CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF PROCESS ENGINEERING

LIFETIME OF FILTER ELEMENT

BACHELOR THESIS

2020 OMAR ALIF ALLAM

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Allam Omar Alif Abdelhakim** Personal ID number: **467842**

Faculty / Institute: **Faculty of Mechanical Engineering**

Department / Institute: **Department of Process Engineering**

Study program: **Bachelor of Mechanical Engineering**

Branch of study: **Power and Process Technology**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Filter element lifetime

Bachelor's thesis title in Czech:

Interval výměny filtrační vložky

Guidelines:

The aim of this work is to analyze the measurements of filter element lifetime and to create a hypothesis explaining the measurement records. In the frame of this work will be carried out research focused on parameters affecting the filter element lifetime. The output will be a hypothesis explaining the results of measurement analysis. Real data of filter elements will be provided for the work.

Bibliography / sources:

Bude specifikována po dohodě s vedoucím práce.
Literature will be specified in agreement with the supervisor.

Name and workplace of bachelor's thesis supervisor:

Ing. Michal Netušil, Ph.D., ŠKODA AUTO a.s.

Name and workplace of second bachelor's thesis supervisor or consultant:

Date of bachelor's thesis assignment: **30.04.2020** Deadline for bachelor thesis submission: **07.08.2020**

Assignment valid until: **30.09.2020**

Ing. Michal Netušil, Ph.D. Supervisor's signature	prof. Ing. Tomáš Jirout, Ph.D. Head of department's signature	prof. Ing. Michael Valášek, DrSc. Dean's signature

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ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude and respect towards my thesis advisor, Ing. Michal Netušil, Ph.D. for the continuous support of my BSc. study and research, for his patience, motivation, enthusiasm, and immense knowledge. Finally, I would like to express my love and affection towards my parents to whom I owe so much that can never be repaid.

ANNOTATION SHEET

Name:	Omar Alif Abdelhakim
Surname:	Allam
Czech Title:	Interval výměny filtrační vložky
English Title:	Filter element lifetime
Number of pages:	45
Number of figures:	15
Number of tables:	2
Academic year:	2019/2020
Language:	English
Department:	Process Engineering
Specialization:	Process Engineering
Supervisor:	Ing. Michal Netušil, Ph.D.
Reviewer:	
Submitter:	Czech Technical University in Prague, Faculty of Mechanical Engineering Department of Process Engineering

ABSTRACT

The internal combustion engine requires clean air in order to operate without problems during the entire service life. This is why air filter in the air intake system is needed to act as a barrier between the ambient air ridden with particulate matter, that can penetrate into sensitive interior parts of the engine. If any kind of contaminants reached the engine cylinders, rings or bearings it will cause abrasive wear to the engine

The scope of this thesis is to analyze the measurements of the filter element lifetime. Several factors affect air filter performance and lifetime, such as pressure drop, efficiency, and dust holding capacity. Other external factors can affect the filter element lifetime as well. For example, engine type and environmental conditions. The primary trapping mechanisms for particles capture include the Brownian diffusion, interception, and inertial impaction

The output of this work is based on experimental data gathered from the laboratory.

KEYWORDS: Air Intake System (AIS), initial/final restriction, dust holding capacity, pressure drop, clogging

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List of abbreviations

FE	Filter Element
AIS	Air Intake System
DHC	Dust Holding Capacity
MAF	Mass Airflow Meter
MPPS	Most Penetrating Particle Size

1. Introduction

1.1 Background about Air filters

Performance of any automotive engine mainly depends on engine technology and filter system used. Automotive filter business is however mainly concerned with air filters, oil filters, fuel filters and cabin filters. The performance of an automobile is bolstered significantly by the presence of high-performance filter media in the engine compartment and in various other locations. The purpose of filter is to control contamination through achieving a balance between the sources of contamination and the ability of a system to tolerate contamination. The ultimate goal is to balance filtration performance with the desired cleanliness level.

Interestingly, during the first stage of car production, no air filters were inspected in the engine. However, within the development of the automotive industry, engineers quickly realized that debris was getting inside the engines, therefore hurting performance and shortening engine life. Early on, the first solution was a water bath to trap particles, which led to a second attempt of an oil bath, thicker and stickier, to trap more impurities. Lastly, car's air filters nowadays are usually made of cellulose paper or synthetic felt media.

First of all, the performance of air filters is critical to the efficient operation for car engines. While air filters do an adequate job of filtering dirt and other particles from entering the engine. However, they are not 100% efficient. This is why, over time, the engine's performance goes down and needs to be repaired or replaced. Air filters can reach an efficiency for up to 99% preventing dust particles from entering the engine. However, over a long period of time, dirt and other particles accumulate, clogging and blocking the air filter passages [8].

For the vast majority of passenger cars, the engine air cleaners with air filters should be replaced about every 48,000-72,000 miles for light/medium duty, depending on the driving conditions [2]. If the vehicle is used regularly on unpaved roads where it is frequently experiencing dusty conditions, it should be changed more often; otherwise when the air filter becomes dirty, the engine is forced to work harder resulting in decreased fuel economy, higher emissions, and even loss of engine power.

In order to make an appropriate filter selection, the influential parameters affecting the filter element lifetime must be evaluated first. The assessment of air filter performance is complex and influenced by several parameters. For example, face velocity, filter medium properties, dust types and their loading conditions. The performance characteristics under study in this paper are the pressure drop, efficiency and dust holding capacity. Discussions in this work have been limited to passenger cars engine air filters.

1.2 Objective

The main objective of this work is to analyze the measurements of filter element lifetime and specifying the parameters affecting the filter element lifetime.

The specific objectives of the thesis include:

- Determining the performance characteristics of air filters in car engines.
- Determining the parameters affecting the filter element lifetime.
- Conducting a practical part by gathering experimental data from laboratory & comparing the new and used filters in respect with the pressure drop and airflow.

1.3 Aim of the study

The aim of this work is to analyze the measurements of filter element lifetime and to create a hypothesis explaining the measurement records. In the frame of this work will be carried out research focused on parameters affecting the filter element lifetime.

The output will be a hypothesis explaining the results of measurement analysis. Real data for filter element is provided for this work.

2. Literature Review

This chapter presents a review of literature on the principles behind how dust particles are removed in the air filters. followed by a brief study on the engine air intake system and pressure losses in the manifold.

