A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters
– Water Injection as a Service Tool to Improve Fuel Consumption and Particulate Filter Service Life

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Preface

Due to the confidential nature of some subjects discussed, there will be two versions of this thesis. For the purposes of publication, one version will have proprietary information redacted. Another version for internal use at Scania CV AB will contain the full text.

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Abstract

In order to meet today’s environmental standards, diesel vehicles must capture the soot and ash emitted from the engine in what is known as a diesel particulate filter (DPF). The continual ash loading of this filter and subsequent exhaust backpressure, increase in fuel consumption, etc. is seen as an unavoidable expense. Replacing the DPF is time consuming and costly, representing significant lost profits to the vehicle owner. However, by reducing the volume of ash in the DPF, the pressure drop and fuel penalty can be curtailed while simultaneously increasing filter life. The thesis paper has presented a study intended to select the ideal method for reducing DPF ash volume in the context of system level integration on a Scania truck.

By following an adaptation of the TRIZ method, this work has selected an ideal solution for improving DPF performance. A brief study of two experimental methods for ash volume reduction is presented. From this study, a wide-ranging concept generation phase was undertaken to evaluate the ways these methods could be implemented on a vehicle. Through collaboration with industry experts at Scania, a system of criteria was established to select the most promising concept. One concept was chosen for demonstration: water injection into the DPF through a sensor hole in the silencer housing.

The proposed injection strategy is such that when the vehicle comes in for scheduled maintenance, this water injection tool can be used to improve vehicle performance and reduce filter changes. In keeping with the criteria and design constraints, this solution eliminates the complication of additional vehicle components, while still effectively reducing ash volume.

An initial prototype and subsequent on-vehicle testing is presented which demonstrates that wetting the DPF in this manner is a viable means of reducing ash volume. The result of this test shows that this method can reduce DPF backpressure from ash by 60% after just 3 minutes of water injection. From these results, suggestion for future improvement to the performance and ergonomics of the injection tool is presented.
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Abbreviation Guide

DPF – Diesel Particulate Filter
CDPF – Catalyzed Diesel Particulate Filter
PM – Particulate Matter
DOC – Diesel Oxidation Catalyst
SCR – Selective Catalytic Reduction
ASC – Ammonia Slip Catalyst
EGR – Exhaust Gas Recirculation
1. Introduction

In 1987, the first particulate emissions standard for medium and heavy duty diesel engines was introduced by the state of California [1]. In the time since that precedent was set, the restrictions on this sort of emission have become stricter and more widespread, being implemented by North America, South America, the European Union, and many Asian nations [2]. This legislative trend has led to a direct need in industry to develop cleaner diesel power solutions.

In the context of diesel engines, approximately 99% of particulate matter (PM) emitted is defined as soot - a combustible material made of carbon and organic material [3]. The other 1% is ash – an incombustible material made of metal oxides, sulfates, and phosphates [3]. While there are several sources, the engine oil is attributed as being the primary origin of this ash [4]. It is the job of the diesel particulate filter (DPF) to capture these materials. Most modern diesel engines eliminate the soot in the DPF through oxidation in a process commonly referred to as regeneration [5]. However because the ash component is incombustible, it remains in the filter after regeneration and accumulates.

The most common DPF solution in industry is the wall-flow monolith type filter [6]. While the wall-flow monolith filter is highly effective in removing PM from the exhaust, this solution has a detrimental influence on fuel economy. Although some backpressure from the DPF is unavoidable, the accumulation and resultant distribution of soot and ash within the filter geometry has a significant contribution to the restriction of flow of exhaust gases [7]. In addition to increasing fuel consumption, this buildup of PM gradually diminishes the accessible filtration area, and ultimately dictates the service life of the DPF [3]. Testing has shown that by reducing the volume of ash in the DPF, fuel efficiency, filtration area, and filter service life can be improved [8], [9].

1.1 Optimizing PM Distribution - Ash Compaction

Convention often draws a connection between mass of ash in the DPF and pressure drop. However research suggests that DPF pressure drop is in reality, much more correlated to the volume the ash occupies in the filter [8], [9].

The scope of this thesis paper will focus on two previous laboratory tested methods by which the volume of ash can be reduced. From this testing, an ideal distribution of ash has been hypothesized. By minimizing the ash on the channel walls, and compacting it at the inlet channel plug - flow is significantly improved [8], [10]. For reference, Figure 1 shows a generalized PM distribution and flow pattern through the DPF. For further detail regarding the DPF, its characteristics, functions, and associated vehicle systems see Chapter 3, Theory and Chapter 4, Problem Definition.

I. DPF Wetting

The first means to reduce ash volume is by wetting the DPF. Testing of DPF wetting has been shown to reduce pressure drop both in the research done in [9], as well as at Scania.
II. Ash Sintering Dopant

A second method, that has not been documented as thoroughly is the concept of introducing a chemical dopant into the DPF ash to make it more dense. This technique has been tested at Scania, and was shown to have a significant reduction in ash volume [8], [10].

For further detail regarding the DPF wetting and ash sintering dopant methods see Chapter 4, Problem Definition.

1.2 Purpose

Ash loading and resultant DPF backpressure, loss in fuel economy, etc. is seen as an unavoidable expense of today’s environmental legislation. The intention of the thesis is to provide a solution to this dilemma by investigating the ways ash volume may be reduced in the DPFs of Scania diesel vehicles. The aim from this volume reduction, is that Scania diesel solutions in the future will consume less fuel and have a longer filter life – providing greater value to the customer while lessening environmental impact.

1.3 Objectives

The key objectives of this thesis paper are:

1. To explore the methods by which the ash volume reduction methods observed in a laboratory setting could be integrated on the system level in a Scania diesel truck.
2. Establish a structure of criteria to assess system integration techniques, and from this assessment select the optimal method.
3. Conduct tests to validate the criteria and check the concepts performance.

1.4 Delimitations

- As this project has been commissioned by Scania CV AB, the scope of the research will encompass the systems and components commonly employed on Scania products.
- This work will explore what it would take to make these concepts function, and perhaps whether or not it is worth the effort to do so.
2. Methodology

Chapter 2 encompasses the chosen approach to meeting the substance of the thesis purpose, objectives and delimitations (see Section 1.2, 1.3, 1.4).

2.1 TRIZ

The approach to this work was an adaptation of the TRIZ method. In this technique, the ideal final result is identified first. Each concept is assessed for contradictions between needs and abilities, dependencies, physical requirements, etc (see Figure 2). Potential solutions are then found to address these contradictions [11]. The intention was to mature the technical level behind DPF wetting and ash doping methods, and find the best solution. To meet this end result, the thesis workflow was divided into six stages (see Section 2.1).

![Figure 2 – Graphic of the adaptation of the TRIZ method used in the thesis work.](image)

2.2 Workflow

The following section describes the workflow of this thesis paper:

![Figure 3 – Thesis workflow, resources and outcomes included.](image)
Work stage definitions:

1. Pre-Study

The pre-study phase was an exploratory study into the current Scania truck system and the relevant mechanisms which could play a role in implementing the considered ash compaction methods. This was conducted through literature review and interview of relevant experts at Scania. Unstructured interviews of Scania employees were conducted throughout the work to gain relevant information. The pre-study stage created a foundation for the preliminary design contradictions, physical requirements, etc. for both ash doping and DPF wetting. This work embodied objective 1 in Section 1.3.

2. Concept Generation for System Integration

The information gained in the pre-study resulted in a number of general concepts for the system level implementation of DPF wetting and ash doping (see Chapter 5). These concepts were based on the counsel of Scania experts as well as literature study of similar solutions in industry.

3. Concept Functional Design

The functional design phase was conducted to elucidate the potential design contradictions of each generated concept. System integration concepts were individually studied through literature review, theoretical calculation, and interview of industry experts. This resulted in an overview of each concepts contradictions – needs and abilities, dependencies, physical requirements, etc.

DPF wetting and ash doping concepts were then organized into matrices encompassing the findings of this stage. Due to the significant difference in relevant considerations, the DPF wetting and ash doping concepts were structured separately. One matrix contains general benefits and drawbacks of different approaches. Another matrix contains design considerations, solutions, and unknowns for each concept (see Chapter 6).

4. Criteria Development

The functional design phase raised numerous contradictions and associated solutions for each concept. However, in order to establish their true feasibility it was necessary to determine the importance of each contradiction. In collaboration with relevant experts at Scania, a list of essential criteria for ash doping and DPF wetting implementation concepts was generated. These criteria embodied the contradictions which were deemed critical to the success of integrating one of these methods into the current system.

5. Concept Selection

In order to determine the relative viability of each concept, the list of criteria was organized in a contradiction matrix adapted from the TRIZ method [12]. This matrix compared each concept against the criteria and offered potential solutions to some contradictions (see Appendix E).

In an exercise with Scania experts, the criteria matrix was utilized to assess a few concepts which were perceived to show the most promise. This exercise weighed these concepts against the design criteria. A final concept was chosen due to its few contradictions and ease of implementation. This work embodied objective 2 in Section 1.3.
6. Prototype & Proof of Concept

A prototype of the selected concept was fabricated and subsequently tested on a truck. The testing provided a proof of concept for this approach to reducing ash volume in the DPF. The collected data gave a preliminary view of the effectiveness of this method as well as direction for further improvement. This stage embodied objective 3 in Section 1.3.

2.3 Thesis Structure

The thesis is organized sequentially with respect to the workflow outlined above (see Figure 4). Chapters 1-4 cover the findings of the pre-study stage. Chapter 5 presents the generated concepts. Chapter 6 encompasses the design considerations relevant to the concepts. Chapter 7 contains the results of the concept selection process and the testing of the concept. Chapter 8 presents the discussion and conclusions of the paper. Finally, Chapter 9 outlines suggestions for future development.

![Figure 4 – Thesis structure.](image-url)
3. Theory

Chapter 3 covers the theory behind the process known as regeneration as well as the foundation of the theory behind exhaust flow through the DPF.

3.1 Regeneration: Oxidation of Soot in the DPF

The job of the DPF catalyst is to take the nitrogen oxide emissions from the engine, and by an equilibrium process, convert the $NO$ to $NO_2$ [5]:

$$NO + \frac{1}{2}O_2 \leftrightarrow NO_2 \quad (1)$$

This $NO_2$ in turn oxidizes the soot particulate matter (in the form of carbon) present in the filter:

$$NO_2 + C \rightarrow NO + CO \quad (2)$$

$$NO_2 + C \rightarrow \frac{1}{2}N_2 + CO_2 \quad (3)$$

The rate at which the regeneration process takes place is a function of temperature and $NO_2$ concentration. Higher temperatures and $NO_2$ concentrations result in an increased filter regeneration rate [5]. For further detail regarding the regeneration process, see Section 4.1.1.

3.2 Fluid Dynamics

Section 3.2 presents the foundation for the theory behind exhaust flow through the DPF.

3.2.1 Darcy’s Law

Darcy’s Law can be used to describe the instantaneous discharge rate through a porous medium – the DPF filter in this case – as a function of fluid viscosity, and pressure drop over a length. For the purposes of simplification, it has been assumed that the cordierite in the DPF is isotropic. Incompressible flow is also assumed.

I. Derivation

For flow which is considered to be incompressible, creeping and stationary, the Navier-Stokes equation can be reduced to:

$$\mu \nabla^2 u_i + \rho g_i - \partial_i p = 0 \quad (4)$$

Where $\mu$ is viscosity, $u_i$ is velocity in direction $i$, $g_i$ is the gravity in direction $i$, and $p$ is pressure.

In this form, Equation 4 is known as the Stokes equation.

Next, with the assumption that the relationship between velocity and viscous resisting force behaves linearly:

$$-(k_{ij})^{-1}\mu \phi u_j + \rho g_i - \partial_i p = 0 \quad (5)$$

Where $k_{ij}$ is second order permeability tensor, and $\phi$ is porosity.
The velocity in direction \( n \) can be described as:
\[
k_{ni}(k_{ij})^{-1} u_j = \delta_{nj} u_j = u_n = \frac{k_{ni}}{\mu} (\phi_i p - \rho g_i)
\]
(6)

With the assumption of isotropy, i.e. \( k_{ij} = 0 \) for \( i \neq j \) and \( k_{ii} = k \), the volumetric flux density can then be written as:
\[
q = -\frac{k}{\mu} (\nabla p - \rho g)
\]
(7)

II. Modification to Accommodate DPF Flow

When considering flow in the DPF, the Reynolds number is greater than 1. This means that the inertial effects of the flow must also be considered. As such, to Darcy’s equation is modified to take inertia into account by adding the Forchheimer term [13].

In order to describe this non-linearity of the relationship between pressure and flow data, the following Darcy-Forchheimer law may be used [13]:
\[
\frac{\partial p}{\partial x} = -\frac{\mu}{k} q - \frac{\rho}{k_1} q^2
\]
(8)

Where \( k_1 \) is inertial permeability.

3.2.2 Darcy–Weisbach Equation

The Darcy-Weisbach equation is a fluid dynamics principle which can be used to relate pressure loss to the average velocity of incompressible fluid flow in a length of pipe [14].
\[
\Delta p = \rho \cdot g \cdot \Delta h
\]
(9)

Where \( \Delta p \) is the pressure loss, \( \rho \) is the fluid density (kg/m\(^3\)), \( g \) is gravitational acceleration (m/s\(^2\)), and \( \Delta h \) is the head loss (m).

Relating head loss per unit length of pipe (\( S \)):
\[
S = \frac{\Delta h}{L} = \frac{1}{\rho \cdot g} + \frac{\Delta p}{L}
\]
(10)

Where \( L \) is pipe length (m)

In terms of volumetric flow:
\[
Q = \frac{\pi}{4} D^2 \cdot v
\]
(11)

Where \( Q \) is the volumetric flow (m\(^3\)/s), and \( D \) is the hydraulic diameter, and \( v \) is the mean flow velocity.

\[
S = f_D \cdot \frac{8}{\pi^2} \cdot \frac{Q^2}{D^5}
\]
(12)

Where \( f_D \) is the Darcy friction factor.

Thus, by relating pressure loss due to friction, volumetric flow, and hydraulic diameter:
\[
\Delta p = \frac{\rho f_D L v^2}{2D} = \frac{8\rho f_D L Q^2}{\pi^2 D^5}
\]
(13)
4. Problem Definition

Chapter 4 contains an overview of the particulate filter, its functions, and other relevant vehicle systems. In addition, the effects of DPF wetting and ash doping are elaborated upon. Applied theory is presented regarding exhaust flow through the DPF, and the potential benefits of ash volume reduction.

4.1 Vehicle System Overview

Section 4.1 introduces the mechanisms present in the DPF. In addition, several other relevant vehicle functions are presented; including the exhaust treatment, lubrication system, and fuel system.

4.1.1 Diesel Particulate Matter Filtration

I. Diesel Particulate Filters (Wall-Flow Monolith)

The function of the DPF is to allow exhaust gases to pass through, while solid matter is captured. The wall-flow monolith type filter is manufactured from a porous ceramic material [6], and in the case of this study, cordierite. The porous nature of this material allows for gas flow while filtering out 70-95% of PM [6]. The filter is configured such that there are a series of adjacent channels, plugged in an alternative pattern at each end (see Figure 5).

![Figure 5 – DPF (outlet) installed in silencer, with cover removed.](image)

The channels open to the inflow of exhaust are referred to as inlet channels whereas those which are plugged at the filter intake are outlet channels (see Figure 6). The filter functions by allowing gas and PM to enter the inlet channels, once the exhaust reaches the plug at the end of the inlet channel the gas is forced to flow through the porous wall to the outlet channel, leaving
PM behind (see Figure 1). The filtered exhaust then continues to flow through the system and to exit the vehicle.

