still needed to know about how the spray angle changes at different pressures to ensure full coverage of the surface. To see the effects, a practical test was performed, and spray angle was measured at different system pressures, see Figure 73. As seen in this test, the relation between spray angle and system pressure does not follow a linear relation.

Figure 73. Spray angles of two different nozzles at three different pressures

After determining the spray angles, the flow rates and the system pressure, it was now possible to set a distance from the fascia and consequently decide the number of nozzles needed to cover the entire width of the fascia. To find the optimal configuration in terms of performance to consumption, without spending too much resources in testing, all known relations and variables were joined in a Matlab-script.

Figure 74 shows the results of such a simulation. The spray duration was set as a constant parameter of 1 second. Also, the spray angle is determined by the nozzle type and system pressure and considered to be a constant parameter.
The figure shows that nozzles placed 5 mm from the fascia resulted in a too high fluid consumption, irrespective of a certain nozzle. The nearest step in distance from surface is 10 mm and showed fluid consumption figures below the requirement, presented in chapter 4.2. Although lower fluid consumption could be achieved with a rotating arm positioned farther from the fascia, namely more than 10 mm, this is not considered because of excessive bulkiness. Thus, the tests were decided to run at a constant distance of 10 mm irrespective of nozzle type. The system pressure of 2 Bar was set as a constant parameter too. Although the 0200 nozzle was slightly above the consumption limit, it was included in the tests due to its advantage of needing only four nozzles, opposed to seven nozzles with the 0060 and the 0100 nozzles.

**Results Concept A**

What is the minimum fluid consumption when using solely high-pressure liquid?

We are looking for any dirt left each time after running the spray over the surface. If there is more dirt left on the fascia than required, the test has failed. Table 11 shows the cleaning performance of the three different nozzle configurations.
Table 11. Cleaning performance of high-pressure fluid

<table>
<thead>
<tr>
<th>Nozzle configuration</th>
<th>Cleaning cycle: 1s</th>
<th>Cleaning cycle: 0.5s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle 0200</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>Distance to fascia:</td>
<td>10mm</td>
<td>10mm</td>
</tr>
<tr>
<td>10mm</td>
<td>12,0 ml/s</td>
<td>12,0 ml/s</td>
</tr>
<tr>
<td>Consumption:</td>
<td>@ 2,0 Bar @ 4 Nozzles</td>
<td>@ 2,0 Bar @ 4 Nozzles</td>
</tr>
<tr>
<td>Fluid consumption:</td>
<td>12 ml</td>
<td>6 ml</td>
</tr>
<tr>
<td>Cleaning performance:</td>
<td>OK</td>
<td>not OK</td>
</tr>
</tbody>
</table>

| Nozzle 0100          | ![Image](image3)   |
| Distance to fascia:  | 10mm               |
| 10mm                 | 10,3 ml/s          |
| Consumption:         | @ 2,0 Bar @ 7 Nozzles | @ 2,0 Bar @ 7 Nozzles |
| Fluid consumption:   | 10,3 ml            |
| Cleaning performance:| OK                  |

| Nozzle 0060          | ![Image](image4)   | ![Image](image5)   |
| Distance to fascia:  | 10mm               | 10mm                |
| 10mm                 | 6,5 ml/s           | 6,5 ml/s           |
| Consumption:         | @ 2,0 Bar @ 7 Nozzles | @ 2,0 Bar @ 7 Nozzles |
| Fluid consumption:   | 6,5 ml             | 3,3 ml             |
| Cleaning performance:| OK                  | not OK              |

In conclusion, 7 nozzles with an orifice of the same size as the 0060 at 2 Bar with a consumption of 6,5 ml/cycle yielded a satisfactory cleaning performance.

However, better results can potentially be achieved by applying the washer fluid in bursts, with other words, dividing up the cycle in a pre-wash and a wash phase. The total consumption would be kept the same. Soaking the dirt and letting it dissolve allows the dirt to be removed more efficiently in the second pass. Consequently, lowering the fluid consumption further.

**Choice of nozzle**
If multiple nozzles are used, overlapping needs to be considered. For an even distribution and minimal number of nozzles it is recommended to choose a nozzle which provides even distribution, see Figure 75.
What is the minimum fluid consumption when using a fluid- and wiper system?