2.1 Filtration and Separation Mechanism

In the realm of air filtration, the specific developments are most likely too numerous to list in their entirety. Below in this section the reader is presented with an overview of various approaches to air filtration, and their distinctive characteristics are briefly outlined as follow.

2.1.1 Surface Filtration

The predominant capture mechanism for surface filters can be thought of as an advanced sieving mechanism, as surface filters capture any particle that is too large to pass through the pore structure. When a particle is larger than the pores of the mesh and simply cannot pass through. The mesh with the uniform pore openings allows for the passage of smaller particles [18] as shown schematically in Figure1. However, as contaminant is loaded onto the surface of the filtration medium, the pressure loss through the filter system increases much more rapidly with surface filters as opposed to depth filtration media. This forms one of the most significant limitations of surface filtration [17].

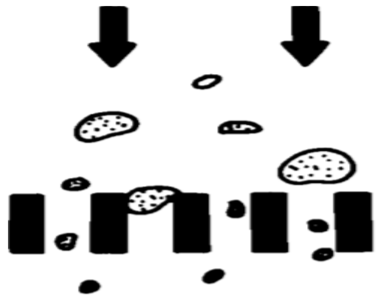

Figure 1. Filtration mechanism by surface straining [18]

2.1.2 Cake filtration

It is the concept of removing particles from the dirty side of the filter by utilizing an accumulated dust layer, which called the filter cake layer as shown in figure 2. When additional dust is loaded, the filter media near to the surface gets clogged. In this way, a filter cake of dust particles is formed which is relevant for subsequent filtration. The accumulation of dust particles collected on the surface of the filter contributes to the filtration process by collecting other particles. Cake filtration is particularly useful when the collected particles are of use, because of the ease of collection [5] [18].

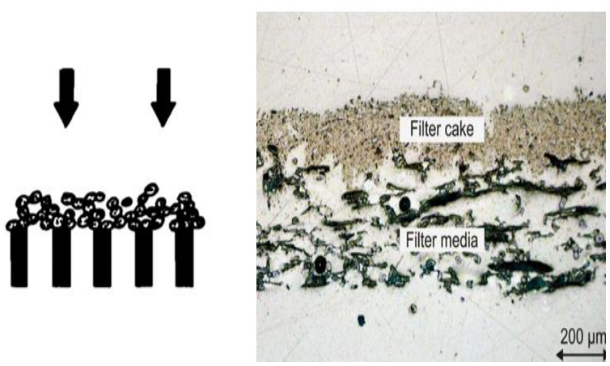

Figure 2. Cake filtration mechanism [18] [5]

2.1.3 Depth filtration

Depth filtration allows for the filtration of particles smaller than the diameter in the filter element's pore structure, as shown in figure 3. However, it differs from surface filtration in the mechanisms of capturing the particles since it is not as straightforward as for surface filters, and the performance characteristics of depth filter change differently as a function of time and particle diameter (section 3.2.1 figure 7 for more details) when compared to surface filtration.

Depth filtration considered to be the most economical method when there is a low concentration of particles to be separated. The mechanisms of particle capture for depth filtration media are [18]:

- Inertial Impaction
- Direct Interception
- Brownian Diffusion.

It is important to note that while all three mechanisms can be addressed separately, all three will act simultaneously in real-world applications. Moreover, all three mechanisms can be thought to work together to contribute to a very high efficiency (99.90%+) for a given depth filtration medium [15].

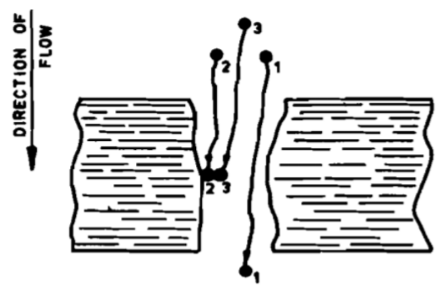

Figure 3. Depth filtration mechanism [18]

2.1.3.1 Inertial impaction

As air flows through a depth filtration medium it must change direction to flow around the fiber in its path. When a particle's inertia is high enough making the drag exerted on it by the airflow is not sufficient to alter the particles trajectory and the particle makes contact with the fiber, this is referred to as inertial impaction.

Inertial impaction takes place in high airflow velocities for particles with a larger diameter (mostly larger than 1 μm) because of its high inertia, dust particles are unable to adjust quickly enough to the abruptly changing streamlines near the fiber and crosses those streamlines to hit the fiber and attaches itself [11].

Figure 4 shows the inertial impaction mechanism. The streamlines of a fluid around the fiber are curved. Particles with a finite mass and moving with the flow may not follow the streamlines exactly due to their inertia. If the curvature of a streamline is sufficiently large and the mass of a particle is sufficiently high, the particles may deviate far enough from the streamline to collide with the media surface [4].

It is important to note that the particle's size and density play a large role in this mechanism of capturing, as does the Stokes drag exerted on the particle. The inertial impaction mechanism can be studied by the use of the dimensionless Stokes number, defined as [11]:

$$Stk = \frac{d_p^2 \rho_p C_s U}{18 \mu d_f} \quad (1)$$

Where

- d_p is the particle diameter
- d_f is the fiber diameter
- C_s is the Cunningham slip correction factor,
- ρ is the particle density.
- U is the free stream velocity of the air
- μ is the dynamic viscosity

Particles having a higher stokes number are less likely to follow the streamline of the fluid and thus have a higher chance of impacting a fiber due to their inertia. If the Stokes' number is higher than one, then the particles separate from streamlines and hit the collector. On the other hand, for Stokes' number lower than one, the inertia effect will not take place. Thus, particles will be separated by direct interception [11].

2.1.3.2 Direct Interception

Particles that follow the streamline of the fluid flow through a depth filtration medium can be separated by direct interception, despite the particle not being arrested via inertial impaction. Direct interception is the term used to describe when a particle following the streamline of the fluid comes in direct contact with a fiber in the depth filtration medium as shown in figure 4. If the particle follows a path that is less than one particle radius away from the fiber, then it is assumed that it will adhere to the fiber and be captured.