![Diagram of channel pattern](image)

*Figure 6 – Small section of the channel pattern used in wall-flow monolith filters (DPF inlet).*

II. Passive Regeneration

The process of regeneration refers to the oxidation of diesel PM into gaseous products. This reduces the amount of solid PM blocking exhaust flow in the DPF. In many applications, this process is accomplished through raising the temperature in the DPF to 550-650°C in order to induce oxidation of the soot [15]. This method is referred to as active regeneration.

For the purposes of this study, an alternate method for soot oxidation will be considered – passive regeneration. In a passive regeneration process, soot oxidation is accomplished not through raised temperatures, but rather by use of a catalyst which enables oxidation to take place within the temperature range of normal operation, 300-400°C [15]. The catalyst is coated onto the filter media in order to encourage the chemical reaction mechanisms of nitrogen dioxide present in the exhaust gas [16] (see Section 3.1).

In cases of excessive PM accumulation, the Scania regeneration strategy includes a post injection of fuel to increase exhaust temperatures and aid the oxidation process (see Section 4.1.4). Alternatively, exhaust braking can also be used to increase exhaust temperatures depending on the vehicle model [17]. In extreme cases, the driver may have to park the vehicle for this process to run; this is referred to as parked regeneration [17].

III. Soot and Ash Accumulation in the DPF

As previously discussed, the PM produced by diesel engines is categorized as either soot or ash. Soot is a carbon based product of the diesel fuel combustion which the DPF captures along its inlet channels. While soot accumulation does restrict flow, the regeneration process is capable of effectively removing the soot from the DPF. However, the incombustible ash is left behind after the regeneration process. This ash comes from lubricant additives, engine wear and corrosion, and trace elements in the fuel [7].

As the filter undergoes multiple regenerations over its service life, the fraction of ash progressively grows until it exceeds the amount of soot caught by the DPF. This ash fraction eventually reaches such a level that regeneration can no longer reduce the PM loaded in the
filter to an acceptable level. The filter must then be removed from the vehicle and either cleaned or replaced.

- **Filter Performance**

  The buildup of ash acts as a barrier between the soot and the walls of the DPF (see Figure 7). For the catalyzed DPF considered in the context of this study, this presents an additional issue. The accumulated layer of ash blocks the soot from making physical contact with the catalyst particles, this has a detrimental effect on the amount of time necessary to oxidize the soot.

![Figure 7 – Sketch of inlet channel ash accumulation and resultant soot distribution/channel hydraulic diameter.](image)

- **Cost: Fuel Economy & Service Life**

  The reduction of catalyst effectiveness discussed above is also linked to a loss in fuel economy. As the surface area available for catalyst-soot contact is reduced, the DPF must rely increasingly on higher exhaust temperatures to facilitate oxidation [7]. The fuel economy is also hurt by ash accumulation as a result of the aforementioned filter flow restriction and exhaust backpressure.

  In addition to its influence on fuel consumption, the periodic replacement of the DPF is an expensive endeavor. The filter is a rather costly component, and its replacement requires a significant amount of time - representing further lost wages for the vehicle owner.

- **Influencing Factors**

  The additives present in diesel engine lubricant are attributed as being the primary source of ash [7]. These additives mostly comprise of calcium and other metal-based detergents. The ash resulting from lubricant is mostly made up of calcium sulfate [18]. Depending on the chemistry of the lubricant, the behavior of the ash can be markedly different. The porosity, permeability, and packing density of the ash all appear to be related to the lubricant composition. For instance, calcium detergent has been found to contribute to a higher pressure drop than zinc-based compounds [18].

  Exhaust conditions can also determine the properties of the ash. At high temperatures, the sintering and consequent filter wall adhesion of the ash can be reduced. Additionally, exposure to high temperatures has been shown to produce a reduction in ash volume, and resultanty a decrease in pressure drop from ash [7].
The method of regeneration implemented has also been shown to affect ash properties. In the case of passive regeneration, temperatures and the amount of accumulated soot are relatively low. When compared to active regeneration, passive regeneration conditions result in less dense ash. Passive regeneration causes greater amounts of ash on the channel walls and little ash accumulation at the channel plugs [7].

Depending on filter material and geometry, the ash buildup and storage capacity can vary. The filter pore size can be optimized such that soot is trapped in a more efficient manner. However, the porosity only has a significant impact as long as the ash has not already accumulated on the filter walls. Once this has happened, the pressure drop as a result of ash loading is more or less the same for the common filter materials [7]. Furthermore, it has been found that ash layer thickness is a function of channel wall morphology [19].

4.1.2 Scania Exhaust Treatment System

Figure 8 – Scania exhaust treatment integrated silencer, consisting of DOC, DPF, and SCR. (Source: Scania)

Due to environmental restrictions, there are a number of elements in the diesel engine exhaust that must be removed before it is released into its surroundings. The current Scania after-treatment system consists of a diesel oxidation catalyst (DOC), the DPF, selective catalytic reduction (SCR), and the ammonia slip catalyst (ASC) (see Figure 9) [8].

Figure 9 also includes exhaust gas recirculation (EGR) – this system is only employed on a few Scania vehicle models [20]. EGR is the process by which exhaust gas is cooled, and recycled through the engine before flowing downstream. This assists in reducing the NOx emissions produced by the engine [21].
Once the exhaust has been run through the engine, it reaches the DOC. The purpose of the DOC is to oxidize carbon monoxide, gas phase hydrocarbons, and organic diesel particulate matter [22]. The DOC also converts NO to NO₂ to assist soot regeneration in the DPF. Next, the exhaust flows through the DPF where the remaining particulate matter is captured. The final treatment is the SCR, this process utilizes a catalyst and urea injection (AdBlue®) in order to reduce the emission of NOx. This ammonia converts the NOx over the SCR catalyst, and the unreacted NH₃ is oxidized in the ASC [23].

4.1.3 Scania Engine Lubrication System

The function of the engine lubrication system is to reduce friction between essential moving components (see Figure 10). This process is essential to maintaining a well running engine. A lack of lubrication has the potential to damage the engine beyond repair as a result of increased temperature from dry friction [24]. Engine oil is transported from the oil sump to the strainer by a pump. The oil then flows through a safety valve which functions as a system pressure regulator. The lubricant is then directed to various engine lubrication points including the connecting rod bearings, the crankshaft bearings, etc. Once the oil has passed through these points, it flows through an oil cooler to help regulate the engine operating temperature. Finally before returning to the sump, contaminants in the lubricant are removed by use of an oil filter and a centrifugal oil cleaner [24].

![Figure 9 – Example of common Scania exhaust treatment system configuration. (Source: Scania)]

![Figure 10 – Scania engine lubrication system, main components [25].]
I.  Engine Oil Consumption

Depending on the engine configuration, there are several causes of oil consumption: the turbocharger, crank case ventilation, valve stem seals, etc. However, the largest contributor to oil loss is considered to be the cylinder system [4]. While the pistons are driven up and down by the combustion process, lubricant is used to line the cylinder walls in order to reduce friction, temperature, etc. There are piston rings in place to seal the combustion gases and prevent the oil from leaking into the combustion chamber. Though the tolerances are such that a fraction of the oil escapes nevertheless. There are three generally recognized mechanisms by which this oil is consumed: throw-off, reverse gas flow, and evaporation (see Figure 11) [4].

![Figure 11 – Engine oil consumption mechanisms](image)

While there are general approximations for the oil consumption rate, the true value can vary significantly. The vehicle operation type (long distance haulage, construction, etc.), driver behavior, and condition of the engine all play a large role in the amount of oil an engine will burn off into the exhaust [26]. This combusted oil turns out to be the primary source of ash deposited in the DPF [8].

4.1.4 Scania Fuel System

The fuel system employed on Scania trucks is commonly referred to as the XPI fuel system (see Figure 12). This system is managed by the engine control unit. The fuel is first pumped from the tank through a pre-filter and water separator by use of a low pressure pump. Then the fuel is further cleaned in the high pressure fuel filter. Next, the fuel is pumped to the high pressure pump. From the high pressure pump, the fuel goes to the fuel rail, the injectors and into the combustion chambers. In order to prevent too much pressure, there is a mechanical dump valve between the rail and the injectors. This valve dumps fuel back to the tank if pressure is too high [27].
I. Multiple Injections

Depending on engine demands, the XPI system may employ multiple injections (see Figure 13). A pilot injection may be used just before the main injection to lessen noise [28]. Additionally, a post injection can be used after the main injection to lessen soot and NOx emissions. This post injection is utilized to control exhaust temperature for downstream exhaust treatment systems, e.g. DPF regeneration [28].

$$\Delta p = \frac{\rho f_D L Q^2}{2D} = \frac{8\rho f_D L Q^2}{\pi^2 D^5}$$  \hspace{1cm} (13)

From Eqn. 13, it can be seen that pressure loss is a function of pipe hydraulic diameter to the fifth power. This mathematically demonstrates an extreme sensitivity to changes in wetted cross sectional area in a pipe. While the Darcy-Weisbach equation does not precisely model the case of flow in the DPF, the importance of the relationship between pressure drop and hydraulic
diameter holds true. This equation lends credence to the significance of the reduction of inlet channel wetted area from PM accumulation along the DPF walls, as it pertains to pressure drop.

In a clean filter (devoid of particulate emissions from the engine), the pressure drop may be characterized using three distinct components [6]. The first is pressure drop from sudden contraction and expansion at the filter inlet and outlet, \( \Delta P_{\text{in/out}} \). The second pressure drop considered is the result of friction along the channel walls, \( \Delta P_{\text{channel}} \). Lastly, the pressure drop due to the permeability of the channel walls, \( \Delta P_{\text{wall}} \).

As the DPF is constructed from a porous material, the Forchheimer extended Darcy equation must be used in order to accurately represent the gradual transition from laminar flow to turbulent:

\[ \Delta P_{\text{wall}} = \left( \frac{\mu}{k_w} \right) * v_w * w + \beta * \rho * v_w^2 \]  

(14)

Where \( \mu \) is dynamic viscosity of exhaust gas \((\text{Pa-s})\), \( k_w \) is permeability of filter material \((\text{m}^2)\), \( v_w \) is exhaust flow per unit of filtration area \((\text{m/s})\), \( \beta \) is inertial resistance coefficient \((1/\text{m})\), \( \rho \) is gas density \((\text{kg/m}^3)\), and \( w \) is wall thickness \((\text{m})\) [6].

The pressure drop resulting from friction in the channels:

\[ \Delta P_{\text{channel}} = 4f * \left( \frac{L}{d_{\text{ch}}} \right) * \left( \frac{\rho v^2}{2} \right) \]  

(15)

Where \( f \) is the Fanning friction factor (dimensionless), \( L \) is substrate length \((\text{m})\), \( d_{\text{ch}} \) is channel diameter \((\text{m})\), and \( v \) is linear velocity of gas in channels \((\text{m/s})\).

The linear gas velocity in the channels:

\[ v = \frac{W}{(\rho * A_F)} \]  

(16)

Where \( A_F \) is substrate open frontal area \((\text{m}^2)\), and \( W \) is total mass flow rate \((\text{kg/s})\).

To calculate the Reynolds number:

\[ N_{\text{Re}} = \frac{v * d_{\text{ch}} * \rho}{\mu} \]  

(17)

Where \( \mu \) is dynamic viscosity \((\text{kg/m}*\text{s})\).

The Fanning friction factor for laminar flow:

\[ f = \frac{K}{N_{\text{Re}}} \]  

(18)

Where the friction coefficient \( K = (f^*N_{Re}) \).

For gas contraction, \( K_{\text{in}} \) may be approximated as [6]:

\[ K_{\text{in}} = -0.415 * \frac{A_F}{A} + 1.08 \]  

(19)

For gas expansion, \( K_{\text{out}} \) may be approximated as:

\[ K_{\text{out}} = (1 - A_F/A)^2 \]  

(20)

The inlet/outlet pressure drop can be calculated as:

\[ \Delta P_{\text{in/out}} = K_{\text{in/out}} * (\rho v^2 / 2) \]  

(21)
The total pressure drop over a clean filter is then:

$$\Delta P_{\text{clean}} = \Delta P_{\text{in/out}} + \Delta P_{\text{channel}} + \Delta P_{\text{wall}}$$ \hspace{1cm} (22)

### 4.2.2 Particulate Loaded Filter

The more pertinent condition is one where the DPF has been loaded with PM. The task of mathematically modelling this state requires a few changes to the initial case of the clean filter. During engine operation, the walls of the filter will be covered with PM. This phenomenon will necessitate consideration of the parameters of the soot in addition to the filter wall (see Eqn. 14). As a result that the pores in the filter wall now have deposits of soot blocking flow, $\Delta P_{\text{wall}}$ increases. Additionally, $\Delta P_{\text{channel}}$ increases due to the channel hydraulic diameter shrinking as a result of the PM deposits (see Eqn. 13). This reduction in hydraulic diameter also has an influence on $\Delta P_{\text{in/out}}$, which will increase as a result of the increasing gas contraction [6].

This additional parameter changes the total pressure drop equation to:

$$\Delta P_{\text{loaded}} = \Delta P_{\text{in/out}} + \Delta P_{\text{channel}} + \Delta P_{\text{wall}} + \Delta P_{\text{particulate}}$$ \hspace{1cm} (23)

Where $\Delta P_{\text{particulate}}$ is pressure drop as a function of the permeability of the particulate layer.

### 4.2.3 Soot-Laden Filter

The condition of a soot-laden monolith requires more detailed versions of the terms in Eqn. 23. A previously developed example [29] of a model for this case is:

$$\Delta P = \mu Q/(2VN) \left\{ \frac{w}{k_w d} + \frac{1}{2k_s} \cdot \ln \left( \frac{d}{d - 2w_s} \right) + \frac{4FL^2}{3} \cdot \left( \frac{1}{(d - 2w_s)^4} + \frac{1}{d^4} \right) \right\} + \rho Q^2/(V^2N^2d^2) \left\{ 2\zeta \cdot \left( \frac{1}{2} \right)^2 + \beta w/4 \right\}$$ \hspace{1cm} (24)

Where $Q$ is gas flow ($m^3/s$), $V$ is monolith volume, ($m^3$), $N$ is cell density ($m^{-2}$), $k_w$ is permeability of soot-loaded wall ($m^2$), $d$ is channel size (hydraulic diameter) ($m$), $w_s$ is soot layer thickness ($m$), $k_s$ is permeability of soot layer ($m^2$), $F = 28.454$ (factor related to friction losses in channels), $L$ is filter length ($m$), and $\zeta$ is channel inlet/outlet friction loss coefficient (dimensionless) [6].

### 4.3 Optimization of Particulate Matter Distribution in the DPF

Under standard conditions, the ash in the DPF is rather incompact. This distribution of ash occupies a significant volume of the DPF. Section 4.3 discusses the benefits of reducing ash volume, and two different approaches to achieving this.

By compacting the PM in the filter, $\Delta P_{\text{in/out}}$, $\Delta P_{\text{channel}}$, $\Delta P_{\text{wall}}$, and $\Delta P_{\text{particulate}}$ can all be reduced when compared to a standard case (see Figure 14). This allows for improved exhaust flow, and increased filter service life as the PM occupies less space [8].
4.3.1 Wetting the DPF

In Application of Pre-DPF Water Injection Technique for Pressure Drop Limitation (SAE Technical Paper 2015-01-0985), the experimental setup consisted of a diesel engine fitted with a calibrated nozzle for water injection at the DPF inlet. The injection of water acts as a transport mechanism for PM to be deposited at the inlet channel plug. Ash on the channel walls greatly restricts gas flow through the filter (see Section 3.2.2). Moreover, due to the low permeability of ash, when it is collected along the channel walls it can result in lowered soot oxidation rates [30]. As a result of this lack of effective soot removal, the flow of exhaust gases are further inhibited. Using liquid water to displace the ash particles improves flow and allows for greater penetration of soot into the filter walls – facilitating better catalytic oxidation. It is shown in [30] that the pressure drop as a result of these low permeability ash particles decreases when ash particles are compacted at the inlet channel plug. The method of wetting the DPF has been submitted for patenting by the company Corning, under US 2013/0045139 A1.