The minimum fluid consumption when using a fluid- and wiper arm is derived from the results of the tests performed for concept B, which also uses a fluid- and wiper system. It is recommended to read the test results of concept B to fully understand the conclusions made here.

The tests in concept B concluded that the fluid consumption can be as low as 5 ml per cleaning cycle to obtain a 90% clean fascia. However due to issues concerning dirt accumulation within the geometry of concept B, the conclusion was that more fluid was needed to have a self-cleaning system. Nevertheless, this is not an issue for the fluid- and wiper arm in concept A. Dirt accumulation surrounding the fascia does not affect the functionality or durability of the system and is dealt with like any other dirt accumulating on the outside of the vehicle, namely either washed away in rainy weather or in a car wash. Therefore, an open system like Concept A, does not need extra fluid to self-clean the system like concept B, which is why the minimum fluid consumption is equal to the previously mentioned 5 ml per cleaning cycle, which is the amount needed to obtain a 90% clean fascia.

**Conclusion A**

Dirt accumulation surrounding the fascia does not affect the functionality or durability of the system and is dealt with like any other dirt accumulating on the vehicle, namely either washed away in rainy weather or in a car wash. Therefore, an open system like Concept A, does not need extra fluid to self-clean the system like concept B, which is why the minimum fluid consumption is equal to the previously mentioned 5 ml per cleaning cycle needed to obtain a 90% clean fascia.

The less enclosed the system is, the less chance is that dirt builds up. Hence, making the system more open and aiming the fluid spray so that it sprays onto the wiper blade, can be a solution to this. In theory, there is a potential to use an additional 9 ml of fluid per cleaning cycle before the fluid consumption reaches the limit of 12 ml/cleaning cycle. In comparison to the other tests that have been performed, especially the ones in Concept A where the lowest uses 7 ml for a successful cleaning cycle, 7 ml of fluid is considered sufficient in terms of cleaning the wiper
blade and surroundings. There is also the potential to use even less than 7 ml depending on factors as explained above, those are however tests which have to be elaborated further in the next concept phase if this concept is to be chosen. In addition, a wiper blade is a classified as contact cleaning and has some abrasive effects on the surface it is cleaning. Therefore, a higher scratch resistive material, such as glass or a hard coating is usually needed.

**Test Concept B – WC Roll**

See 4.4.2 for concept details.

**Proof of Concept:**

- What is the minimum fluid consumption when using a fluid- and wiper system?

**Hypothesis:**

The fluid- and wiper system is a well proven concept in many applications e.g. windshield wipers in vehicles. It is expected that no dirt will be left after running the cleaning cycle. Some doubt exists when running with very little or no fluid, expecting traces of dirt left on the fascia.

**Methodology:**

The “All Time Vision Rear View Camera (ATVC)” from the Scania accessories product library was used as a test object, see Figure 76. There are similarities between the designs of Concept B and the ATVC which allowed us to save some testing time. Both has a cylindrical fascia, wiper blade and a nozzle for the washer fluid.

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**ALL TIME VISION REAR VIEW CAMERA (ATVC)**

**Part nr.: 2247173**

**Part Description:**

Scania AMOS 118º ATVC Self-cleaning camera for professional vision solution. The camera has a self cleaning mode. The camera lens is build in a glass tube which can rotate via an industrial stepping motor. Upon activation, water (or wiper fluid) is sprayed onto the glass surface via a nozzle, the rotation is activated and the glass surface is cleaned via build in wiper. The stepping motor is controlled via the I/O Box (2289333). Activation is done via the Monitor or an input in the I/O Box. The ATVC I/O box supplies power to the camera and the optional pump/water tank (2289345). The AMOS 118º ATVC PAL is in Mirror mode as a standard. The AMOS 118º ATVC PAL Mirror is designed to be applied as a rearview camera. This makes it also easy to adapt to third party monitors. • Next generation CMOS sensor • Rotation endless 360º • 0,5m video cable 7p and 0,5m water hose with valve to connect to waterpump • The connection between the ATVC I/O box and the ATVC camera must be made via a cable with 7pins connectors

Figure 76. All Time Vision Rear View Camera (ATVC), (Scania CV AB, 2019)

The ATVC was fitted easily with a quick modification of the testing jig and dirt was applied as in the previous tests.