The particles that hit the fiber is captured because of its finite size (more than 0.1 μm). In addition, it is assumed that if the dust particles follow the streamlines perfectly, then, they have negligible inertia and Brownian motion. Interception is the only mechanism that is not a result of a particle departing from its original gas streamline.

The interception mechanism depends on the dimensionless parameter, R, which is the ratio of particle to fiber diameter [11]:

$$R = \frac{d_p}{d_f} \tag{2}$$

It should be noted that a particle may be intercepted by a combination of inertial impaction and direct interception as shown in figure 7 section 3.2.1, where inertial impaction and interception are taking place at the same period during filtration. In the case of a particle flowing through the medium with a low Stokes number that does not necessarily follow the streamline of the fluid in which it was originally traveling, the particle can in theory deviate from the stream line and still “miss” the fiber; likewise, a particle may deviate from its original path and still strike the fiber.

2.1.3.3 Brownian Diffusion

Filtration by Brownian diffusion occurs when small particles collide with the air molecules and move in an erratic path (Brownian movement). The mechanism is an irregular wiggling motion of dust particles caused by random variations in the relentless bombardment of gas molecules against the particle. As particle diameter continues to decrease ranging from (0.01-0.1 μm) neither of the two aforementioned capture mechanisms dominate to the separation of particles [15]. Particles in this size range quickly reach thermal equilibrium with the gas that surrounds them; resulting in the particles undergoing what is referred to as Brownian motion. In this condition the average velocity of the smaller particles will be greater than that of larger particles. Under Brownian motion, the capture of a particle by what is termed diffusional deposition is a function of the magnitude of the diffusional motion and the convective motion around the fiber; that can be expressed by the dimensionless Peclet number as follow [11]:

$$Pe = \frac{Ud_f}{D} \tag{3}$$

where the diffusion coefficient of particle *''D''* calculated as follow [11]:

$$D = \frac{k_B T C_s}{3\pi\mu d_p} \tag{4}$$

Where $k_B, T, \mu\ and\ d_p$ are the Boltzmann constant, absolute temperature, air dynamic viscosity and particle diameter, respectively and C_s is the Cunningham slip correction factor that can be expressed as [11]:

$$C_s = 1 + K_n \left[1.207 + 0.44 \exp\left(-\frac{0.78}{K_n}\right)\right] \tag{5}$$

Where K_n is the Knudsen number of particle with λ as mean free path of gas molecules [11]:

$$K_n = \frac{2\lambda}{d_p} \tag{6}$$

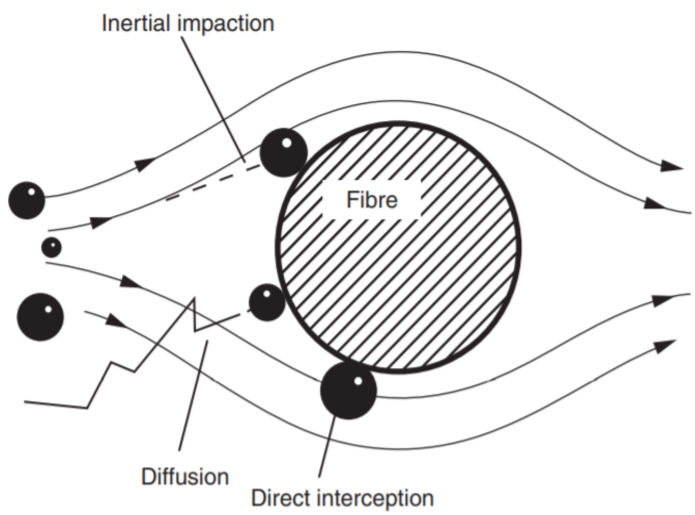

Figure 4. Particle collection mechanism [4]

2.2 Engine Air intake system & pressure losses in pipes

2.2.1 Air Induction/Intake system (AIS)

Mechanism of AIS

An engine air intake system's crucial role is to eliminate pollutants from the incoming air stream, which may cause engine wear resulting in loss of performance, increased exhaust pollution, increased operational and repair costs, or catastrophic failure.

The AIS is important for the process of internal combustion in engine. This system acts as a guide for the air that will be used in the combustion chamber by collecting air and directing it to individual cylinders. The location of the air intake system always near to the engine.

The main components of the air intake system are including:

- Air filter.
- Mass air flow meter
- Throttle body
- Intake manifold
- Turbo with the intercooler for additional charge system

Air Filter

The ambient air from the atmosphere enters the system through an intake duct and gets into the filter box, which contains the filter element. FE is one of the main components in the AIS. This component is designed to remove moisture, dirt and debris from the air before it reaches the engine. Effect of the flow restrictions in the air filter increases the pressure ratio over the turbo which gives the same boost but on the cost of a higher working temperature. A low restriction intake system will be rewarded with more power and less heat. It must do this over a reasonable time period before servicing is required, as if dirt is allowed to enter the engine cylinders, the abrasive effects will result in rapid wear in cylinders and piston rings [4].

Mass Air Flow Meter

As the engine is accelerating, the air needed in the combustion chamber is increased, thus increasing the airflow into the system. Therefore, the air entering the system in most of the vehicles is manipulated by the mass airflow meter (MAF) in which the flow through the air filter is made smooth and streamlined to reduce the turbulence of flow. AFM is also responsible for updating the engine control unite to modify fuel supply. From the mass flow meter, which is usually located on the intake manifold, then, does it goes to the throttle body [25].

Figure 5 below shows a schematic diagram for air intake system and the airflow path.