Previous testing at Scania has investigated the effect of wetting the DPF, subsequently drying the filter, and then measuring its pressure drop in a flow rig [8]. The findings of this study can be seen in Figure 15). The deduction of the bench test was that by wetting the DPF, the backpressure from ash had been reduced by 70% [8].
A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters

Figure 15 – The effect of wetting the DPF on pressure drop over the filter. The blue line indicates pressure drop before adding water to filter, the orange line indicates after water injection, the grey line indicates pressure drop over a new filter free of ash. (Source: Scania)

I. Soot Penetration

As water transports the PM along the channel walls, the penetration of soot into the channel wall may increase [9]. This would result in a more homogeneous distribution of the soot. From Eqn. 13, it can be reasoned that the pressure drop over a homogenous porous substrate would be significantly lesser than that of a heterogeneous one with low permeability, i.e. ash deposit.

Heterogeneous distribution can be considered as a section of low permeability, i.e. soot penetrated, saturated wall and a section of high permeability, i.e. the clean component of the channel wall. The composite permeability of these two sections can be modelled as parallel resistances (see Figure 16) [31].

Figure 16 – Circuit diagram of the DPF flow resistances resulting from a heterogeneous distribution of PM. Where \( \Delta P \) is the pressure drop, \( R \), soot is the flow resistance caused by soot permeability, and \( R \), clean wall is the flow resistance caused by the permeability of a clean, porous channel wall.

The advantage of water injection is that greater soot penetration results in a homogeneous substrate, and further, the PM layer avoids saturating the channel walls. The confluence of these phenomena result in a reduced pressure drop.
4.3.2 DPF Ash Dopant

Another promising method of reducing ash volume in the DPF is the introduction of a chemical which would in effect reduce the sintering temperature of the ash. By doing so, the ash-dopant mixture would melt under normal exhaust temperatures; making it denser. An added benefit of the sintering mechanism is that it increases ash particle size [32]. These larger ash particles are then less likely to penetrate the porous channel walls. This makes the ash more prone to be picked up off the channel walls by the flow of exhaust gases and deposited at the inlet plug as desired [8].

I. Sintering Thermodynamics

The term sintering, refers to the process by which atomic diffusion in a powder takes place at temperatures which are elevated, $T > 0.5$ Melting Temp. The result of this process is an increased density of the material [32].

From a thermodynamics aspect, Gibbs free energy must decrease in order for sintering to take place. This is accomplished by trading solid-solid interfaces ($\Gamma_{ss}$) from solid-vapor interfaces ($\Gamma_{sv}$) e.g. $\Gamma_{ss} < \Gamma_{sv}$ [32].

The equation describing this thermodynamic potential is:

$$G(p, T) = U + pV - TS$$  \hspace{1cm} (25)

Where $p$ is pressure (Pa), $T$ is temperature (K), $U$ is internal energy (J), $V$ is volume ($m^3$), and $S$ is entropy (J/K).

The change in system energy which results in sintering can be modelled as:

$$dE = \Gamma_{ss} dA_{ss} + \Gamma_{sv} A_{sv} < 0$$  \hspace{1cm} (26)

Where $\Gamma_{ss}$ is solid-solid interface (J/g), $\Gamma_{sv}$ is solid-vapor interface (J/g), $dA_{ss}$ is change in the total surface area of the grain boundaries, and $dA_{sv}$ is total free surface area.

In the case of sintering, $dA_{ss} > 0$ and $dA_{sv} < 0$, and the process ceases when $dE = 0$ [32].

II. Sintering and Ash Morphology in DPF

Bench testing conducted at Scania has shown that the addition of a dopant with a lower melting temperature to the ash can effectively result in a densification process which reduces the volume of ash. This densification process could theoretically reduce DPF pressure drop by reducing ash-filled volume, and increasing hydraulic diameter (see Eqn. 24).

Various examples in literature such as [33], [34], and [35] have drawn conflicting conclusions regarding the effects of ash sintering. In [33], [34] sintering is credited with giving the ash increased stickiness, causing adherence of ash along the DPF walls, and increasing filter backpressure. However, the data presented in [35] appears to contradict this assertion, and attributes sintering with reducing DPF pressure drop.

III. Dopant Particle Settling Time

One concern with introducing a dopant into the engine fluids is the possibility of the dopant particles settling to the bottom of their respective reservoir rather than circulating through the
system as intended [26]. The rate at which a particle settles in a given fluid can be modeled using the Stokes Law (See Appendix B for related calculations):

\[ V = \frac{2r(p_r - p_f)}{9\mu} \cdot g \cdot R^2 \]  

(27)

Where \( p_r \) is density of the particle (kg/m\(^3\)), \( p_f \) is density of the matrix (kg/m\(^3\)), \( \mu \) is dynamic viscosity (kg/m\(\cdot\)s), \( R \) is particle radius (m), and \( g \) is gravitational acceleration (m/s\(^2\)).

### 4.4 Economics of DPF Ash Volume Reduction

There is a necessary consideration as to which approach to ash volume reduction brings the most value. There is a tradeoff between increasing DPF service life and reducing pressure drop. A system strategy optimized to prolong DPF service life would not necessarily provide the maximum reduction in backpressure and vice versa (see Figure 18).

#### 4.4.1 DPF Pressure Drop & Filter Life

From the DPF pressure drop model outlined in [36], an approximation of the benefits of various ash volume reduction approaches can be derived. In the model, exhaust volumetric flow rate through the DPF was taken as a constant 0.56 m\(^3\)/s. In Figure 17, the red data markers indicate points at which the DPF must be replaced. The blue data markers indicate ash volume reduction as a maintenance service. It can be seen that reducing ash volume could significantly lessen the number of times a vehicle would need to come in for DPF replacement.

![Effect of ash volume reduction on DPF service interval](image)

*Figure 17 – Influence of ash volume reduction on DPF life. Shown is the standard system in contrast to two volume reduction strategies – increasing filter life, and ash compaction as a maintenance service.*
Problem Definition

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Figure 18 – The effect of ash volume reduction on DPF pressure drop. Shown is the standard system in contrast with ash volume reduction strategies; from increasing filter life to continuous compaction.

Figure 17 and Figure 18 are approximations intended to illustrate the difference in DPF pressure drop between various approaches to ash compaction. While general conclusions may be drawn from the relative pressure drops in the same figure, comparison between figures would be invalid. Furthermore, this model has not been validated – the true scale of the pressure drop over the filter may vary in reality.

4.4.2 Improving Fuel Economy

Exhaust backpressure is paired with an increase in fuel consumption. Taking this into account, the fuel consumption gains from ash volume reduction can be quantified. For a Scania 13 liter engine, it is estimated that every 100 mbar in backpressure corresponds to a 1.7% increase in fuel consumption [8]. In Figure 19 it can be seen that ash volume reduction has a notable improvement in fuel economy. From the model in Figure 19, a system which continuously reduces the ash volume consumes on average, 0.06 l/100km less fuel than the standard system – or a 0.2% improvement. Whereas ash compaction as a maintenance service could save on average, 0.04 l/100km – or a 0.14% improvement.

Figure 19 – Fuel consumption as a function of vehicle mileage. Shown is the model for the current system in contrast with continuous ash compaction, and one where ash volume is reduced as a maintenance service.
5. Ash Volume Reduction Concepts

Chapter 5 contains the developed concepts for integrating either DPF wetting (Section 5.1) or ash doping (Section 5.2, 5.3) into the systems on a Scania truck.

5.1 Wetting of the DPF

Section 5.1 covers concepts for integrating a DPF wetting method into the vehicle systems. For the relevant design considerations for these concepts, see Chapter 6.

5.1.1 Water Injection – DPF Inlet

One potential approach to wetting the DPF would be to inject water into the DPF inlet (see Figure 20). In the silencer housing, there is a cluster of sensors between the DOC outlet and the DPF inlet [37]. These sensors are used to measure temperature, and pressure drop over the DPF for engine management (see Figure 21).

![Flow of Exhaust Gas, PM](image)

**Figure 20 – Sketch of DPF inlet water injection concept.**

There is only about 8 cm between the DOC outlet and the DPF inlet in the current configuration. This makes it difficult to install an effective on-board water injection system without simultaneously obstructing the flow of exhaust gases [38]. However, one of the sensors could be removed during routine maintenance to allow water to be sprayed into the DPF inlet [37].
5.1.2 Water Injection – DPF Outlet

Previous testing at Scania has shown that wetting the DPF from the filter outlet also shows good performance [8]. In Figure 29 the silencer housing is shown, highlighting the DPF service lid. This lid is used to access the filter for replacement. Directly behind the service lid is the DPF outlet (see Figure 5). A potential method for wetting the DPF could be to install an injector system in the service lid to transport water directly to the DPF outlet (see Figure 22).

5.1.3 Water Injection – DOC Inlet

Water could be injected through the DOC to reach the DPF inlet (see Figure 23). In older Scania truck models, there is a diesel fuel injector present at the DOC inlet. This injector is used to help facilitate oxidation in the exhaust treatment catalysts. While this method is being phased out of production [37], it is possible that a similar system could be used for wetting the DPF.
Alternatively, there is a NOx sensor at the DOC inlet which could potentially be removed during maintenance to inject water [37].

![Sketch of DOC inlet water injection concept.](image)

**Figure 23 – Sketch of DOC inlet water injection concept.**

### 5.1.4 Wetting of the DPF - Condensed Exhaust Water

Instead of an extraneous water injection system, there is the possibility to control the operation of the diesel engine to produce an excess of condensed water. This can be achieved in a number of ways. The products of the idealized diesel combustion are carbon dioxide and water vapor [17]. As a result, high quantities of water vapor are present in the exhaust gas under normal operating conditions; usually around 6-7% [17]. A heat exchanger of some form in the exhaust flow could also be used to reduce exhaust temperature to facilitate water condensation.

An alternative to adding a heat exchanger could be to capitalize on the conditions of a cold start. When the engine is initially started, the exhaust is at its lowest operating temperature. A high fuel-air ratio at a low engine revolution increases the water content of the exhaust [10]. This combined with low exhaust temperatures can result in additional condensed water in the exhaust flow [17].

### 5.1.5 Wetting of the DPF - Pre-DPF SCR

Scania and MAN aim to have a common after-treatment system between the two company’s vehicles by 2020 [38]. Part of the proposed after-treatment system is an additional urea dosing upstream of the DPF (see Figure 26) [38]. This urea injector could be used as a way to periodically inject water into the DPF.

### 5.2 Ash Sintering Dopant

Section 5.2 encompasses the concepts relevant to introducing an ash volume-reducing dopant to the DPF. For the design considerations of these concepts, see Chapter 6. Relevant calculations may be found in Appendix A - Dopant Concentrations, and Appendix B – Dopant Particle Settling Times.

#### 5.2.1 Dopant Transport Mechanisms – Engine Oil Consumption

Dopant introduced into the engine lubricant formula could be used as a method to transport the dopant to the DPF (see Figure 24). Due to the ash being produced from engine oil, a desired
mass fraction of dopant in the lubricant would have an equivalent mass fraction in the ash produced [8]. This dopant in the ash from oil could then effectively make it to the DPF to serve its purpose. For further detail regarding the lubrication system, see Section 4.1.3.

![Figure 24 – Concept of dopant in engine oil flow to DPF.](image)

5.2.2 Dopant Transport Mechanisms – Fuel Additive

A more direct method by which the dopant could be introduced to the exhaust is by addition to the fuel (see Figure 25). After combustion in the engine, the dopant could be transported by the flow of exhaust gas. For further detail regarding the fuel system, see Section 4.1.4.

![Figure 25 – Concept of dopant in fuel flow to DPF.](image)

5.3 Dopant Transport Mechanisms – Other

Section 5.3 encompasses methods of transporting dopant to the DPF which do not involve the engine combustion system. For the relevant design considerations for these concepts, see Chapter 6. Additional detail can also be found in Appendix C and E.

5.3.1 Dopant Transport Mechanisms – Solution of Water and Dopant

Depending on the DPF wetting system (see Section 5.1), it could be possible to add dopant to the water solution.

5.3.2 Dopant Transport Mechanisms – Pre DPF SCR

In the future Scania-MAN pre-DPF SCR system, the dopant could be added to the urea mixture as a method of dosing the DPF. Alternatively, there could be a chemical metering pump to introduce dopant to the AdBlue flow exclusively upstream of the DPF (see Figure 26). For calculations relevant to the concentration of dopant in AdBlue see Appendix A.
5.3.4 Dopant Transport Mechanisms – DOC Intake

A dosing system at the DOC intake could be used to transport dopant to the DPF with exhaust flow (see Figure 27). A similar strategy has been used on Scania trucks for the purposes of injecting fuel into the DOC to help facilitate oxidation [37].

5.3.5 Dopant Transport Mechanisms – Filter Media Coating

United States Patent No. 8,356,475 B2 (McGinn, et al. 22/01/13) outlines a method for slow release of a catalyst in a particulate filter. The proposed approach is such that an alkali metal oxide-based catalyst is incorporated in a glass. This allows the catalyst to slowly leach from the glass over time. The rate at which this process takes place can be controlled by changing the characteristics of the glass. A similar approach could possibly be employed to release a dopant from the filter media into the captured ash (see Figure 28).

The results of analysis presented in [39] has shown with an alkali coating on the DPF, the alkali is not constrained to the filter wall but will migrate into the ash layer. This could allow ash not directly in contact with the filter wall to sinter.
6. Concept Design Considerations

Chapter 6 contains the relevant considerations for integrating the proposed concepts in Chapter 5 into the Scania vehicle systems. The chapter provides an overview of the benefits and drawbacks of various approaches. In addition, the chapter presents design considerations, solutions, and unknowns relevant to both the functional design, and system integration of the concepts. This information is the product of literature review and interview of Scania employees with expertise in the discussed mechanisms.

6.1 DPF Wetting Design Considerations

Section 6.1 encompasses the various design considerations relevant to implementing the DPF wetting concepts outlined in Chapter 5 on a Scania truck. For further detail, see Appendixes C and E.

6.1.1 Water Injection System

I. Internal Positioning

In the experiments conducted in [9], water from a tank was injected directly into the inlet of the DPF. However, the current Scania exhaust treatment configuration has been optimized to take up as little space as possible (see Figure 8). This creates a problem in that internally, there is very little space to inject water directly into the DPF.

Testing at Scania has shown that wetting the DPF from the outlet side of the filter also shows good performance in reducing pressure drop [8]. This presents a possible solution to the issue of limited space at the DPF inlet. The area of the DPF outlet is covered by a service lid to allow for DPF replacements. This region is otherwise relatively unobstructed in the current design configuration (see Figure 29).

![Service lid for particulate filter](image)

*Figure 29 – Rear view of integrated silencer housing. (Source: Scania)*

II. External Positioning

Another design issue is the amount of space available outside the silencer housing. Depending on the vehicle configuration, there can be very limited space on both sides of the silencer (see Figure 30). This can make direct access to the DPF a time consuming process, requiring up to several hours of disassembly [37].
III. Disruption of Exhaust Flow

Today in Scania trucks, there is an occasional problem with lumps of solid urea forming in the SCR. This damages SCR performance and restricts exhaust flow. While the precise source of this problem is still contentious, there has been a link found between slight misalignment of the DPF mounting tabs at the DPF outlet, and SCR urea lump formation [38]. This indicates a high sensitivity to flow pattern in the silencer for the system to function properly. Any modification to the existing fluid dynamics within the silencer system - e.g. water injector nozzles, could exacerbate this issue and would require extensive development and testing.