It takes the cylindrical fascia 21 second to make a full rotation and according to a product video the ATVC sprays fluid for seven seconds, which is equivalent to a fluid consumption of 12 ml/cleaning cycle with the in-built nozzle. The ATCV came with a flat spray nozzle out of the box which was bypassed and replaced by a mist nozzle. Both nozzles had similar consumption. The original nozzle has a consumption of 1,7 ml/s at 3 Bar system pressure, while the mist
nozzle is tested to have a flow rate of 1.25 ml/s at 2.8 bar system pressure and has an orifice size of 0.45 mm.

![BETE nozzles, type HA](image)

*Figure 77. BETE nozzles, type HA (BETE nozzles, 2019)*

The system was tested a few times with different amounts of liquid applied. Each time, the cylindrical fascia could make a full revolution. The dose of liquid was determined by the time the nozzle faced the fascia while spraying liquid multiplied by the fluid rate of the nozzle. The fascia or any other parts were not manually cleaned in between the cleaning cycles. Figure 78 shows the test sequence for concept B.

![Test sequence for Concept B](image)

*Figure 78. Test sequence for Concept B*

**Results B**

*What is the minimum fluid consumption when using a fluid- and wiper solution?*

The wiper blade is effective and wiped off the dirt with the slightest use of liquid. Even with no liquid applied the wiper managed to be successful, see Table 12.

<table>
<thead>
<tr>
<th>Test</th>
<th>Duration</th>
<th>Fluid consumption</th>
<th>Clean fascia?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21 s</td>
<td>29.4 ml/cycle</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>5 s</td>
<td>7.0 ml/cycle</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>2 s</td>
<td>2.5 ml/cycle</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>0 s</td>
<td>0 ml/cycle</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Since the system was not dried in between the tests, it is difficult to say how reliable the results from the test with no liquid is. Examining the wiper blade after all tests were done, it was found that it was still wet. After a few cycles, dirt accumulation on the wiper blade appeared. Although the long-term effects were not examined this can clog the system, cause premature wear and lower the cleaning effects, see Figure 79.
Conclusion B

Consequently, it is important that dirt accumulation is prevented, which can be solved by distributing the spray partially over the wiper blade, which not only cleans the fascia but also keeps the wiper blade and its surroundings clean.

The tested ATVC camera has a width of 45 mm, while the design parameters were set for a fascia with a width of 90 mm. Thus, two mist nozzles are required for the use in concept B, which would result in twice the fluid consumption. However, the test concluded that the minimum fluid consumption was not driven by the amount needed to obtain a 90% clean fascia, it was rather driven by the necessary amounts of liquid needed for preventing the dirt accumulation within the enclosure of concept B.

Thus, the minimum fluid consumption is equal to the fluid needed to have a self-cleaning system, which is difficult to determine. However, it is known that turning the nozzles partially towards the wiper blade and optimizing flow will theoretically help. Other factors such as, position of wiper blade, avoiding pockets and optimizing the geometry around the wiper is advised. These factors need to be further elaborated and tested. In comparison with the other tests performed, it is however considered possible to use a maximum of 10 ml/cleaning cycle, to, on top of cleaning the fascia, achieving a self-cleaning system.
**Test Concept C – Wave Front**
See 4.4.3 for concept details.

**Proof of concept:**
- How to move the wave up and down on the fascia?
- Does the wave front have a cleaning effect?
- How fast can the wave front move?

**Methodology**
For this concept, the flat fascia was used together with four flat spray nozzles which has a consumption of 0,06 l/min at 1,5 bars, see nozzle type in Figure 80.

![Figure 80. Flat nozzle PNR Nordic, (PNR Nordic, 2019)](image1)

Two sets of nozzles were connected by hoses, top and bottom, allowing separate settings and pump power outputs. Each set of nozzles had a tank and a pump of identical type, see test setup in Figure 81.

![Figure 81. Test setup Concept C](image2)

At the beginning, the pump power output was set to be the same across the two systems, consequently creating a wave located in the middle of the fascia. In the second run, the input voltage to the pumps was altered to move wave front up and down.

**How to move the wave up and down on the fascia?**

**Hypothesis:**
The wave front could be moved up and down on the fascia by changing the pump power output by increasing output of one nozzle system and lowering the opposite, and vice versa, moving of the wave front is possible. This can be explained by the direct correlation between pump power output, fluid velocity and the kinetic energy. In theory, this would mean that two nozzles aimed at each other delivering a spray with the same fluid velocity and running along the same surface would meet at a centre distance between the opposing nozzles. In other words, raising the fluid pump power in one of the nozzle systems would lead to a higher fluid velocity, which in turn would result in a higher kinetic energy, which leads to the net zero energy point moving closer to the nozzle with the lower kinetic energy.