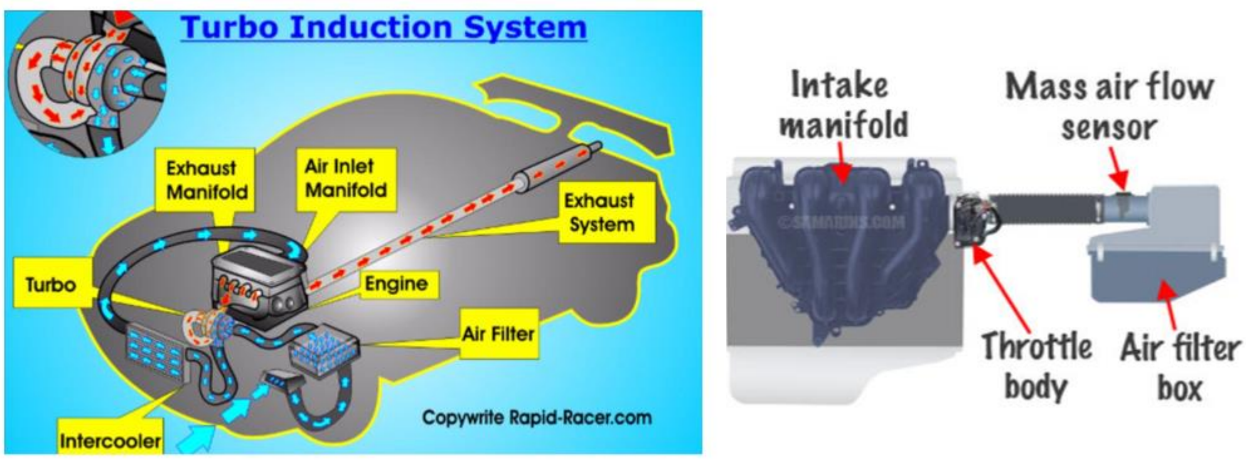

Figure 5. Engine air induction system diagram [25]

Throttle Body

After air being measured, the air continues through the air intake tube to the throttle body. Its main function is to control the amount of air entering the intake/inlet manifold, where the air is split to each cylinder and combustion chamber, normally byways of a cable linked to the throttle pedal at the cabin's car. For example, When the accelerator is depressed, the throttle plate opens and allows air into the engine, resulting in an increase in engine power and maintaining the driver's desired vehicle speed. When the accelerator is released, the throttle plate closes and effectively chokes-off airflow into the combustion chamber [25].

Intercooler

An intercooler is an intake air cooling mechanical device used commonly on turbocharged and supercharged engines. As the air is compressed by a turbo/supercharger it gets very hot, very quickly. As its temperature increases, its oxygen content drops, so by cooling the air, an intercooler provides a denser and more oxygen to the engine thus improving the combustion by allowing more fuel to be burned. It also increases reliability as it provides a more consistent temperature of intake air to the engine which allows the air fuel ratio of the engine to remain at a safe level.

Intake manifold

After intake air passes through the throttle body, it gets into the intake manifold. An engine intake manifold is the part of the engine, between the throttle body and the engine cylinders. The manifold has a plenum or an air chamber where air is stored and a set of runners connected to the intake ports of the engine on the engine head. With port fuel injection, only air flows through the manifold. In a multi-cylinder engine, the primary function of the intake manifold is to transport combustion air to the engine cylinder, and to create the fuel air mixture, unless the engine has direct injection. When the throttle valve opens, air flows into the plenum. During the intake stroke, the intake valve opens and air-fuel mixture flows through the runners into the cylinder where combustion takes place. The intake manifold is not just a passageway for the mixture to flow into but it also contributes to a better distribution of the fuel and air.

2.2.2 Pressure losses in Pipes

An intake manifold is ostensibly a network of pipes and ducts which feed air into the engine to feed the combustion process. As such it is open to analyse and optimise any network of pipes and ducts may be. One well documented and theorised section of pipe flows involves a head loss, or pressure loss due to certain geometries within the flow, specifically for bends, valves, entrance and re-entrance flows [28].

Pressure losses in pipes are split into two categories, major and minor. Major losses occur due to the physical length of the pipe and the viscous losses associated with the friction between the wall and the fluid [10].

While Minor losses occur due to variations in geometry through the piping such as bends, elbows, valves, entrances and re-entrances.

The terms major and minor do not refer to the relative sizes of the losses necessarily, but in typical piping systems involving many long straight sections with few bends and valves the major losses are more substantial than the minor. In the case of an intake manifold however, the ‘minor’ losses are far more significant, and typically dominate the pressure losses experienced [28].

3. Parameters Affecting filter service lifetime

3.1 ISO 5011

The ISO 5011 (International Organization for Standardization) is a test procedure or protocol with built-in options. It defines a precise filter test using precision measurements under controlled conditions. Temperature & humidity of the test dust and air used in the test are strictly monitored and controlled. The use of a standard test dust ensures consistency and is representative of the size range of dust particles found in real conditions. It is used to permit the direct laboratory performance comparison between air cleaners.

In order to compare two ISO 5011 test results, we need to understand which options have been selected. The test measures the percentage of dust retained by an air filter as the dust is introduced into a stream of air flowing through the air filter at a constant flow rate. There is both an initial measurement and an overall measurement [6].

The ISO 5011 test is performed mainly on three main parameters that help in determining the filter element lifetime:

1. Filtration efficiency.
2. Dust holding capacity.
3. Flow restriction.

The test filter element is placed in the test rig, dust is induced in the dust injector which is then blown towards the tested filter element. Downstream of the test filter there is an absolute filter, along with an airflow meter, airflow controller and an exhausted. The pressure is measured before and after the filter element, which gives the differential pressure (or pressure drop). At a specified allowed pressure drop the test is terminated. The filter element is then weighed to determine the increase in mass and the dust holding capacity. The absolute filter is also weighed to calculate filter efficiency. The diagram in figure 6 below shows a Layout of a test rig for the investigation of a filter media [4].

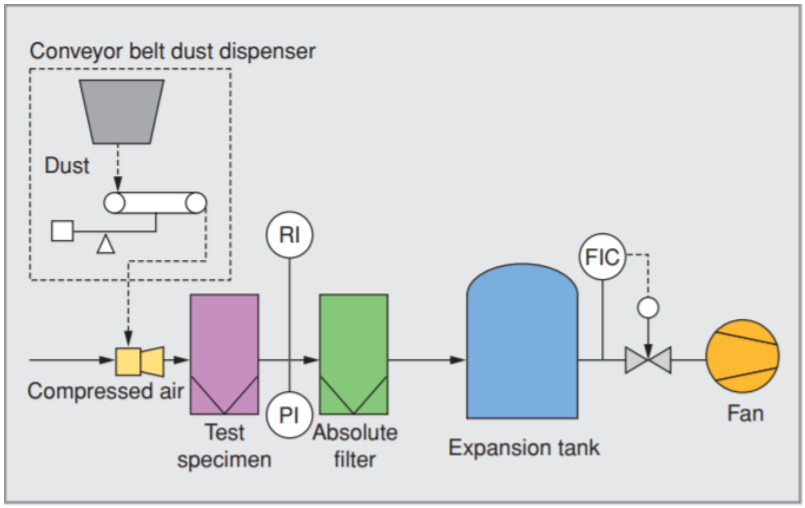

Figure 6. Schematic diagram of a test rig [4]

3.2 Filtration Efficiency

Efficiency of air filter can be defined simply as when analyzing the air filter performance, is the number of particles that are filtered by the air filter element. It is measured in percentage and represents the volume of dirt/contaminates an air filter prevents from entering the engine. The final efficiency varies over the service lifetime and is generally lower when considering the initial efficiency. This is due to the formation of the so-called cake layer on the surface of the filter medium. The engine air filters are designed to actually increase their efficiency by using this initial layer (cake layer) of dust as an added filter layer. Initial filter efficiency is usually 98% approximately but increases to more than 99% by the end of the service life of the filter [3].