IV. Sources of Water in Current Systems

See Appendix C, E for further detail

- SCR Urea Tank

The current SCR system employed on Scania trucks utilizes urea injection as a method of facilitating catalytic reaction in the SCR. This urea solution, commonly referred to as AdBlue consists of 32.5% high purity urea and 67.5% water which is stored in a tank on the truck. Injection of this solution directly into the DPF could result in the formation of urea lumps in the filter [38]. However, water could be poured into this tank when it is empty for periodic DPF wetting.

- Diesel Exhaust

See Section 5.1.4

- Charge Air Cooler

The purpose of the charge air cooler is to cool down the air after the turbocharger to near ambient temperatures [20]. Depending on environmental conditions, e.g. humidity, temperature, etc. condensed water can form in this cooler. This water condensation in the charge air cooler has been known to cause hydrolock in Scania engines [37]. However, removing this water from the charge air flow would result in an increased pressure drop [20].
• EGR Cooling

Another source of condensed water in the diesel system is from the reduction exhaust gas temperature through the EGR cooler. By reducing the temperature of gases in the EGR cooler, more water would condense [17]. This water would need to be removed from the EGR system before entering the combustion chamber to prevent hydrolock damage in the engine [17]. Much like the case of the charge air cooler, effectively removing this water from the flow would most likely be paired with an increased pressure drop [20].

• Other Fluid Tanks

On current Scania trucks there are a number of fluid tanks for functions such as windshield cleaning, headlamp cleaning, etc. [37].

**Table 1: Benefits and drawbacks of various water sources to be used for DPF water injection.**

<table>
<thead>
<tr>
<th>System Sources of Water for DPF Injection</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water in AdBlue Tank</td>
<td>- Pre-DPF injection system already designed</td>
<td>- AdBlue would need to be purged from system before injecting water to prevent urea lump formation [38] - Not compatible with current production line [38]</td>
</tr>
<tr>
<td>Charge Air Cooler</td>
<td>- Compatible with most vehicle models</td>
<td>- Dependent on environmental conditions – relative humidity, etc. [20] - Separating water from the flow would require an additional pressure drop [20]</td>
</tr>
<tr>
<td>EGR Cooler</td>
<td>- Control over condensed water flow</td>
<td>- EGR condensation can cause formation of acids which can damage engine components [20] - Risk of hydrolock [40] - Unknown effectiveness - Increased pressure drop [20]</td>
</tr>
<tr>
<td>Windshield Wiper Fluid &amp; Other</td>
<td>- Readily available source of water</td>
<td>- Would require driver to refill more frequently</td>
</tr>
</tbody>
</table>
### Table 2: Relevant considerations for DPF wetting through water injection

<table>
<thead>
<tr>
<th>ID</th>
<th>Considerations</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Freezing of water reserved for injection</td>
<td>Antifreeze additive</td>
</tr>
<tr>
<td>2.</td>
<td>Space limitation at DPF inlet</td>
<td>Maintenance service, DPF outlet injection, DOC inlet injection, condensed water in exhaust flow</td>
</tr>
<tr>
<td>3.</td>
<td>How much water to use</td>
<td>** X</td>
</tr>
<tr>
<td>4.</td>
<td>Can excess water in the current system be used?</td>
<td>** X</td>
</tr>
<tr>
<td>5.</td>
<td>Requirements on water purity to be used for this system</td>
<td>** X</td>
</tr>
<tr>
<td>6.</td>
<td>Complexity of developing on-board injection system (additional components, etc.)</td>
<td>Water injection as a maintenance service rather than an on-board injection system</td>
</tr>
<tr>
<td>7.</td>
<td>What injection timing strategy produces the best results?</td>
<td>** X</td>
</tr>
<tr>
<td>8.</td>
<td>Will water injection during vehicle operation cause damaging thermal shock to exhaust system?</td>
<td>Due to the relatively low quantities of water necessary for this procedure, thermal shock should not be a problem [38]</td>
</tr>
<tr>
<td>9.</td>
<td>Will lowered exhaust temperatures cause urea lumps to form?</td>
<td>Water injection will not significantly lower exhaust temperature [38]</td>
</tr>
<tr>
<td>10.</td>
<td>Can water be injected through DOC to DPF?</td>
<td>** Due to the high flow rate of exhaust water vapor, DOC should be resistant to damage from additional water injections in small quantity [38]</td>
</tr>
<tr>
<td>11.</td>
<td>Effect of water injection on DOC oxidation performance</td>
<td>Small amounts of water should not damage oxidation process [38]</td>
</tr>
<tr>
<td>12.</td>
<td>Effect of increased water vapor on downstream systems (SCR, etc.)</td>
<td>Small variations in exhaust water content should not be a concern [38]</td>
</tr>
<tr>
<td>13.</td>
<td>Effect of water injection on DPF durability</td>
<td>See solution ID. 12</td>
</tr>
<tr>
<td>14.</td>
<td>Effect of water injection on precious metals &amp; soot oxidation rates in coated DPF due to transient increase of water content</td>
<td>See solution ID. 12</td>
</tr>
<tr>
<td>15.</td>
<td>Can SCR urea tank be used for water injection?</td>
<td>Water and urea would need to be separated for a DPF injection system. Risk of urea lumps forming in DPF [38]</td>
</tr>
<tr>
<td>16.</td>
<td>Effect of injector system on silencer exhaust gas flow pattern</td>
<td>Significant flow pattern disruptions (urea lumps in SCR, increased pressure drop) could be avoided through water injection upstream of silencer – DOC water injection, use of water injection as maintenance service [38], [41]</td>
</tr>
</tbody>
</table>
| 17. | Effect of dopant & water systems combined                                       | - ** A water soluble dopant could pass through DPF to downstream systems, effect needs to be considered [38] | ** Indicates testing required, X indicates unknown aspects.
6.1.2 Design Considerations – Condensed Exhaust Water

I. Deployment Strategy

Using the engine exhaust as a source of condensed water is almost certainly paired with an increase in fuel consumption [17]. The timing and quantity of condensed water deployed to the DPF could have influence over the expected fuel savings from reduced backpressure. Additionally, this method is dependent on cool exhaust temperatures. As a result, the frequency of DPF wetting may be limited to when the vehicle has been sitting overnight [17].

Table 3: Relevant considerations for DPF wetting through engine control

<table>
<thead>
<tr>
<th>ID</th>
<th>Considerations</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Fuel penalty of producing condensed water during cold start/operation</td>
<td>**</td>
</tr>
<tr>
<td>2.</td>
<td>Determining effectiveness of method for wetting DPF</td>
<td>**</td>
</tr>
<tr>
<td>3.</td>
<td>Limitations on volume of condensed water produced</td>
<td>**</td>
</tr>
<tr>
<td>4.</td>
<td>Limitations on flow of condensed water through exhaust conduit</td>
<td>**</td>
</tr>
<tr>
<td>5.</td>
<td>Fuel consumption from parked regeneration versus producing increased condensed water in exhaust</td>
<td>**</td>
</tr>
<tr>
<td>6.</td>
<td>Will prolonged low exhaust temperatures increase NOx emission (DOC catalyst minimum temperature)</td>
<td>**</td>
</tr>
<tr>
<td>7.</td>
<td>Risk of hydrolock in EGR cooling</td>
<td>Water would need to be separated from flow before it reaches the combustion chamber [17]</td>
</tr>
</tbody>
</table>

** Indicates testing required, X indicates unknown aspects.
6.1.3 Benefits, Drawbacks of DPF Wetting Methods

Table 4 – Benefits and drawbacks of various approaches to wetting the DPF.

<table>
<thead>
<tr>
<th>Method</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPF Inlet Injection</td>
<td>- The use of a sensor hole for injection would be relatively simple</td>
<td>- Due to disruption of exhaust flow, this could only be a maintenance option [38]</td>
</tr>
<tr>
<td>DPF Outlet Injection</td>
<td>- Better access to DPF face</td>
<td>- Risk of disrupting exhaust flow</td>
</tr>
<tr>
<td></td>
<td>- Has the potential to be used as an on-board system</td>
<td>- Complexity of additional components</td>
</tr>
<tr>
<td>DOC Inlet Injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Less risk of disrupting silencer flow pattern (urea lumps, etc.)</td>
<td>- Difficult access to NOx sensor on vehicle models with large silencer configuration [41]</td>
</tr>
<tr>
<td></td>
<td>- Previously utilized function (post-injection)</td>
<td></td>
</tr>
<tr>
<td>Condensation in Exhaust Flow</td>
<td>- Could be implemented with no mechanical changes to existing system</td>
<td>- Unknown viability, effectiveness [17]</td>
</tr>
<tr>
<td>Pre-DPF SCR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Injection system already designed</td>
<td>- AdBlue would need to be purged from system to prevent urea lump formation [38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Not compatible with current production line [38]</td>
</tr>
</tbody>
</table>
6.2 Ash Doping Design Considerations

Section 6.2 encompasses the relevant design considerations for integrating the ash doping concepts outlined in Chapter 5 into the Scania vehicle systems. For further detail, see Appendices C and E.

Table 5: General considerations for adding dopant to DPF

<table>
<thead>
<tr>
<th>ID</th>
<th>Considerations</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>** Indicates testing required, X indicates unknown aspects.</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Environmental, human health concerns?</td>
<td>Study of relevant legislation</td>
</tr>
<tr>
<td>2.</td>
<td>Least amount of dopant to produce desired results</td>
<td>**</td>
</tr>
<tr>
<td>3.</td>
<td>Optimal vehicle integration</td>
<td>**</td>
</tr>
<tr>
<td>4.</td>
<td>Effect of dopant on DOC</td>
<td>- Postmortem analysis of DOC has shown fuel-borne sodium is captured by the catalyst. [42]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Study conducted in [43] concluded that alkali impurities in the fuel damaged DOC performance.</td>
</tr>
<tr>
<td>5.</td>
<td>Effect of dopant on SCR</td>
<td>- Biodiesel, containing high alkali content have been linked to catalyst damage (e.g. reduction in SCR ammonia storage capacity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Study conducted in [43] concluded that alkali impurities in the fuel damaged SCR</td>
</tr>
<tr>
<td>6.</td>
<td>Dopant captured in DOC</td>
<td>**</td>
</tr>
<tr>
<td>7.</td>
<td>Dopant surviving combustion (fuel or oil additive)</td>
<td>**</td>
</tr>
<tr>
<td>8.</td>
<td>Thermal stability of dopant</td>
<td>**</td>
</tr>
<tr>
<td>9.</td>
<td>Effect of dopant on DPF</td>
<td>- True influence of ash sintering on ash morphology, pressure drop in DPF needs to be confirmed (see Section 4.3.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Ash adherence to walls could potentially be mitigated by water transport to the DPF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Study conducted in [43] concluded that alkali impurities in the fuel damaged DPF catalyst performance.</td>
</tr>
<tr>
<td>10.</td>
<td>Effect of dopant &amp; water systems combined</td>
<td>- A water soluble dopant could pass through DPF to downstream systems, effect needs to be considered [38]</td>
</tr>
</tbody>
</table>
6.2.1 Design Considerations – Dopant in Engine Oil

I. Filtration System

The current oil cleaning system is very effective at removing unwanted components from the engine oil. It can be assumed that a dopant in particle form would be removed in the centrifugal oil cleaner [26]. To avoid this, the dopant could be introduced into the oil with some form of surfactant to keep the dopant mixed in the oil solution [26].

II. Implementation Strategy

- Oil Additive Formula
  The dopant could be integrated into the engine oil formula.

- Oil Filter Slow Release
  In industry, there exist engine oil filters which release various additives (e.g. US Patent No. 20090050547). These filters continuously release additives into the oil as a result of the pressure drop over the filter. The dosing rate can be controlled as a function of this pressure drop and the geometries of the additive container.

- On-Board Oil Additive Dosing
  An on-board system could take several forms. The same technology utilized in additive release oil filters could be implemented in-line elsewhere in the lubricant system as a sort of chemical metering pump. A more complex system, e.g. with a supply tank, dosing pump, and control unit much like the system outlined in [44] could also be implemented.

- Dosing as Maintenance Service
  When the vehicle comes in for maintenance, a prescribed amount dopant could be added to the engine oil.
### Table 6: Relevant considerations for adding dopant to engine oil

<table>
<thead>
<tr>
<th>ID</th>
<th>Considerations</th>
<th>Solutions</th>
</tr>
</thead>
</table>
| 1.  | What quantity of dopant in oil produces best results | ** - Additive release filter  
- Lubricant formula  
- On-board dosing system,  
- As periodic maintenance service |
| 2.  | Dosing strategy                             | - Surfactant [10]  
- Small particles [10]  
- Dopant in solution [10] |
| 3.  | Prevention of dopant settling in engine oil | - Evaluation of filtration system  
- Constraints on oil transport in the cylinders  
- Settling rate |
| 4.  | Limitations on particle size                | - **  
- Test effect on oil performance  
- Study limitation of dopant concentration in oil |
| 5.  | Effect of dopant on lubricant properties & performance | - **  
- Prevent interaction of dopant with oil components  
- Use of surfactant to prevent dopant particles from collecting, growing larger |
| 6.  | Clogging of lubricant flow (oil filter obstruction) | ** - Prevent interaction of dopant with oil components  
- Use of surfactant to prevent dopant particles from collecting, growing larger |
| 7.  | Long-term solubility & stability in engine oil | ** X |
| 8.  | Formation of injector nozzle deposits       | ** X |
| 9.  | Damage to engine bearings, cylinder lining  | - **  
- Ensure dopant is non abrasive |
| 10. | Corrosion                                   | ** X |

** Indicates testing required, X indicates unknown aspects.
Table 7: Benefits and drawbacks of various approaches to dosing engine oil with an ash compacting dopant

<table>
<thead>
<tr>
<th>Engine Oil Dopant Strategies</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Additive Formula</td>
<td>- No mechanical changes to existing system</td>
<td>- Extensive testing of dopant effect on oil, engine components required [26]</td>
</tr>
<tr>
<td>Oil Filter Slow Release</td>
<td>- Readily available technology - Control over dosing rate</td>
<td>- Requires redesign of current oil filter system [26] - Extensive testing of dopant effect on oil, engine components required</td>
</tr>
<tr>
<td>On-Board Oil Additive Dosing</td>
<td>- Could be alternative to oil filter release system if spacing is an issue</td>
<td>- Additional component(s) - Extensive testing of dopant effect on oil, engine components required</td>
</tr>
<tr>
<td>Dosing Engine Oil as Maintenance Service</td>
<td>- Simplicity - Cost effective</td>
<td>- Extensive testing of dopant effect on oil, engine components required - Frequency, effectiveness of dosing dependent on driver behavior</td>
</tr>
</tbody>
</table>

6.2.2 Design Considerations – Dopant in Diesel Fuel

I. Filtration System

The current Scania XPI fuel system consists of two fuel filters, a pre filter with 75% effectiveness of filtering particles 12 micron or larger. This filter is also highly sensitive, a pressure drop greater than just 0.3 bar indicates the pre filter is clogged [45]. Additionally, the pre filter also contains a water separation function. This presents a risk that water-soluble dopants could be unintentionally filtered out of the system here [45]. The fuel filter after the pump is less sensitive to pressure drop, however it is 75% effective at picking up particles of 5 microns [45]. In order to pass the filtration and reach the fuel injectors, the dopant would need to be considerably smaller than 5 microns.

II. Implementation Strategy

- **Fuel Filter Additive Release**

  The same method of releasing additive agents into the engine oil discussed above has also been used in fuel filters to dose various chemicals into the fuel. Additive release fuel filters have been utilized as a means of transporting catalyst performance enhancers to the DPF as outlined in [46].