**Methodology:**
No dirt was needed this time, since the only the behaviour of the water sprays is interesting to see. In the absence of any test dirt, the rig could run without the protective dust cover. The nozzles were placed as close to the fascia as possible with an approximate angle of attack according to Figure 82.

![Figure 82. Angle of attack flat fan nozzles Concept C](image)

**Result:**

Moving the wave front was possible by changing the pump power output. However, with increasing power, the distortion of the shape of the wave font increased as well. Therefore, controlling the wave movement is not simple. Also, the range of movement is limited, meaning that the wave front could not reach the perimeter of the nozzle, which means that the fascia was only partially cleaned, see Figure 83.

![Figure 83. Moving the wave front up and down](image)

An alternative way to move the wave front was achieved by keeping the pump power output constant and changing the impact point of the nozzles instead, see Figure 84. This would require a well-coordinated rotational movement of the nozzles, so that the incident angle of the nozzles meet at different locations over the fascia.
Does the wave front have a cleaning effect?

Hypothesis:
The turbulent zone, also referred to as the wave front, which is created by the two moving fluids colliding with each other. This could result in a friction zone on the surface which removes the dirt.

Methodology:
To determine the cleaning performance of the wave front. Two tests with dirt removal were performed; the first test used four nozzles opposed to each other, creating the wave front, while the second test used only two nozzles; acting as a base of comparison. Several variables were kept as constants, see Table 13 for detailed values. In addition to the table, nozzle position and dirt application were kept as constant parameters.

Table 13. Test properties

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning time</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Pump pressure output</td>
<td>1.5 bar</td>
</tr>
<tr>
<td>Nozzle fluid consumption</td>
<td>0.06 liters/min at 1.5 bar</td>
</tr>
<tr>
<td>Dirt mixture</td>
<td>150 ml water + 150ml standard test dirt</td>
</tr>
</tbody>
</table>

Result:
The blue lines in Figure 85 highlights the spray angles and the wave front. The fascia is only partially cleaned. The near perimeter of the nozzle and, more importantly, the zone where the opposing sprays are colliding is left uncleaned. In summary, the wave front does not have a cleaning effect.
Moreover, the liquid, after colliding, was splashing and separating from the surface in the perpendicular or sideways direction. Similar results can be seen in a different test with nozzles spraying horizontally. The same wave front phenomenon was detected and confirmed that the turbulent area where the two fluid sprays join results in a less efficient cleaning.

**How fast can the wave front move?**
Since no cleaning effect could be obtained from previous tests no further testing resources were spent.

**Further development concept C**
The results of the tests showed that the wave front did not have a cleaning effect, which is why this cleaning principle was discarded. However, the tests showed that rotating the nozzles ensures the fluid to hit the entire fascia. With the nozzles being on the side of the fascia, this had an advantage toward concept A, which is why concept C was updated, see Figure 56.

![Figure 85. Cleaning performance test of wave front](image)

![Figure 86. Sketch of revised concept C, diagonal nozzles](image)
The revised concept consists of two opposed nozzles in either corners of the fascia, which spray fluid sequentially to prevent a wave front forming. The nozzles hit the centre of the fascia and then rotate inwards, thus changing the impact area on the fascia. To verify the fluid consumption, a test was performed. Figure 57 shows the result of the respective nozzle spraying into the centre of the fascia from the side. It showed that a 90% clean fascia could be achieved with the 0390 nozzle at fluid consumption of 12 ml/cleaning cycle.

Conclusion concept C

The revised concept C with two rotating nozzles opposed to each other in either corner can achieve the cleaning performance requirements while having a fluid consumption within the limit of 12 ml/cleaning cycle. Small rotations will make it possible for the fluid to hit the entire area of the fascia, thus cleaning efficiently with high pressure along the entire area of the fascia. Due to the low impact angle on the surface and the long distance to the impact point, in comparison to concept A1, it will however not be able to clean as efficiently as concept A1. This is clearly shown by the doubled fluid consumption, but nonetheless still is within the fluid consumption limit.
This appendix presents the individual assessments for the cleaning systems’ scores received in
the weighted evaluation matrix.