Air filter requirements are usually specified with an initial efficiency, along with a final efficiency. For example, let's assume a filter efficiency results of 95%, which means that the air filter retained 95% of the test dust, allowing 5% to be passed through the air filter.

To determine the efficiency of a filter element, there is only one generally accepted standard test procedure and that is the ISO 5011. Modern air filters achieve filtration efficiency of up to 99.8% for diesel cars and 99.5% for gasoline cars [4]. For instance, K&N Air Filters tested generally range between 96% and 99% in overall efficiency using coarse test dust [24]. The question is how the initial and overall efficiencies are determined.

As stated before, when filter media loads up with more dust, filtering efficiency improves. The filter is given an efficiency percentage and rated in two ways. The initial percentage (initial efficiency), which measures the efficiency after 20 grams of dust being fed to the tested air filter, and the final percentage (overall efficiency), which is taken at a specific restriction of 2.5kPa over the initial new filter reading. The overall efficiency must be higher than the initial efficiency to avoid re-entrainment and bouncing of dust particles [2].

Filter efficiency can be calculated as the ratio between the mass increase of an absolute filter (absolute filter captures any dust that passes the test filter) versus the total mass increase of absolute downstream filter and the mass of dust being fed [6]:

$$E[\%] = \frac{\Delta M_A}{\Delta M_A + \Delta M_B} . 100 \quad (7)$$

Where:

- *E [%] …. Efficiency.*
- ΔM_A *….. Mass increase of upstream absolute filter.*
- ΔM_B *….. Mass increase of downstream absolute filter.*

3.2.1 Filtration separation mechanism efficiency vs particle size diameter

Here in this section, we will briefly discuss the filtration theory of how different separation methods are applied efficiently depending on the particle size diameter.

This filtration theory is the same on all types of air filters that are used in the automotive industry and some other applications (like respiratory protection, building ventilation system, etc.); the only difference can be in the filtration efficiency percentage as it varies based on the material type of air filters. Figure 7 shows the graph of the grade efficiency as a function of particle size based on the example of an air filter element consisting of synthetic fibers [4].

Firstly, as shown in figure 7 the filtration efficiency was decreasing at first then increased until it reached its maximum efficiency. This is contributed to the three main mechanisms for particle separation methods (diffusion, direct interception and inertial impaction).

Secondly, it is obvious that the filtration efficiency is decreasing at particle size range between 0.01-0.5 μm. As very tiny particles pass through the filter, the diffusion separation mechanism is considered to be the primary filtration mechanism for capturing the particles at this stage. As mentioned before the diffusion separation takes place at size range between 0.01-0.1 μm.

Thirdly, within increase in the particle size diameter between 0.1 to around 0.5 μm, the filter seems to be less efficient reaching its minimum efficiency, that defines the most penetrating particle size (MPPS) at this point.

MPPS is a term used for defining the most difficult particles to be captured. Particles are considered to be too large to be captured by diffusion effect and too small for a significant interception effect. At this gap, for this certain size, the efficiency can drop to 85% approximately.

Lastly, at Particles larger than 1 µm, the filter is getting to its maximum efficiency, where interception and inertial impaction are predominant at this stage. Any size of dirt is potentially harmful to the engine, but high concentrations of particles in the range of 1-20 microns are considered to be the most harmful to modern engines [4].

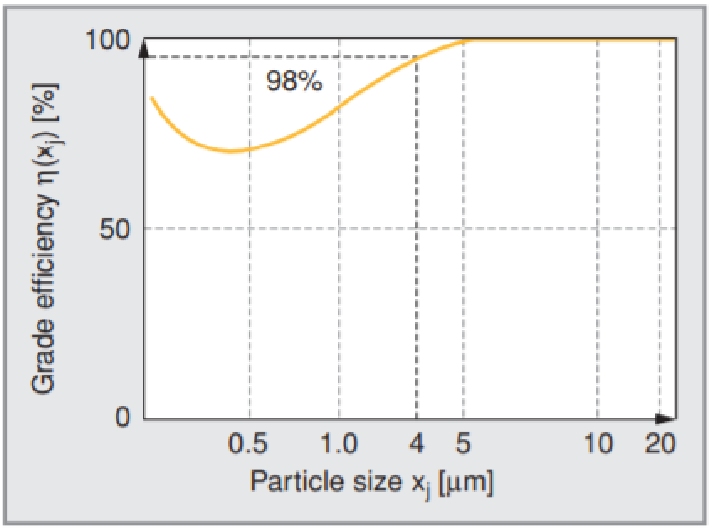

Figure 7. Filter efficiency vs. particle size [4]

3.2.2 Media Face Velocity

Furthermore, Efficiency of an air filter is driven largely by two main factors; the velocity of the air entering to be filtered (called face velocity) as it moves through the filter, and the size range or particle size of the airborne particulate to be filtered.

The Media face velocity can be expressed as follow [16]:

$$media\ face\ velocity\ [m/s] = \frac{Q_f}{A_m} \tag{8}$$

Where

- $Q_f \dots . filter\ volumetric\ flow\ [m^3.s^{-1}]$
- $A_m \dots media\ area\ [m^2]$

According to Indian Institute of Technology Delhi, it can be seen that the data corresponding to the lower filtration velocity produces higher efficiency results. What may be a little more difficult to discern is the effect of particle size on filtration velocity [9].