- **Dosing at Fuel Refill Pump**

  Another method that has been used as a means of introducing a fuel additive to aid in DPF performance is the integration of a dosing system at the fuel refill pump. For example, the
system outlined in [47] electronically recognizes when a compatible vehicle is refueling and dopant is pumped into the fuel tank at a prescribed fraction of the fuel flow rate.

- **On-Board Fuel Dosing System**

There are a number of on-board fuel dosing systems that have been developed over the years. These devises often consist of an additive storage tank, control system, and a dosing pump such as the system outlined in [44].

- **Dosing Fuel as a Maintenance Service**

A simple alternative could be to add a given amount of dopant to the fuel system when a vehicle is brought in for routine maintenance.

*Table 8: Relevant considerations for adding dopant to diesel fuel*

<table>
<thead>
<tr>
<th>ID</th>
<th>Considerations</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Design</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 1. | Dosing strategy | - Additive release filter  
- On-board dosing system  
- As periodic maintenance service  
- Dosing at fuel refill pump |
| 2. | What quantity of dopant in fuel produced best results | ** |
- Small particles [10]  
- Dopant in solution [10] |
| 4. | Formation of injector nozzle deposits | ** |
| 5. | Fuel filter clogging | - **  
- Particles smaller than 5 micron (after pump fuel filter)  
- Use of surfactant [10] |
| 6. | Long term solubility & stability in fuel | ** |
| 7. | Effect of dopant on high pressure components | ** |
| 8. | Dopant reaction with fuel components | - **  
- High dilution  
- Use of surfactant [10] |
| 9. | Dopant reaction with oil in fuel | ** |
| 10. | Potential for dopant to be filtered out in water separator in pre filter | ** |
| 11. | Corrosion in fuel system, cylinder lining, etc. | ** |
| 12. | Limitations on particle size | - Evaluation of filtration system  
- Constraints on oil transport in the cylinders  
- Settling rate |

** Indicates testing required, X indicates unknown aspects.
Table 9: Benefits and drawbacks of various approaches to dosing diesel fuel with an ash compacting dopant

<table>
<thead>
<tr>
<th>Method</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
</table>
| Fuel Filter Slow Release | - Readily available technology  
                           - Control over dosing rate                                               | - Extensive testing of dopant effect on fuel, engine components required  |
| Dosing at Fuel Pump      | - Readily available technology  
                           - No extensive modification to existing system  
                           - Good for retrofit applications [47]                                    | - Could probably only apply to fleet vehicles [47]                        |
|                          |                                                                          | - Extensive testing of dopant effect on fuel, engine components required  |
| On-Board Fuel Additive Dosing | - Could be alternative to fuel filter release system if spacing is an issue  
                          - Extensive research in this area                                           | - Additional components  
                          - Extensive testing of dopant effect on fuel, engine components required |
| Dosing Fuel as Maintenance Service | - Least degree of modification to current systems                          | - Extensive testing of dopant effect on fuel, engine components required  |
|                          |                                                                          | - Frequency, effectiveness of dosing dependent on driver behavior         |
6.2.3 Design Considerations – Other Ash Dopant Methods

Table 10: Benefits and drawbacks of alternative approaches to transporting ash compacting dopant to the DPF

| Alternative Dopant → DPF Transport Strategies |
|-------------------------------|---------------------------------|---------------------------------|
| **Method**                      | **Benefits**                      | **Drawbacks**                      |
| Pre-DPF SCR Injection          | - Bypasses engine components, related concerns  
- Eliminates need for dopant in engine oil, fuel analysis/testing  
- Pre-DPF SCR injection is planned to be implemented on future Scania trucks [38]  
- Direct control over dosing rate  
- Considered dopants are soluble in AdBlue [26] | - Requires additional components  
- Dependent on Scania implementing this concept of a pre-DPF SCR  
- Proposed dopant concentration exceeds the maximum allowable value outlined in ISO-22241-1 – effect unknown.  
- Not compatible with current production line |
| Dopant Coating on DPF Filter Media | - Reduces risk of dopant effect on system components other than the DPF | - Unknown viability, effectiveness |
| Intake Air                      | - Would not have to change the fuel or engine oil chemistries | - Requires additional components  
- Testing still required to determine dopant effect on engine components |
| DOC Intake                      | - Bypasses engine components, related concerns  
- Eliminates need for dopant in engine oil, fuel analysis/testing | - Requires additional components |
| Combination of Dopant & Water Injection | - Combination of the performance benefits of both systems  
- Bypasses engine components, related concerns  
- Eliminates need for dopant in engine oil, fuel analysis/testing | - May require additional components  
- Water soluble dopant could pass through DPF to downstream after-treatment systems |
7. Results

Chapter 7 presents the final chosen concept. The results of prototyping and subsequent testing of the final concept is also given.

7.1 – Concept Evaluation & Selection

From the design considerations in Section 6.1, as well as interview of Scania employees, a system of criteria to evaluate concepts was established (see Table 11). These criteria were not given a numerical weight. Instead, concepts were discussed and their agreement with the criteria was evaluated. Using this approach, several concepts which seemed most promising were assessed in collaboration with the project supervisors and workshop experts at Scania. The chosen concept was selected because it was seen as the easiest to implement. Additionally this concept demonstrated lack of conflict with the established criteria. For the complete criteria matrix, see Appendix E.
### Table 11: Section of the criteria matrix utilized to evaluate ash compaction concepts.

<table>
<thead>
<tr>
<th>ID.</th>
<th>Criteria</th>
<th>Justification</th>
<th>DPF Inlet injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressure drop reduction</td>
<td>Concept does not cause risk of increasing pressure drop. SCR urea lumps.</td>
<td>Mitigation strategy: Use of DPF access plug rather than integrated injection system.</td>
</tr>
<tr>
<td>2</td>
<td>Complexity</td>
<td>Concept does not require modification to existing systems</td>
<td>Mitigation strategy: Use of DPF access plug rather than integrated injection system.</td>
</tr>
<tr>
<td>3</td>
<td>Energy requirement</td>
<td>Concept does not require additional energy to function (electric, fuel, etc.)</td>
<td>Mitigation strategy: Use of DPF access plug rather than integrated injection system.</td>
</tr>
<tr>
<td>4</td>
<td>Effectiveness</td>
<td>Volume of water available to be utilized</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Consumption</td>
<td>Concept water supply must be sufficient to wet DPF</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Safe</td>
<td>Concept does not damage existing systems</td>
<td>See corresponding risk ID. 1</td>
</tr>
<tr>
<td>7</td>
<td>Water distribution</td>
<td>Concept effectively wets the entire DPF</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
</tr>
<tr>
<td>8</td>
<td>Storage</td>
<td>Water supply does not freeze due to environmental conditions</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>Cost</td>
<td>Concepts' perceived value exceeds cost of additional components, vehicle energy consumption, development, etc.</td>
<td>At risk Mitigation strategy: see ID.2</td>
</tr>
<tr>
<td>10</td>
<td>Emissions</td>
<td>Concept does not cause vehicle to fail current emissions standards (NOx during cold start, etc.)</td>
<td>N/A</td>
</tr>
<tr>
<td>11</td>
<td>Controllability</td>
<td>Ability to control flow rate, frequency, etc.</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Retains Value</td>
<td>Concept has a realistic way to be sold as a Scania product</td>
<td>Cost/benefit assessment required</td>
</tr>
<tr>
<td>13</td>
<td>Compatibility</td>
<td>The concept functions as expected regardless of environmental conditions, vehicle model, etc.</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>Ergonomics, Service Interval</td>
<td>Concept does not inhibit normal driver behavior (downtime, etc.)</td>
<td>At risk: if driver will inject Mitigation strategy: maintenance service, on board system</td>
</tr>
</tbody>
</table>
7.1.1 – Final Concept: DPF Water Injection Maintenance Service

From the evaluation exercise, injecting water as a maintenance service – through the differential pressure sensor orifice was chosen (see Figure 31). This location allows for direct injection of water into the DPF inlet (see Figure 20) [41]. The silencer sensor cluster is easily reached in most Scania vehicle models. It would take little time to access the cluster for water injection [41].

![Diagram of water injection tool](image)

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water hose</td>
</tr>
<tr>
<td>2</td>
<td>Worm-drive hose clamp</td>
</tr>
<tr>
<td>3</td>
<td>Sensor orifice</td>
</tr>
<tr>
<td>4</td>
<td>Steel tube</td>
</tr>
<tr>
<td>5</td>
<td>End cap</td>
</tr>
</tbody>
</table>

*Figure 31 – Top: Proposed water injection tool (section view), Bottom left: Concept component descriptions, Bottom right: Location of pressure sensor on current silencer housing (medium size).*

7.1.2 Justification for Concept Selection

The concept was selected for a number of factors which highlighted its viability over the other considered concepts [41]:

- Inlet injection is the most direct approach to wetting the DPF without extensive disassembly.
- The tool is simplistic and requires very little development or fabrication.
- The tool can be implemented most easily when compared to the other considered concepts.
- Utilizing this tool as a maintenance service allows for the process to be inexpensive and requires no modification to the current vehicle systems.
- From the theoretical model shown in Section 4.5, it can be seen that maintenance injection is a viable strategy for both reducing DPF pressure drop, and increasing filter service interval.
- Serves as a proof of concept for all water injection methods.
- When compared to introducing a dopant to the vehicle systems, DPF wetting has very few concerns for damage, and requires less testing to ensure effectiveness.
7. Results

### 7.2 Proof of Concept

Section 7.2 presents the proof of concept process, including the prototyping of the chosen concept as well as the results of its testing on a vehicle.

#### 7.2.1 Prototype

In order to determine the potential effectiveness of the final concept, a simple prototype was fabricated to conduct an on-vehicle test. The injection tool consists of a 6 mm diameter steel tube plugged at one end, with a series of 1 mm holes along its length (see Figure 32). When inserted in the sensor orifice, and attached to a water hose, this tool creates a spray of liquid water into the DPF inlet.

![Prototype water injection tool](image)

*Figure 32 – Prototype water injection tool. Full length (top), detail view of water spray holes (bottom).*

#### 7.2.2 Testing

The prototype was employed on a test vehicle (see Figure 33, Figure 34) to determine its effect on DPF backpressure, as well as its influence on the overall system. In order to achieve
repeatability, the test collected data over the course of a diagnostic program normally used to check the pressure sensor. This allowed for the DPF backpressure to be measured over a set range of engine rpms controlled by the engine’s computer [48]. In addition to engine rpm and DPF pressure, the exhaust flow rate and temperatures before the DOC and directly after the DPF were recorded.

The test vehicle had a relatively new DPF with very little ash (28000 km). A measurement of the pressure drop over this filter was taken to establish a reference point. Next, in order to demonstrate the greatest improvement in pressure drop, an ash filled DPF was installed in the test vehicle silencer (see Figure 34). Using the pressure sensor diagnostic program, the initial pressure drop over the DPF was recorded to establish a baseline.

The water injection tool was utilized to wet the filter for a period of 3 minutes. This injection was conducted while the engine was idling to allow the exhaust gas flow to aid in transporting the water through the length of the filter. Prior measurement indicated that every for every 10 seconds, approximately 1 liter of water flows through the injection tool. A visual check of the DPF outlet was made to determine whether the filter had been completely wetted (see Figure 37). The DPF was then dried by running a temperature sensor diagnostic program which raises the temperature in the silencer [48]. Afterwards, a visual check was conducted to ensure the filter had been thoroughly dried (see Figure 37). Drying the DPF before collecting data allowed for the true reduction in pressure drop from ash compaction to be determined without interference from water.

A follow up test was conducted on the same filter, injecting water for 2 minutes 30 seconds, followed by a drying period. The data collected from the repeated test was very similar to the initial results (see Figure 35). This indicates that the ash volume had been reduced as much as possible in the first water injection.
II. Reduction in Backpressure

The resultant effect of on-vehicle water injection on DPF pressure drop is presented in Figure 35. As can be seen, the reduction in backpressure from water injection is approximately 3.8 millibar at a flow rate of 183 l/s. This improvement is roughly equivalent to a 60% reduction in backpressure from ash. These results are in agreement with a prior bench test conducted at Scania utilizing a flow rig (see Figure 15, Figure 36). Figure 35 shows the collected data corrected for sensor error – the original data and further detail can be found in Appendix D.
III. DPF Drying Time

When the DPF is wet, the backpressure over the filter is relatively high until the water evaporates [49]. There is a risk that this temporary increased resistance to flow could cause the filter to separate from its canning under higher loads. As a result, it is important to be able to quantify the amount of time it would take for the filter to dry out before the vehicle can be driven.

For the purposes of this test, the drying time was judged by visually checking the DPF outlet after heating the silencer (see Figure 37). After several trials, it was established that the liquid
water can be effectively removed by running diagnostic programs which heat the silencer for a total of 45 minutes.

Figure 37 - Left: DPF outlet immediately after water injection process. Right: Partially wet DPF outlet after a period of drying.
8. Discussion & Conclusion

I. Discussion

The introduction of an ash sintering dopant into the engine and after-treatment systems is perceived to have a likelihood for collateral damage; be it corrosion in the engine, deactivation of catalysts, etc. In literature there are conflicting conclusions regarding if ash sintering improves exhaust flow through the DPF [33], [34], [35]. Due to the potentially harmful nature of the chemicals in question and the contradictory nature of prior experiments, it was concluded that the testing and development of ash doping would be expensive and time consuming.

The confluence of concerns associated with ash doping led to DPF wetting being recognized as a more favorable method. This approach to reducing pressure drop over the DPF has a more established efficacy – both in literature and prior testing at Scania [8], [9]. Interview of workshop experts concluded that wetting the DPF through a sensor hole in the silencer housing could be conducted as a maintenance service [41]. This approach is easily accessible in the current vehicle configuration and takes little time to implement [41] (see Section 6.3.2). The effectiveness of this method has been shown to be in agreement with the results of previous testing at Scania (see Figure 35, Figure 36). As a result of injecting water for a period of 3 minutes, the DPF pressure drop resulting from ash can be reduced by approximately 60%.

From a practical point of view, there are ancillary implications of using time allocated for other maintenance – e.g. oil changes – to conduct this procedure. For a significant portion of Scania customers, the vehicle is purchased with a service contract [41]. This means that time spent conducting additional maintenance can represent lost profits for Scania. The common figure for time to replace the filter is around 3 hours [37]. Before replacement is required, the repetitions of this water injection process must cumulatively take less than 3 hours to complete. Otherwise, the cost of the procedure would outweigh the savings from prolonging replacement [41]. In the testing presented in Section 6.3.2, drying the filter required 45 minutes. Further study is necessary to determine whether the vehicle can be returned to the customer without conducting a complete drying process, as this would considerably reduce the maintenance time.

Due to time limitations, there was little opportunity to optimize the design of the selected concept. Additionally, a lack of available filters for testing did not allow for a thorough validation of the proof of concept. Further testing and development could significantly improve the performance and ergonomics of this tool.

The expectation of this study was to ascertain the most viable method for reducing ash volume in the DPF. The result of the method outlined in Chapter 2 has arrived at a solution which has been shown to have real world effectiveness. Furthermore this concept is in agreement with the selection criteria established in collaboration with experts at Scania. As a maintenance tool, water injection has the potential to be cost effective means of reducing fuel consumption and increasing filter service life.
II. Conclusion

The thesis paper has presented a method intended to devise and select the most beneficial approach to reducing ash volume in wall-flow diesel particulate filters. Through theoretical calculation, interview of industry experts, and study of relevant literature a broad spectrum of ash reduction methods were generated. Utilizing an adaptation of the TRIZ method, a concept was chosen and tested on a vehicle. The outcome of this work has taken the hypothesis of a laboratory experiment and demonstrated its real world effectiveness in the context of a Scania diesel truck.