**Audi telescopic nozzle**

Audi’s lidar sensor cleaning system has a traditional telescopic arm with the same functionality
as the headlamp cleaning systems that have been popular on the market for many decades. It is
a reliable and durable system, and at the same time scalable to most applications. These
advantages come to a price of a reduced cleaning performance. In terms of headlamp cleaning
the cleaning performance has been considered good enough, however this does not imply to a
lidar sensor. To not risk losing the functionality of the sensor, a better cleaning system is
requested, which improves the cleaning performance without increasing the fluid consumption.

**Pros:**

- Hydraulic extension of telescopic arm
- Few components/systems (low complexity)

**Cons:**

- Poor cleaning performance
- High fluid consumption

**Static nozzle**

The static lidar sensor cleaning system consists of a fixed nozzle solution. It is even more
durable and reliable than Audi’s system since it does not contain any moving parts. It is a
scalable, modular and compact solution, with the possibility to adjust the position of the nozzles
anywhere around the fascia, depending on the location of the truck. Having fixed nozzles,
however, means that the fluid hits the same point on the fascia during the cleaning cycle, hence
needing a cone spray which leads to a high fluid consumption in order to achieve the desired
cleaning performance.

**Pros:**

- Adjustable for all locations on truck (highly modular)
- No moving parts (low complexity)

**Cons:**

- Poor cleaning performance
- High fluid consumption

**Concept A1**

Concept A1 follows the hypothesis of delivering the same fluid impact pressure over the whole
fascia, and thus minimising the fluid consumption. This has been shown to be succesful from
the tests. However, achieving this with a rotating arm comes with side effects such as a less
scalable, durable and modular system. The arm can only be mounted in one way and does not
work with different fascia sizes, while at the same time requiring more space around the fascia,
thus making the solution less compact.

**Pros:**

- Low fluid consumption
- Good cleaning performance

**Cons:**

- Moving parts, many components (high complexity)
- Needs more space around the fascia (less compact)
Concept A2

Concept A2 follows the hypothesis of using a wiper blade to clean the fascia, and thus minimizing the fluid consumption. The fluid is used to dissolve the dirt and lowering the friction between dirt and wiper blade. The tests showed that this cleaning solution can use the least fluid of all concepts. However, this concept shares the same side effects as described for Concept A1, such as a less scalable, compact and modular system. To this, it is also considered less durable than Concept A1, due to the life length of the wiper blade. In addition, having a wiper blade suggests using a glass fascia, due to the risk of scratches on the fascia.

Pros:  
+ Low fluid consumption  
+ Good cleaning performance

Cons:  
- Moving parts, many components (high complexity)  
- Needs more space around the fascia (less compact)  
- Maintenance of wiper blade and scratches on fascia (less durable)

Concept B

Concept B aimed to minimize both fluid consumption and sensor disturbance. The tests showed that both goals could be met. As with the previous concepts, this comes to a price of lowered durability and scalability, as well as higher complexity. Having a wiper blade, the sealing between fascia and sensor hardware, driving the rotation of the fascia, are all factors which add up to a less durable system, while adding complexity. The packaging of nozzle, enclosure and sensor hardware, make the system less compact. As described in the conclusion of the tests on this concept, the fluid consumption could range somewhere between 3-10 ml, depending on how well the self-cleaning function can be designed. In the evaluation, the worst case 10 ml per cycle was used, which affects the scoring negatively.

Pros:  
+ Low fluid consumption  
+ Good cleaning performance  
+ No sensor disturbance

Cons:  
- Moving parts, many components (high complexity)  
- Needs more space around the fascia (less compact)  
- Maintenance of wiper blade and scratches on fascia (less durable)

Concept C

Concept C follows the same cleaning principle as Concept A1, which is that the best cleaning efficiency is achieved at the point of impact of the fluid. Hence, to clean the whole fascia this point of impact needs to be moved, which is realized by rotating the nozzles in Concept C. This Concept ended up with scores worse than the reference systems but better than concepts A1/A2/B in terms of compactness, scalability, modularity and durability.

Pros:  
+ Low fluid consumption  
+ Good cleaning performance  
+ Adjustable to different sizes of fascia (scalable)  
+ Leaves space around fascia (compact)

Cons:  
- Moving parts, many components (high complexity)  
- Needs more space around the fascia (less compact)