Main points from the graph are outlined as follow in regard to the relation of the particle size to the face velocity of the untreated cellulosic filter media [9]:

- Particle size Beyond 0.5μm: for all face velocities, the filtration efficiency at the beginning was slightly decreasing until reaching its minimum efficiency as particles were following Brownian motion and captured through diffusion mechanism.

- Particle size more than 0.5μm: for all face velocities, it is observed clearly that the filtration efficiency improved significantly and increased to over 99 percent, as particles are more likely to follow the streamlines of the air passing through the filter and as such will avoid contact with the filtration medium. Therefore, this is where the mechanisms of interception and impaction for dust particle capture are predominated.

- Larger particles between 1-6 μm: at a face velocity of 0.3 m/s showed higher efficiency than the face velocity of 0.1m/s. A similar association with face velocities more than the 0.3m/s. This showed that the increase in filtration efficiency of particles with face velocity due to inertial impaction was evident in this range of particle size.

- The particle size at 2 μm: at a face velocity of 0.5m/s, the efficiency was increasing until the dust particles size was 4 μm; the efficiency decreased to 89%, and a similar association was observed at a face velocity of 0.85 m/s & 1.2 m/s as well. This unusual behavior is attributed to rebound of particles after colliding the filter surface and followed by subsequent re-entrainment of particles in the air streams at higher velocity.

To sum up, an important factor for reaching the desired efficiency is the face velocity. Depending on filter medium, there is a critical face velocity that has to be kept. If the face velocity is too high or low particulate matter may pass through the filter since the filter mechanisms require a specific velocity interval to function. The face velocity related to the dust concentrations and particle size distributions differs from one another. This data is important for air filters and enables estimating their expected service life. It has been observed that the filtration efficiency of filter media decreased at higher face velocities for relatively large particles. This happened apparently due to particle bounce and re-entrainment phenomenon. Particle bounce of dust particles can affect the filter element lifetime tremendously.

3.2 Dust Holding Capacity (DHC)

Another point that we have to shed our light on is the dust holding capacity, which is the amount of dust a filter element can carry when it operates until a maximum restriction value is reached at a specified airflow rate. It is an important metric when dimensioning the service life of the filter element.

It is determined according to the same test procedure ISO 5011. It is defined in [g/m2] or the DHC defined in [g].

Capacity is relative to the filter element's physical size, more precisely the area of the filter media, which varies according to the number of pleats. Greater area means higher capacity for holding the dust, thus longer service life for the filter element. For example, if an air filter with a DHC of 250 grams means it will keep that much dust before cleaning or replacement is necessary [4].

The main affecting factor on the dust holding capacity is the type of filter media & the size. There are numerous different filter media, each with their special properties for example, treated paper (the kind of air filter considered in this thesis), dry paper and synthetic felt media. Moreover, to enhance the dust holding capacity without pressure drop is to apply a treatment on the filter media. At the same time, the size of the filter must allow for a face velocity at maximum airflow that is low enough to prevent particles permeating the air filter into the engine.

3.2.1 Dust Particles Characteristics

The ambient air that surrounds us contributes oxygen to the internal combustion engine, which is filled with the particulate matter at varying concentrations. Particles suspended in the air may consist of mineral particles, organic content, soot from incomplete combustion. For the complete combustion of 1 kg of fuel, the engine requires 14 kg or 10.8 m^3 of air. Assuming an annual mileage of 12,500 miles and fuel consumption of approximately 30 mpg, the engine inducts 12,400 m^3 of air a year. This means that between 24 g and 6.2 kg of dust are directed into the vehicle engine over a period of ten years [4].

Depending on the type of vehicle and location where the car is used, the dust concentration in the air ranges between less than 0.2 to 50 mg/m^3 as shown in figure 8. Furthermore, it is stated that the dust particles contained in the air that get into the engine are in the range between 0.01 to 2000 µm in diameter [4].

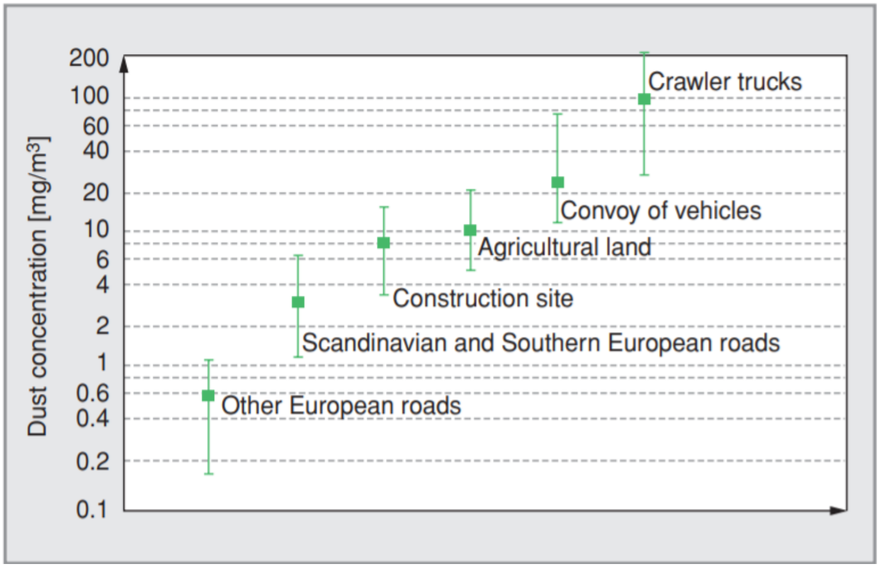

Figure 8. Average mass concentration of dust under different conditions of use [4]

In case the air is poorly or inadequately filtered, these particles of dust will penetrate into the engine and, and to some extent, into the oil. They can also penetrate into critical areas such as the clearance gaps between the cylinder liners and pistons causing mechanical wear in the engine [4].

It has been illustrated that Particles are generally characterized by their size, but other considerations, such as particle hardness versus component hardness, have to be considered, as they have a major effect on the wear of engine bearings, pistons and cylinders. They are playing a contributory role for the analysis of engine frictional wear. Besides, shape and roughness are also critical factors that cause abrasion [13].

Figure 9 show that the wear in engine parts increases with increasing particle size. Particles with sizes in range between 10-30 µm are causing the most severe wear in the bearings and the peak occurred at 20 µm. Almost same results were obtained by Fodor in the same range, although his experiments showed that a dust particle size of 15 µm gave the maximum bearing wear rate [13].