The development process began with studying the means by which two previously tested techniques for reducing ash volume – DPF wetting, and ash sintering could be integrated on the system level of a diesel truck. The resultant system integration concepts were evaluated for their contradictions between needs and abilities, dependencies, and physical limitations. This evaluation produced the selected concept of injecting water into the DPF inlet through the pressure sensor hole located on the silencer housing.

The driving function behind this concept is to improve the service life of the particulate filter while simultaneously reducing fuel consumption. When a vehicle comes in for regular maintenance, this injection tool can be used to decrease the volume of ash in the DPF. This brings value to Scania by reducing the maintenance time that would be spent on the lengthy process of filter replacement. Additionally, this brings value to the customer in fuel savings as well as the reduced expense and frequency of DPF replacements.

Prototype testing of the injection tool on a Scania truck has demonstrated a 60% reduction in DPF backpressure from ash. These results are in agreement with previous laboratory testing. The simplicity, low cost of development, and quickness of this procedure exhibits a realistic and valuable means of enhancing vehicle performance while mutually reducing cost.
9. Future Work

Due to the time limitations of this thesis paper, the opportunity to further develop the chosen ash compaction tool was restricted. The initial prototype has demonstrated that there is significant potential in this approach. However, there are elements of this tool which could be improved upon.

9.1 Practical Design & Ergonomics

For the purposes of testing, the sensor orifice on the silencer had to be reamed out in order to accommodate the diameter of the water injection tool. This would be an undesirable operation to have to conduct on all vehicles - a smaller diameter tube could avert this issue. Furthermore, the configuration of the current prototype is such that the maintenance worker must manually rotate the water injection tool in order to evenly wet the DPF. The angle and pattern of the spray holes in the tube could be optimized to improve coverage and reduce the amount of work.

Experts in the Scania workshop have expressed that this concept in its ideal form, would be at least partially automated in order to reduce the amount of time spent by maintenance workers [41]. This could be accomplished using a fixed volume of water so the system can be run without supervision. Another beneficial modification would be to integrate a union nut into the tool so the injector tube can effectively be sealed into the silencer. This would allow for the tool to be used even when the engine is idling. Finally, the current prototype was specifically fabricated to function in the medium-size silencer housing. The tool could be adapted to accommodate a broader spectrum of the Scania production line.

9.2 Further Testing

The proof of concept was a demonstration of the benefits of this tool, and its effect on the system. However, the limited number of available ash-filled filters did not allow for repeated testing. Validation is necessary to acquire a more concrete representation of the performance of this method.

A potential improvement in the performance of this tool could be to use the water spray to introduce a dopant into the DPF. This approach could bypass many of the concerns regarding the dopant concept as its deposit would be isolated to the DPF. As a result, the ash could continue to be compacted long after the water has evaporated.
References


[37] M. Wadstrand, Interviewee, YSNC, DPF wetting & physical constraints on silencer system. [Interview]. 28 February 2017.


A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters


Appendix A

Dopant Concentration: Engine Oil, Diesel Fuel, AdBlue

One important consideration is the quantity of dopant necessary in each fluid to achieve the desired results. In previous laboratory testing at Scania, 1 weight percent (wt.%) dopant in simulated ash showed good performance in reducing ash volume. Assuming the ash producing component of engine oil is 1 wt.% of engine oil, the weight percent of dopant in engine oil would then be 0.01 wt.%.

IV. Dopant in Engine Oil.

Assumptions: Engine oil SAE 10W-40, and 43 L engine oil capacity. It is also assumed that 0.01 wt.% dopant in engine oil would represent 1 wt.% in ash. The considered dopant was sodium chloride with a density of 2.165 g/cm³. Oil consumption is taken to be 0.075% of fuel consumption. However, the true quantity of this parameter can vary significantly. Fuel consumption is taken to be an average of 0.26 liters per kilometer.

Calculating engine oil mass:

\[ \rho_{oil} \times V_{oil} = \frac{0.865 \text{ kg}}{l} \times 43 \text{ l} = 37.195 \text{ kg} \]  
(1A)

Where \( \rho_{oil} \) is engine oil density (kg/l), and \( V_{oil} \) is given volume of oil in the engine.

Mass fraction of dopant in oil, for a desired 1 wt.% dopant in ash:

\[ \omega_{i,dopant} = \frac{m_i}{m_{tot}} = 0.0001 \]  
(2A)

Where \( m_i \) is desired mass of dopant in oil (kg), \( m_{tot} \) is total mass of the dopant-oil mixture.

Calculating oil consumption rate as a function of fuel consumption:

\[ C_{oil} = 0.075\% \times C_{fuel} = 0.00195 \text{ l/km} \]  
(3A)

Where \( C_{oil} \) is oil consumption (l/km), and \( C_{fuel} \) is fuel consumption (l/km).

The mass oil consumed per kilometer is:

\[ m_{oil, consumed} = C_{oil} \times \rho_{oil} = 0.000169 \text{ kg/km} \]  
(4A)

From Eqn. 2A, the desired mass of dopant (0.01 wt.% engine oil) consumed per kilometer can be taken as:

\[ m_{dopant, consumed} = 0.0001 \times m_{oil, consumed} = 1.687 E - 8 \frac{\text{kg}}{\text{km}} = 0.01687 \frac{\text{mg}}{\text{km}} \]  
(5A)

The volume of dopant consumed per kilometer is:

\[ V_{dopant, consumed} = \frac{m_{dopant, consumed}}{\rho_{dopant}} = 7.791 E - 9 \text{ l} \]  
(6A)

The volume concentration, \( \phi_i \), of dopant in engine oil can be calculated as:

\[ \phi_i = \frac{V_{dopant, consumed}}{C_{oil} + V_{dopant, consumed}} = 0.000004 \]  
(7A)
The volume dopant in engine oil deployed per kilometer is then:

\[
\frac{\text{Liters dopant}}{\text{km}} = \phi_i \ast C_{oil} = 7.8 \times 10^{-9} \text{l/km}
\] (8A)

Table 1A – Values relevant to dopant in engine oil calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Density (kg/l)</td>
<td>0.865</td>
</tr>
<tr>
<td>Engine Oil Volume (liters)</td>
<td>43</td>
</tr>
<tr>
<td>Mass 43 L Oil (kg)</td>
<td>37.195</td>
</tr>
<tr>
<td>Oil Consumption Rate (%fuel consumption)</td>
<td>0.075%</td>
</tr>
<tr>
<td>Mass oil consumed per km (kg/km)</td>
<td>0.000169</td>
</tr>
<tr>
<td>Oil Consumption (l/km)</td>
<td>0.00195</td>
</tr>
<tr>
<td>Desired mass fraction dopant in oil</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mass of 0.01wt% Dopant in Oil (kg)</td>
<td>0.00372</td>
</tr>
<tr>
<td>Mass Dopant – Oil Mixture</td>
<td>37.567</td>
</tr>
<tr>
<td>Volume of Dopant in Oil (liters)</td>
<td>0.00172</td>
</tr>
<tr>
<td>Volume Concentration, in Oil Solution</td>
<td>0.000004</td>
</tr>
<tr>
<td>Dopant in engine oil, parts per million (ppm)</td>
<td>4</td>
</tr>
<tr>
<td>Dopant deployed to DPF (liters per km)</td>
<td>7.8 \times 10^{-9}</td>
</tr>
</tbody>
</table>

V. Dopant in Diesel Fuel

Assumptions: The dopant density, fuel and oil consumption rates were taken to be the same as in the engine oil calculations conducted above. Additionally from the calculations above, it was assumed that the desired dosing rate for 1 wt.% in ash is approximately 1.687E-8 kg/km or 7.8E-9 l/km.

The volume concentration, \(\phi_i\) of dopant in diesel fuel can be calculated as:

\[
\phi_i = \frac{V_{dopant, consumed}}{0.26 l + V_{dopant, consumed}} = 2.997 \times 10^{-8}
\] (9A)

The mass fraction of dopant in fuel per km is then:

\[
w_{i,dopant} = \frac{m_{dopant, consumed}}{m_{dopant, consumed} + m_{0.26l, fuel}} = 7.8 \times 10^{-8}
\] (10A)

Where \(w_{i,dopant}\) is mass fraction of dopant in fuel, \(m_{0.26l, fuel}\) is mass of 0.26 liters of fuel (kg).

Table 2A – Values relevant to dopant in diesel fuel calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction dopant in fuel</td>
<td>7.8 E-8</td>
</tr>
<tr>
<td>Volume Concentration, in Fuel Solution</td>
<td>3 E-8</td>
</tr>
<tr>
<td>Dopant in fuel, parts per million (ppm)</td>
<td>0.03</td>
</tr>
<tr>
<td>Dopant deployed to DPF (liters per km)</td>
<td>7.791 E-9</td>
</tr>
</tbody>
</table>
VI. Dopant in AdBlue

Assumptions: An AdBlue tank volume of 75 liters was considered, sodium chloride was the considered dopant with a density of 2.165 g/cm$^3$, an average AdBlue consumption was taken to be 8% of fuel consumption, average fuel consumption was taken to be 26 l/100km. From calculation in parts I & II, it can be assumed that the desired dosing rate to achieve 1 wt.% dopant in ash is approximately $1.69 \times 10^{-8}$ kilograms dopant per kilometer.

To find dopant in AdBlue concentration equivalent to 1 wt.% in ash, first the AdBlue consumption in l/km is calculated:

$$C_{AdBlue} = 8\% \times C_{fuel} = 0.0208 \text{ l/km} = 0.0227 \text{ kg/km} \quad (11A)$$

Where $C_{AdBlue}$ is AdBlue consumption (l/km), and $C_{fuel}$ is fuel consumption (l/km).

Therefore, the mass fraction of dopant in AdBlue could be calculated as:

$$w_{i, \text{dopant}} = \frac{1.69 \times 10^{-8} \text{ kg/km}}{C_{AdBlue} + 1.69 \times 10^{-8} \text{ kg/km}} = 7.434 \times 10^{-7} \quad (12A)$$

Where $w_i$ is the mass concentration of dopant in AdBlue solution.

The mass per unit volume of dopant in AdBlue for 1 wt.% in ash would be:

$$0.0169 \text{ mg/km/} 0.0208 \text{ l/km} = 0.813 \text{ mg/liter} \quad (13A)$$

The volume concentration of dopant in AdBlue for 1 wt.% in ash can then be found:

$$\phi_i = \frac{V_{\text{dopant, consumed}}}{C_{AdBlue} + V_{\text{dopant, consumed}}} = 3.753 \times 10^{-7} \quad (14A)$$

From ISO standard 22241-1, the maximum allowable amount of sodium in AdBlue solution is 0.5 mg/l.

Taking this into account, the mass per unit volume of the sodium component in the proposed dopant-AdBlue solution would be:

$$\frac{0.813 \text{ mg}}{l} \times \frac{M_{\text{sodium}}}{M_{\text{dopant}}} = 0.32 \text{ mg/l} \quad (15A)$$

Where $M_{\text{sodium}}$ is molar mass of sodium (g/mol), and $M_{\text{dopant}}$ is molar mass of the dopant (g/mol).

Alternatively if the maximum sodium content is considered, then calculating equivalent wt.% dopant in ash from 0.5 mg/l sodium in AdBlue:

Mass consumed sodium per kilometer at the maximum allowed level of 0.5 mg/l would be:

$$m_{\text{sodium, consumed}} = \frac{0.5 \text{ mg}}{l} \times \frac{0.0208 \text{ l}}{km} = 0.0104 \frac{\text{mg}}{km} \quad (16A)$$
A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters

Next, the resultant mass of sodium chloride consisting of 0.0104 mg sodium is:

\[ m_{\text{dopant, consumed}} = \frac{0.0104 \text{ mg}}{M_{\text{sodium}}/M_{\text{dopant}}} = 0.026 \text{ mg/km} \]  \hspace{1cm} (17A)

The volume consumed dopant per kilometer can then be calculated:

\[ V_{\text{dopant, consumed}} = \frac{m_{\text{dopant, consumed}}}{\rho_{\text{dopant}}} = 1.22E-8 \text{ l/km} \]  \hspace{1cm} (18A)

The new volume concentration of dopant in AdBlue can then be found:

\[ \phi_i = \frac{V_{\text{dopant, consumed}}}{C_{\text{AdBlue}} + V_{\text{dopant, consumed}}} = 5.77E-7 \]  \hspace{1cm} (19A)

If 0.016 milligrams deployed dopant per kilometer is equal to 1 wt.% in the ash, then the new weight percent of dopant in ash from 0.026 mg dopant per kilometer can be taken as:

\[ w_i = \frac{0.026 \text{ mg/km}}{0.016 \text{ mg/km}} = 1.564 \text{ wt%} \]  \hspace{1cm} (20A)

Table 3A – Values relevant to dopant in AdBlue calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum level of sodium in AdBlue (mg/l)</td>
<td>0.5</td>
</tr>
<tr>
<td>Density of sodium chloride (g/cm³)</td>
<td>2.165</td>
</tr>
<tr>
<td>Average AdBlue consumption (% fuel consumption)</td>
<td>8%</td>
</tr>
<tr>
<td>Dopant mass fraction in AdBlue (1 wt.% )</td>
<td>7.434 E-7</td>
</tr>
<tr>
<td>Volume concentration dopant in AdBlue (1 wt.% )</td>
<td>3.753 E-7</td>
</tr>
<tr>
<td>Dopant in AdBlue parts per million (ppm) (1 wt.%)</td>
<td>0.375</td>
</tr>
<tr>
<td>Mass per unit volume dopant in solution (mg/l) (1 wt.%)</td>
<td>0.813</td>
</tr>
<tr>
<td>Mass per unit volume sodium in AdBlue (mg/l) (1 wt.%)</td>
<td>0.32</td>
</tr>
<tr>
<td>Dopant deployed to DPF (liters per km) (1 wt. %)</td>
<td>1.69 E-8</td>
</tr>
<tr>
<td>Molar mass sodium (g/mol)</td>
<td>22.99</td>
</tr>
<tr>
<td>Molar mass sodium chloride (g/mol)</td>
<td>58.44</td>
</tr>
<tr>
<td>Mass per unit volume sodium in AdBlue (mg/l) (1 wt.%)</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Appendix B
Dopant Particle Settling Time Calculations

Particle settling time is an important consideration when introducing an ash sintering dopant to a particular fluid, e.g. engine oil or diesel fuel. The lack of miscibility of the considered dopant in diesel fuel or engine oil indicates that given enough time, the dopant particles will settle out of the solution. This indicates a need for a surfactant of some sort to keep the dopant mixed in the desired fluid.

The governing equation of the settling rate of a particle in a given fluid is given as Stokes Law:

\[ V = \frac{2 \pi (\rho_p - \rho_f) \cdot g \cdot R^2}{9 \cdot \mu} \]  

(25)

For the purposes of comparing dopant particle settling time in both diesel fuel and engine oil, the same particle radii were considered. The particle radii range from 2.5e-6 m to 7.5e-6 m. These particle sizes were chosen based on the micron ratings of the engine oil filter and fuel filters.

III. Dopant Particle in Engine Oil

Assumptions: in order to generate an estimate of the settling time in engine oil, the effect of temperature on engine oil dynamic viscosity was disregarded. Furthermore, as the dopant particle composition has not been definitively chosen yet, its density cannot be derived. Sodium chloride was chosen as a placeholder for these calculations - due to its density (2165 kg/m³) being relatively similar to that of other considered compounds.

Table 1B: Values relevant to calculating dopant particle settling rate in engine oil.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix dynamic viscosity, ( \mu ) (kg/m²s)</td>
<td>0.05</td>
</tr>
<tr>
<td>Particle density, ( \rho_p ) (kg/m³)</td>
<td>2165</td>
</tr>
<tr>
<td>Matrix density, ( \rho_f ) (kg/m³)</td>
<td>865</td>
</tr>
<tr>
<td>Gravitational acceleration (m/s²)</td>
<td>9.81</td>
</tr>
</tbody>
</table>

To give a more real-world perspective on the effect of particle size on settling rate, the time it would take for a particle to travel 0.5m was calculated. For reference, some Scania fuel tanks are 0.7m in height.
As can be seen in Figure 38, there is a drastic difference in the time it takes smaller versus larger particles to settle out of the engine oil. For instance, a particle of $2.5 \times 10^{-6}$ m radius may take 16 days to settle, whereas one with a radius of $7.5 \times 10^{-6}$ m could settle out in less than two days.

IV. Dopant Particle in Diesel Fuel

Assumptions: in order to generate an estimate of the settling time in diesel fuel, the effect of temperature on diesel dynamic viscosity was disregarded. Furthermore, the same assumptions regarding dopant particle density made in the engine oil calculations above were retained.

Table 2B: Values relevant to calculating dopant particle settling rate in diesel fuel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix dynamic viscosity, $\mu$ (kg/m^s)</td>
<td>9.00e-3</td>
</tr>
<tr>
<td>Particle density, $\rho_p$ (kg/m^3)</td>
<td>2165</td>
</tr>
<tr>
<td>Matrix density, $\rho_f$ (kg/m^3)</td>
<td>820</td>
</tr>
<tr>
<td>Gravitational acceleration (m/s^2)</td>
<td>9.81</td>
</tr>
</tbody>
</table>

Diesel fuel has a significantly lower dynamic viscosity and density than the engine oil. This results in a much faster settling rate for dopant particles in the fuel (see Figure 39).
Figure 39 – Time to settle through 0.5 m diesel fuel as a function of dopant particle radius.

**Note:** For the purposes of this thesis, it has been assumed that the proposed dopant is soluble in AdBlue. Therefore, settling time calculations for this case would not be a relevant consideration.
Appendix C
Concept Benefits, Drawbacks, & Unknowns

Appendix C presents an overview of the benefits, drawbacks and unknowns of various ash volume reduction approaches.

C.1 DPF Wetting

C.1.1 Water Injection – DPF Inlet

Benefits

- Simplicity
As a regular maintenance option, it would not require modification to inject water through one of the sensor holes [37].

- Available external space
The side of the silencer is relatively unobstructed, accessing the sensor hole for maintenance injection could be relatively easy [37].

- Accessibility
In Figure 30, it can be seen that accessing the DPF service lid would require a lot of disassembly. However, the sensor cluster on the side of the silencer in Figure 21 is easily reachable. As a maintenance option, this could reduce the necessary downtime to inject water into the DPF inlet.

- Cost
While this solution may not be the most effective in terms of even distribution of water into the DPF, it could be relatively cheap to develop [41].

Drawbacks

- Restrictive solution
Installing an on-board injection system at the DPF inlet would probably restrict exhaust flow [38]. This likely limits direct injection at the DPF inlet to a maintenance service. The use of water injection as a DPF pressure drop limitation strategy during drive cycles as outlined in [9] would be eliminated. While this method could still be used to increase DPF service life and periodically improve fuel economy, it would not have as radical an improvement as an on-board system could.

- Water distribution
If a sensor hole were to be used for periodic water injection, it would be difficult to tell if water was being distributed evenly throughout the DPF inlet face [37].
C.1.2 Water Injection – DPF Outlet

Benefits

- Exhaust flow
An on-board water injection system could potentially be placed at the DPF outlet without obstructing the flow of exhaust gases [38].

- Less restrictive
In contrast to inlet injection, water injection at the DPF outlet might be accomplished without disrupting exhaust flow. As a result, this method could be used either as an on-board pressure drop limitation method, or as a periodic maintenance service.

- Water penetration
Testing at Scania has shown that water injection at the DPF outlet shows good performance when compared to injection at the inlet. Furthermore, because the outlet channels of the DPF are unhindered by PM, the injected water could reach the full length of the filter channels [8].

- Water distribution
The face of DPF outlet can be accessed without completely removing the filter from the silencer. This could improve a maintenance workers ability to wet the DPF more effectively [37].

Drawbacks

- Maintenance time
Reaching the DPF service lid for water injection as a maintenance provision could require a fair amount of disassembly depending on the vehicle configuration [37].

- Complexity & Cost
From the perspective of an on-board injection system, there would be a need for a number of extra mechanisms: a control system, a pressure source for the water, water injector nozzles, etc. On the other hand, DPF outlet injection as a maintenance service could also necessitate the modification of the DPF service lid to include a nozzle system to facilitate quick and easy water injection for workers.

- Pressure drop & Exhaust flow pattern disruption
The flow of exhaust gases in the silencer is a sensitive process and slight variations have been known to cause problems such as formation of urea lumps in the SCR [38]. The addition of an injector system at the DPF service lid could have an impact on the fluid dynamics between the DPF and SCR. Significant testing and development would have to be done to ensure an injector system did not damage silencer performance [38].
C.1.3 Water Injection – DOC Inlet

Benefits

- Pre-existing technology

In older Scania trucks, a fuel injector was placed upstream of the DOC inlet in order to help raise exhaust temperatures using post-injection. This function could be replaced with a water injector [37].

Pre-injection of fuel at the DOC inlet was phased out of production because it was seen as an expensive system that could be eliminated [38]. However, a water injection system in the same location could be significantly cheaper [41]. There would be significantly less safety concerns, requirements on the precision of timing, and quantity of fluid deployed [38].

- Silencer flow pattern

An injector system of some sort within the silencer would have an unavoidable influence on the fluid dynamics in that system [38]. However if the water were to be deployed upstream of the silencer, it could have a negligible effect [38].

Drawbacks

- Cost

An on-board DOC inlet injection system could require an additional control system, injector, etc. which represent added cost and complexity.

C.1.4 Sources of Water for Injection

I. EGR Cooling

Benefits

- Water production timing

The EGR system consists of a heat exchanger which if desired, could be adjusted to produce condensed water [20]. The cold start approach outlined in Section 5.1.4 relies on cool exhaust temperatures, etc. However, EGR cooling could presumably be used to produce condensed water independent of those factors.

Drawbacks

- Risk of hydrolock

Increasing the amount of condensed water from the EGR into the cylinders creates a risk of hydrolock [40]. Due to the incompressibility of water, when it is in the cylinder in sufficient amounts it will cause piston failure. In many cases, hydrolock can damage the engine beyond repair.
• Acid precipitation
Particularly in areas where diesel fuel has a high sulfur content, there is a risk of forming sulfuric acid when water condenses in the EGR system [20]. This acid has the potential to erode and or corrode components in the diesel system [50].

• Extra components & Pressure drop
In order to avoid hydrolock, water condensed in the EGR would need to be separated from the flow before it reaches the cylinders. This process of water separation would probably also be paired with a pressure drop [20].

• Compatibility
The EGR system is growing increasingly rare on Scania trucks. This method of water collection would only apply to a small section of the product line [20].

Unknowns

• Effectiveness
As with the cold start method discussed in Section 5.1.4, it is unclear how effective this solution could be without proper testing.

II. Charge Air Cooler

Drawbacks

• Environmentally dependent
Water condensation in the charge air cooler is dependent on the relative humidity in the intake air [20]. Whether or not the humidity is high enough could decide if condensation takes place at all. This means that depending on the vehicles’ geographic location, or season of the year the system could not collect water at all.

• Pressure drop
The current system does not actively separate water from the airflow in a way in which it could be readily collected. Adding this function to the system would most likely cause an increase in the pressure drop over the charge air cooler [20].

III. AdBlue Tank

Drawbacks

• Ergonomics
The AdBlue tank volume is designed such that it is usually refilled at the same time as the fuel tank [8]. Using this as a continuous system would inconvenience the driver by having to periodically fill the tank with water instead of AdBlue. However, as a maintenance option perhaps the pre-DPF SCR injection system could be used to wet the DPF by putting water in the AdBlue tank
A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters

- Urea lumps
The urea would need to be purged from the system before this solution could be used DPF wetting [38]. Otherwise there is a risk of urea lumps forming and further blocking exhaust flow.

IV. Windshield Wiper Fluid & Other

Benefits

- Readily available
The windshield washer fluid reservoir has a volume of 14.5 liters [51]. Based on prior testing at Scania, this volume would be more than sufficient to repeatedly wet the DPF.

Drawbacks

- Refill frequency
Utilizing this fluid for DPF injection would increase consumption requiring the driver to refill more frequently. However, it is worth noting that the washer fluid reservoir is easily accessible for the driver (see Figure 40).

![Figure 40 – Illustration of the washer fluid reservoir and its location on the vehicle. The bottom image shows the access steps to the cabin. (Source: Scania)](image)

Unknowns

- Effect of fluid chemistry on after-treatment systems
While the windshield wiper fluid contains water, it also consists of antifreeze, detergents, and dye [10]. The effect of this solution would need to be studied to establish that it does not damage the after-treatment system components.
C.1.5 Condensed Exhaust Water Flow to DPF

I. Cold Start

Benefits

- Cost & Degree of modification to existing systems
Other DPF wetting methods would require mechanical modification to existing components and additional parts. However, this solution could theoretically be implemented without any mechanical changes to the current system.

Drawbacks

- Fuel consumption
Increasing the fuel-air ratio for a period of time to wet the DPF would cause an increase in fuel consumption [38].

- Environmental regulation
At engine startup, exhaust braking is intentionally used to quickly raise exhaust temperatures in order to aid the after-treatment catalysts which require a certain heat to begin functioning. Prolonging the period at which exhaust temperatures are lower, could also increase NOx emissions [38].

Unknowns

- Effectiveness
Other methods of transporting water to the DPF, e.g. direct injection would have more definite outcome. But it is at present, unclear how well this procedure could wet the DPF in terms of water volume, distribution, etc. Additionally as discussed in the drawbacks, this method is paired with a fuel penalty which might outweigh the benefits of reduced DPF pressure drop.

C.2 Dopant Transport Mechanisms

C.2.1 Dopant Transport Mechanisms – Engine Oil Consumption

Benefits

- Simplicity of Dopant Transport
As the engine oil is the primary source of ash, this method of transporting dopant to the DPF is substantiated. Furthermore, this concept could potentially be implemented without modification to existing mechanical systems.

- Service interval
Engine oil changes are a necessary maintenance that must be conducted periodically over the life of the vehicle. This means that restocking dopant into the system would not impede normal driver operations, represent extra downtime, or additional lost profits.
A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters

**Drawbacks**

- **Chemical interactions**

The major drawback of this proposed method is the large number of unknowns associated with the chemistry behind this concept. While this approach to dopant transport is straightforward, the true viability of this concept is entirely dependent on the effect of the dopant on the engine oil, and engine components – which are unknown at this time. Without testing, it would be difficult to ascertain whether this technique is possible to implement without damaging other systems.

- **Filtration**

The centrifugal oil cleaner currently used on Scania engines is highly effective at removing particles denser than the engine oil from the lubrication system. This presents a potential challenge in that it may necessitate the use of a surfactant to prevent dopant particles from growing too large and being centrifuged out [26].

- **Dosing rate**

Oil consumption is known to take place, however the amount can vary. While some values are used for theoretical calculation, the actual consumption is dependent on the individual vehicle [26]. This means that if the dopant were to be mixed with the engine oil as an additive, there is no way of truly knowing the rate at which it is being transported to the DPF for all vehicles.

- **Dilution**

When compared to fuel dosing, the required dilution in oil for an equivalent amount of dopant to be transported to the DPF is significantly higher. A higher dilution could have a greater impact on the overall properties of the fluid.

**Unknowns**

- **Testing – Lubricant chemistry**

Through interview of industry experts at Scania lubricant suppliers, Lubrizol Ltd. and Infineum UK Ltd. significant testing would be necessary to determine the long term stability of dopant in the current lubricant formula. Without this testing, it would be difficult to estimate the impact the addition of a particular dopant would have on oil performance. Furthermore, some dopants being considered are used as markers in engine oil testing to detect failure of other systems. This creates an additional problem in that regardless of its impact on oil performance, the proposed dopant would render all supporting bench engine test data used for formal oil approvals invalid. Due to this issue, repeated testing could require considerable investment.

- **Testing – Lubricant system materials**

In addition to consideration of the dopants interaction with the lubricant chemistry, the impact on the various materials in the lubricant system must also be considered. Whether the dopant causes corrosion, etc. needs to be answered definitively before implementation [26].
• Value to Scania
While this concept may not require extensive modification to the mechanical systems in the current vehicles, it might necessitate substantial changes to the lubricant chemistry [26]. Selling this product would need significant investment in testing and analysis.

• Testing – Surfactant
Interview of industry experts at Lubrizol Ltd. have speculated that there may be a surfactant technology currently available to hold the dopant in the oil solution. However, testing would be required to demonstrate long term stability.

**C.2.2 Dopant Transport Mechanisms – Fuel Additive**

*Benefits*

• Extensive background
There have been several studies conducted regarding various approaches to dosing diesel fuel with various additives in order to improve DPF performance [47], [52], etc. This is advantageous in that many of the considerations regarding the system, fuel chemistry, dosing strategies, etc. have already been thought out and investigated.

• Dosing rate
Deploying a fuel additive to the DPF is a more direct method than that of oil consumption. Engine oil consumption rate can vary dependent on a number of factors, whereas the fuel consumption of a given vehicle is less ambiguous.

• Dilution
There is a large difference between the volumes of fuel and lubricant on the average Scania truck. Where the engine oil capacity may be 43 liters, the fuel tank could carry up to 1000 L depending on the model. If the desired dosing of the dopant is 1 wt.% of the ash, that would in theory represent 0.01 wt.% of the engine oil. Changing 0.01 wt.% of engine oil could have significant implications on the lubricants performance [26]. However if the dopant were to be added to the fuel instead, the required amount of dopant be lesser, and the dilution would be much higher. The benefit of a higher dilution is that the impact the additive has on the properties of the overall solution could be somewhat mitigated [10].

*Drawbacks*

• Implementation strategy
Where an oil additive could be sold relatively easily, it is not realistic to expect all fuel vendors to modify their formula. This could necessitate a more complex approach to retain this concepts worth to Scania and its customers.

• Corrosion & Water
Due to the fact that diesel fuel can come in contact with water, a general consideration for any new additive is that it should not increase reactivity with water or increase corrosion levels [52].
Unknowns

- Dopants effect on system

As with the engine oil consumption approach, the effect and extent of dopant-system interaction is speculative without any testing.

- Additive interaction

Depending on the vendor, there is some variation in diesel additive chemistry and composition [10]. This creates some chance that the dopant could chemically react with other fuel additives present. This could result in changes in the fuel performance and properties. Additionally, the dopant could react with other elements present to creating larger particles which may be filtered out before making it through the combustion chamber to the DPF.

- Oil-in-Fuel interaction

Due to tolerances in the engine system, there is a component of engine oil mixed in with the fuel [53]. Even if it is decided to only add dopant to the fuel, it may be necessary to test how it interacts with the oil.

- Injector deposits & Thermal stability

The fuel injectors have some design tolerances within 3-5 microns [53], this creates a high sensitivity to flow blockage. As a result, any dopant would need to be tested to ensure it cannot cause deposits in the injectors. Additionally, in the injection system a component of high pressure fuel is used to hydraulically actuate the injectors. In this process, fuel temperature is raised to about 180˚ C, the dopant would need to be able to withstand this rapid heating without creating potentially harmful compounds [53].

C.2.4 Dopant Transport Mechanisms – Pre DPF SCR

Benefits

- Direct dopant transport

Whereas other dopant transport methods would need to be analyzed for their effect on lubricant and fuel chemistries, engine components, etc. this approach could bypass those concerns.