Based on figure 9 Particles between 5-20 µm are considered more damageable for bearings and clearance gap. And particles less than 1 µm may contribute to engine wear as well, but they are more harmful to the air mass meter in the engine air intake system [4].

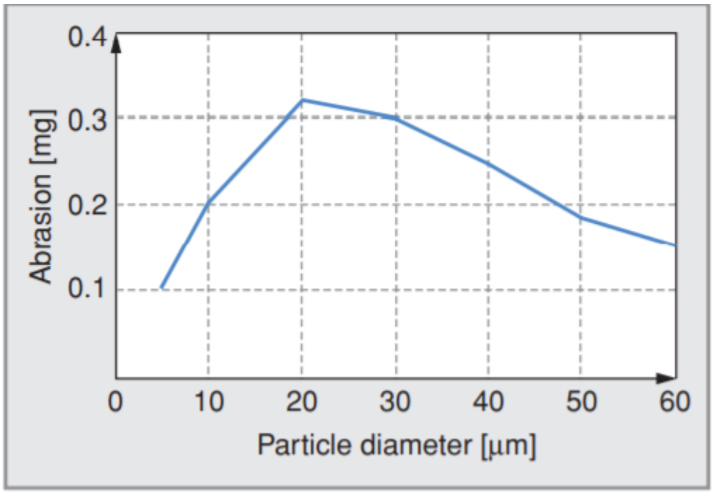

Figure 9. Effect of wear relevance as a function of particle size [4]

3.3 Flow Restriction

In addition to the efficiency of the filter at arresting the unwanted contaminate and the dust holding capacity of the filter element, the amount of work required to push or draw the air through the filter is another important parameter. The magnitude of the pressure drop through the filter is typically specified as the change in pressure from just upstream of the filter to just downstream of the filter commonly measured in pascals. The differential pressure drop can be divided into an initial restriction when the filter is new and the final restriction at the specified pressure drop when the filter is considered to be fully utilized.

Typically, to decide whether to remove the air filter or not, the clogged filter's restriction rise relative to the initial restriction of the new filter is measured. However, Predicting the filter element lifetime for specific engine size or vehicle is considered to be complex. The engine air filter should be serviced after it reaches a specific restriction rise limit due to contaminant loading. Further, the point at which the engine air cleaners are serviced, affects both, filtration performance and overall vehicle performance due to accumulation of contaminants that can reach the engine causing an abrasive wear as discussed before. Engine air cleaners having excessive restriction values can significantly degrade the overall engine performance. Serving air filters at the required increase in the restriction helps the filter reach its highest performance, ensuring optimum engine safety [22].

Minimizing the pressure drop through an air filter was the goal of many of the early works which sought to characterize flow through a filter using computational fluid dynamics [14]. This paper found that by balancing the viscous and inertial losses of flow through a pleated medium the overall pressure loss through a clean filter could be minimized. Pressure loss, however, is not a fixed parameter for all filtration applications. While some systems continually expel the contaminant from the system leading to a relative constant pressure loss over time.

Figure 10 shows an initial rise in the differential pressure, that is a typical characteristic for the behavior of depth filters. The steeply rise in the differential pressure is caused due to more dust being loaded into the filter. As after a certain period the filter media will get clogged causing this instant rise. Thus, to avoid a power loss of the engine or any kind of more abrasive contaminates, the filter element should be replaced when a specified maximum pressure drop is reached as laid down by the manufacturer, usually 2.5kpa above the initial restriction level [4]. It is stated that the total restriction limit for the car intake system for diesel engines is between 5-7.6kPa, and for gasoline engines 3.8-5kPa [8].

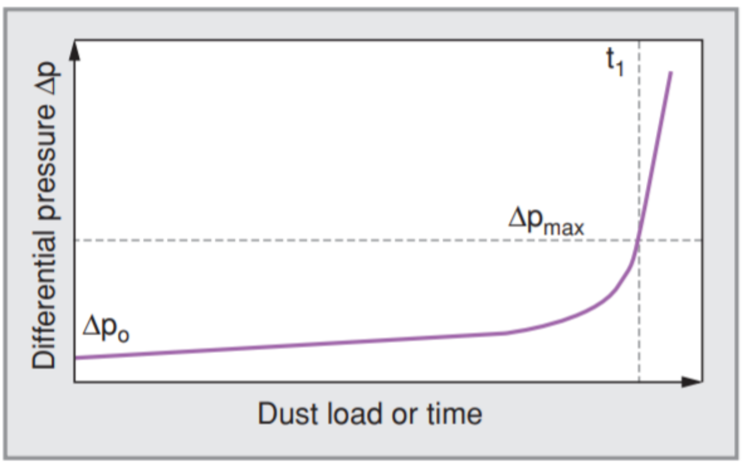

Figure 10. Increase of differential pressure as a function of dust load over time [4]

4. Types of air filter media

Air filters for the internal combustion engine have been around for decades. Starting with a simple oil bath cleaner and lately with pleated paper filter media and synthetic felts [27].

Nowadays, the purpose of any kind of air filter is to control contamination through achieving a balance between the sources of contamination and the ability of a system to tolerate contamination. The ultimate goal is to balance filtration performance with the desired efficiency and dust holding capacity. In the modern car machines a varieties of textile fibers are used for auto filter preparations as per as the suitable requirements and end uses. For example, the most common filter media used in the industry is shown in the chart below in figure 11, about 48% of the EAC are using treated paper filters (to enhance performance levels) followed by 31% using dry paper filters and 28% using synthetic felt media. Each have a different characteristic regarding efficiency and dust holding capacity. Air filter media in motor vehicles consist of randomisations of natural cellulose or synthetic (e.g. polyester) fibers [2].

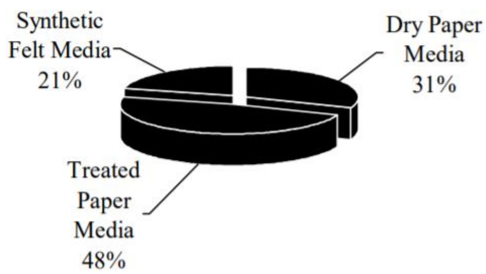

Figure 11. usage of AIF technologies [2]

All car engine air filters are enclosed in a filter airbox near the center-top of the engine. For a high quality of filtration, the filter medium in general must be resistant to engine oils, fuel fumes, and crankcase gases that reach the medium from the intake air. Furthermore, materials must be characterized by high thermal stability; as when riding the vehicle, there is an increase in temperature for up to 90°C [4].