- Dopant concentration

From ISO standard 22241-1, the maximum allowable concentration of sodium in AdBlue is 0.5 mg/L. In order to achieve a desired 1 wt.% of dopant in DPF ash, the concentration would need to be approximately 0.32 mg/L. Testing and further analysis is required to establish whether this limit can be exceeded without damaging associated systems e.g., SCR catalytic activity, AdBlue parameters, etc.
Appendix C

Drawbacks

- Dopant – Catalyst interaction
The aforementioned limitations on sodium, are a result of the fact that such alkali compounds have been known to damage catalytic performance - in the case of the SCR, ammonium storage capacity [38]. Increasing alkali concentration above the average levels could have a negative impact on the overall after-treatment system performance. However, it is worth noting that this risk of effect on catalyst performance would probably be present for any concept in which the dopant will have to flow through these systems e.g. dopant in oil, fuel, etc.

Unknowns

- Dosing rate
One potential concern is the uncertainty in the amount of dopant to introduce to a particular AdBlue solution. The aforementioned ISO standard indicates that the composition may vary. This leads to some level of ambiguity as to how much dopant to add to the solution without some sort of chemical analysis of the levels already present in the AdBlue.

C.2.6 Dopant Transport Mechanisms – DOC Intake

Benefits

- Development cost
One of the major benefits of a dopant dosing system downstream of the engine is that the effects of the dopant on engine components, fuel and oil chemistry, etc. could be neglected.

- Design flexibility
Another benefit of a dosing system downstream of the engine is that there would be significantly less limitations on materials, dopant concentration, particle size, etc.

Drawbacks

- Modification to existing system
An on-board dosing system would require a dopant tank, injector, control system, etc. These additional complications represent extra development costs for Scania and a higher vehicle price for the end customer.
Appendix D
Water Injection Test Data

Appendix D presents the original data collected from the on-vehicle prototype testing of injecting water into the DPF inlet.

As can be seen in Figure 41, there is some error in the collected data. Logically, a volumetric flow rate of zero should correspond to a pressure drop of zero. Accordingly, the data presented in Figure 35 was corrected by utilizing trend lines of the data sets to predict their intercept with the y-axis (DPF pressure drop). This intercept value was then used to shift the data sets such that they cross through the origin of the graph (see Figure 35).

![Figure 41](image_url) – Original data collected from on-vehicle water injection testing (see Section 6.3.2), not corrected for error.
Appendix E

Criteria Matrix

Appendix E presents the criteria matrix used to select the final concept. In this matrix, there is a list of criteria against which all of the generated concepts are weighed. There are no numerical values made for the criteria or respective concepts score. Instead, solutions to potential conflicts between respective criteria points are provided. This is intended as a tool to give a qualitative perspective on which concept is perceived to be most viable. All DPF wetting concepts and water sources were judged under the same set of criteria. Similarly, all dopant transport methods were judged by a set of criteria specific to the dopant case.

The criteria are intended to embody the essential factors which a chosen concept must meet to succeed. These essential factors are the result of interview of Scania experts and the thesis supervisors.

Appendix E Guide:

The following criteria matrix is divided into:

- DPF wetting concepts and potential water sources, pages 74-76
- Dopant transport methods for engine oil, page 77
- Dopant transport methods for diesel fuel, page 78
- Other considered dopant transport methods, page 79
<table>
<thead>
<tr>
<th>Parameters</th>
<th>DPF Inlet Injection</th>
<th>DPF Outlet Injection</th>
<th>DOC Inlet Injection</th>
<th>Exhaust Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID.</td>
<td>Criteria</td>
<td>Mitigation strategy</td>
<td>Risk</td>
<td>Risk</td>
</tr>
<tr>
<td>1</td>
<td>Pressure drop reduction</td>
<td>Mitigation strategy: Use of DPF access plug rather than integrated injection system.</td>
<td>At risk</td>
<td>N/A - presumably avoided due to injection upstream of silencer.</td>
</tr>
<tr>
<td></td>
<td>Complexity</td>
<td>Mitigation strategy: Use of pre-installed nozzle &amp; water connector for periodic maintenance rather than on-board injection system.</td>
<td>At risk</td>
<td>Mitigation strategy: Use of pre-installed nozzle &amp; water connector for periodic maintenance rather than on-board injection system.</td>
</tr>
<tr>
<td></td>
<td>Energy requirement</td>
<td>Mitigation strategy: Use of DPF access plug rather than integrated injection system.</td>
<td>At risk</td>
<td>Mitigation strategy: Use of pre-installed nozzle &amp; water connector for periodic maintenance rather than on-board injection system.</td>
</tr>
<tr>
<td></td>
<td>Effectiveness</td>
<td>Volume of water available to be utilized</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Consumption</td>
<td>Concept water supply must be sufficient to wet DPF</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Safe</td>
<td>See corresponding risk ID. 1</td>
<td>See corresponding risk ID. 1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Water distribution</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>Water supply does not freeze due to environmental conditions</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>Concepts’ perceived value exceeds cost of additional components, vehicle energy consumption, development, etc.</td>
<td>At risk Mitigation strategy: see ID.2</td>
<td>At risk Mitigation strategy: see ID.2</td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
<td>Concept does not cause vehicle to fail current emissions standards (NOx during cold start, etc.)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Controllability</td>
<td>Ability to control flow rate, frequency, etc.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Retains Value</td>
<td>Concept has a realistic way to be sold as a Scania product</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td></td>
<td>Compatibility</td>
<td>The concept functions as expected regardless of environmental conditions, vehicle model, etc.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Ergonomics, Service Interval</td>
<td>Concept does not inhibit normal driver behavior (downtime, etc.)</td>
<td>At risk: if driver will inject Mitigation strategy: maintenance service, on board system</td>
<td>At risk: if driver will inject Mitigation strategy: maintenance service, on board system</td>
</tr>
</tbody>
</table>

A Method for Reducing Ash Volume in Wall-Flow Diesel Particulate Filters
<table>
<thead>
<tr>
<th>ID.</th>
<th>Criteria</th>
<th>Justification</th>
<th>Water in AdBlue tank (Pre-DPF SCR)</th>
<th>EGR Condensation</th>
<th>Windshield Wiper Fluid</th>
<th>Charge air cooler</th>
<th>Maintenance service</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressure drop reduction</td>
<td>Concept does not cause risk of increasing pressure drop, SCR urea lumps.</td>
<td>N/A - presumably avoided due to injection upstream of silencer.</td>
<td>Mitigation strategy: pre-silencer water injection.</td>
<td>Mitigation strategy: pre-silencer water injection.</td>
<td>Risk: removing condensed water from charge air flow could require an increased pressure drop (centrifuge)</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Complexity</td>
<td>Concept does not require modification to existing systems</td>
<td>N/A - No additional components.</td>
<td>At risk</td>
<td>At risk</td>
<td>At risk</td>
<td>Mitigation strategy: service plug, pre-installed nozzle attachment for quick water injection</td>
</tr>
<tr>
<td>3</td>
<td>Energy requirement</td>
<td>Concept does not require additional energy to function (electric, fuel, etc.)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>??</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Effectiveness</td>
<td>Volume of water available to be utilized</td>
<td>??</td>
<td>??</td>
<td>14.5 liters</td>
<td>??</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Consumption</td>
<td>Concept water supply must be sufficient to wet DPF</td>
<td>?? At Risk</td>
<td>N/A</td>
<td>?? At Risk</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Safe</td>
<td>Concept does not damage existing systems</td>
<td>Risk: formation of urea deposits Mitigation strategy: when AdBlue empty, fill tank with small amount of water at truck refill, then spray thru system</td>
<td>Risk: Hydrolock Mitigation strategy: effective removal of condensate before it enters combustion chamber.</td>
<td>Risk: ?? Mitigation strategy: evaluation of effect of wiper fluid chem on catalysts, filter media, etc.</td>
<td>Risk: Hydrolock Mitigation strategy: effective removal of condensate before it enters combustion chamber.</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>Water distribution</td>
<td>Concept effectively wets the entire DPF</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Storage</td>
<td>Water supply does not freeze due to environmental conditions</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>Cost</td>
<td>Concepts’ perceived value exceeds cost of additional components, vehicle energy consumption, development, etc.</td>
<td>N/A (use of pre-existing systems (ref: CAS-1))</td>
<td>N/A (use of pre-existing systems)</td>
<td>At risk (requires some sort of additional water transport mechanism)</td>
<td>At risk (requires some sort of additional water transport mechanism)</td>
<td>Risk dependent on approach, see ID. 2</td>
</tr>
<tr>
<td>10</td>
<td>Emissions</td>
<td>Concept does not cause vehicle to fail current emissions standards (NOx during cold start, etc.)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>11</td>
<td>Controllability</td>
<td>Ability to control flow rate, frequency, etc.</td>
<td>N/A</td>
<td>??</td>
<td>N/A</td>
<td>?? Risk: Condensation highly dependent on environmental conditions</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Retains Value</td>
<td>Concept has a realistic way to be sold as a Scania product</td>
<td>N/A (use of pre-existing systems (ref: CAS-1))</td>
<td>?? (would require development of injection system)</td>
<td>?? (would require development of injection system)</td>
<td>?? (would require development of injection system)</td>
<td>N/A</td>
</tr>
<tr>
<td>13</td>
<td>Compatibility</td>
<td>The concept functions as expected regardless of environmental conditions, vehicle model, etc.</td>
<td>N/A</td>
<td>Risk: EGR no longer commonly used in product line</td>
<td>N/A</td>
<td>Risk: The ability to condense water is highly dependent on environmental conditions, e.g. RH</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>Ergonomics, Service Interval</td>
<td>Concept does not inhibit normal driver behavior (downtime, etc.)</td>
<td>At Risk: if going to periodically pour water into AdBlue tank</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td>Environmental Sources</td>
<td>Extraneous water tank</td>
<td>Heat Exchanger in Exhaust</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-----------------------</td>
<td>-----------------------</td>
<td>--------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID.</td>
<td>Criteria</td>
<td>Justification</td>
<td>Risk</td>
<td>Risk</td>
<td>Risk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Pressure drop reduction</td>
<td>Concept does not cause risk of increasing pressure drop, SCR urea lumps.</td>
<td>Mitigation strategy: presilencer water injection.</td>
<td>Mitigation strategy: presilencer water injection.</td>
<td>Risk: May increase pressure drop in exhaust flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Complexity</td>
<td>Concept does not require modification to existing systems</td>
<td>At risk</td>
<td>At risk</td>
<td>At risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Energy requirement</td>
<td>Concept does not require additional energy to function (electric, fuel, etc.)</td>
<td>N/A</td>
<td>??</td>
<td>?? (At Risk)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Effectiveness</td>
<td>Volume of water available to be utilized</td>
<td>??</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Consumption</td>
<td>Concept water supply must be sufficient to wet DPF</td>
<td>??</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Safe</td>
<td>Concept does not damage existing systems</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Water distribution</td>
<td>Concept effectively wets the entire DPF</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>N/A - with properly designed injector system this should not be a concern.</td>
<td>??</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Storage</td>
<td>Water supply does not freeze due to environmental conditions</td>
<td>Mitigation strategy: antifreeze additive</td>
<td>Mitigation strategy: antifreeze additive</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Cost</td>
<td>Concepts’ perceived value exceeds cost of additional components, vehicle energy consumption, development, etc.</td>
<td>At risk (requires some sort of additional water transport mechanism)</td>
<td>At risk (requires some sort of additional water transport mechanism)</td>
<td>At risk (requires additional heat exchanger, coolant, etc.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Emissions</td>
<td>Concept does not cause vehicle to fail current emissions standards (NOx during cold start, etc.)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Controllability</td>
<td>Ability to control flow rate, frequency, etc.</td>
<td>??</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Retains Value</td>
<td>Concept has a realistic way to be sold as a Scania product</td>
<td>?? (would require development of injection system)</td>
<td>?? (would require development of injection system)</td>
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<tr>
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<td>Risk: Water sources dependent on environment, season, geographical location</td>
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<td>14 Ergonomics, Service Interval</td>
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### Dopant Deployment Method:

#### Parameters

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<tr>
<td>1</td>
<td>Concept does not require modification to existing systems</td>
<td></td>
<td></td>
<td>Risk: would require re-design of current fuel filter</td>
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<tr>
<td>2</td>
<td>Energy requirement</td>
<td>Concept does not require additional energy to function (electric, fuel, etc.)</td>
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<tr>
<td>3</td>
<td>Concentration</td>
<td>Amount of dopant required (relative to solution) to achieve an equivalent amount in DPF</td>
<td>Risk: high concentration effect on overall fluid properties (0.03 ppm in fuel is 1 wt% dopant in ash)</td>
<td>Risk: high concentration effect on overall fluid properties (0.03 ppm in fuel is 1 wt% dopant in ash)</td>
</tr>
<tr>
<td>4</td>
<td>Dosing rate</td>
<td>Max. allowable dopant volume deployed to DPF (l/km)</td>
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<td>5</td>
<td>Safe</td>
<td>Concept does not damage existing systems</td>
<td></td>
<td>Risk: engine corrosion, injector deposits, filter blocking Mitigation strategy: requires testing**</td>
</tr>
<tr>
<td>6</td>
<td>Storage (long term stability)</td>
<td>Dopant is stable in solution</td>
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<td>??</td>
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<tr>
<td>7</td>
<td>Filtration</td>
<td>The dopant should not be filtered out</td>
<td></td>
<td>Risk: dopant filtered out of system Mitigation strategy: surfactant, particle size, testing required**</td>
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<td>8</td>
<td>Emissions (catalytic performance)</td>
<td>The dopant does not damage after-treatment performance</td>
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<td>9</td>
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<td>Maximum concentration of dopant in a given solution allowed</td>
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<td>10</td>
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<td>Concepts dosing rate can be controlled Mitigation strategy: technology for control of additive flow rate in filter exists</td>
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<td>11</td>
<td>Cost</td>
<td>Concepts’ perceived value exceeds cost of additional components, vehicle energy consumption, development, etc.</td>
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<td>Ergonomics, Service interval</td>
<td>Concept dosing strategy does not inhibit normal driver behavior (downtime, etc.)</td>
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<td>Solution-Dopant interaction</td>
<td>Dopant does not damage essential functions of solution</td>
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<td>14</td>
<td>Retains Value</td>
<td>Concept has a realistic way to be sold as a Scania product</td>
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<td>Compatibility</td>
<td>The concept functions as expected regardless of environmental conditions, vehicle model, etc.</td>
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<td>Pre-DPF SCR AdBlue</td>
<td>Maintenance (direct spray into DPF)</td>
<td>Dopant in intake air</td>
<td>Dopant/Water Solution</td>
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<td>?</td>
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<td>Risk: dependent on wetting method</td>
</tr>
<tr>
<td>2</td>
<td>N/A (pre-existing system)</td>
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<td>At risk</td>
<td>Risk dependent on wetting method</td>
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<tr>
<td>3</td>
<td>0.375 ppm in AdBlue, 0.813 mg/l NaCl (0.32 mg/l sodium) Mitigation Strategy: lower concentration, study effect of dopant on SCR, AdBlue chemistry</td>
<td>N/A (presumably can use any desired concentration)</td>
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<td>? (ISO std. (0.5 mg/l sodium) would be 1.22 E-8 l/km --&gt; 1.564 wt% in ash)</td>
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<td>5</td>
<td>Risk: deactivation of catalyst ammonia storage capacity Mitigation strategy: testing required**</td>
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<td>N/A (use of pre-existing components)</td>
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<td>12</td>
<td>Risk: cannot change AdBlue formula, so driver or maintenance worker would need to add dopant to SCR tank periodically</td>
<td>Risk: dependent on driver coming in for maintenance</td>
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