Dry paper media is constructed of cellulose and the synthetic felt media is constructed of 100% synthetic fibers mostly polyester. The synthetic felt media provides excellent durability, heat resistance, water resistance and filtration performances [2].

According to Neville J. Bugli, it is illustrated that the synthetic felt media used in engine air cleaners showed a competitive advantage in dust holding capacity over the treated paper media. On the other hand, the treated paper media showed a higher initial efficiency with about 2 times lower dust penetration compared to synthetic felt media [2].

4.1 Treated Paper Media

According to the chart from Neville J. Bugli, treated paper media are the most common used filters in the industry. The advantage of filters using treated paper media are considered to be relatively cheap and easy to replace, besides to its structure with pleat patterns and impregnation. They are generally constructed of cellulose fibers

As shown in figure 12. the ‘‘paper’’ in this type of filter is pleated to increase surface area, therefore more space for dirt to become trapped. It is widely believed that paper filters flow poorly and thus restricts engine performance. In fact, as long as a pleated-paper filter is sized appropriately for the airflow volumes encountered in a particular application, such filters present only trivial restriction to flow until the filter has become significantly clogged with dirt.

Figure 12. Typical air paper FE in passenger cars (5Q0 129 620 B)

4.1.1 Pleat patterns and impregnation in treated paper filter

Pleat patterns are particularly crucial for the functional efficiency of the filter element. The typical structure of filter pleats must be kept unchanged during its service time; besides, the filter media must exhibit high stability under pulsating forces and not allow any dust to permeate even under high dynamic conditions. For example, engine pulsation, that may result in collapsing the filter surface. If the arrangement of pleats remains unchanged, it is possible for the specific dust holding capacity measured in the laboratory to be achieved throughout the filter's lifetime in reality. Moreover, The treated paper air filter media is normally impregnated to improve the resistance to moisture, which significantly improves the bending resistance of the cellulose medium and protects the fibers from environmental influences [4]. The treated paper media utilizes a resin system to improve efficiency, and fiber strength in addition to its rigidity and durability [2].

The important parameters for paper air filters are its porosity, particle retention, flow rate, efficiency and dust holding capacity. For instance, a paper air filter needs to be very porous and have a weight of 100 - 200 g/m^2 [24]. In addition, paper air filters provide a specific dust holding capacity of 190-220 g/m^2 depending on the aggregate of car, and a critical velocity ($V_{critical}$) equals to 10 cm/s. Besides to an efficiency of 99.5%$^+$ for gasoline cars and 99.8%$^+$ for diesel cars [4].

4.2 Examination of treated paper filter media

First of all, before inspection of the filter element into the vehicle. The performance of the filter media should be determined firstly by the manufacturer; Mann+hummel company conducted a dust loading test under laboratory conditions and with defined flow rates, in order to evaluate the performance of the treated paper filter media (5Q0 129 620 B).

During the initial filtration process, dust particles are accumulated in the filter media's inner structure. Thus, increasing the surface usable for particle capturing and enhancing filtration performance. The gradual initial rise in the pressure drop is typical behaviour of depth filters.

The dust loading capacity for the cellulose paper media depends on the formation of a dust cake on its surface. When additional dust is loaded into the filter, the filter media below the surface becomes clogged. After a certain period of time, when a high proportion of the pores are clogged with particles due to formation of cake layer, the pressure-drop rises steeply. For example, at 145g of dust being fed at a flowrate of 850 kg/h, the pressure drop was increasing with a constant rate till the clogging point is reached causing a sudden increase in the pressure drop.

After 5mbar for all flow rates. The clogging point is obvious at this stage as shown in figure 13, as a result pressure drop increasing rate risen suddenly. This rise is identified by the so-called clogging point. Then a second clogging point is reached after 10 mbar. And again, the rate of pressure-drop rising increased rapidly. Same rising in pressure drop is obvious at all flowrates. A similar conclusion was reached by Mann+hummel while they were testing an engine air intake filter [5].

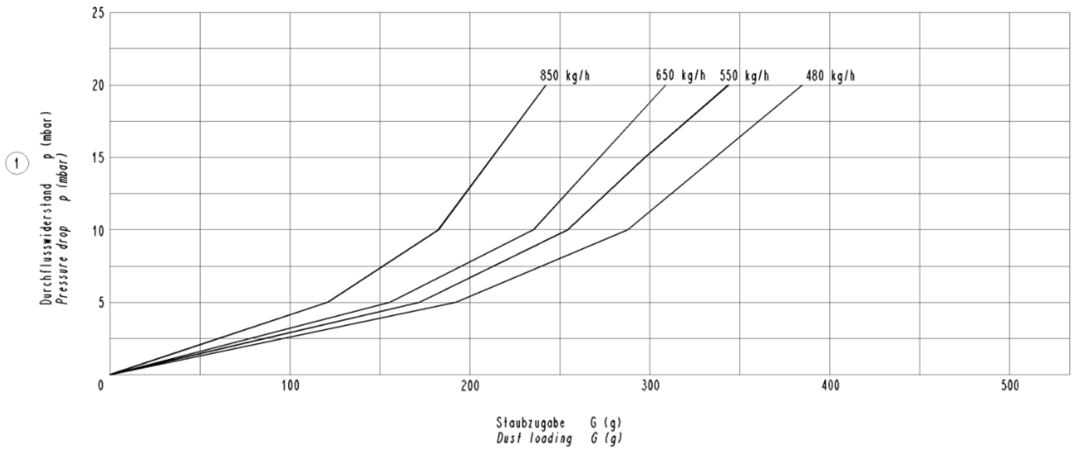

Figure 13. pressure drop against dust loading

5. Practical Part

5.1 Data collection

The current experimental data discussed in this section is done on a treated paper air filter (5Q0 129 620 B) used by Volkswagen group (VW).

Based on studies, researchers found that the current maintenance practice for replacement of air filters is indicated by the following parameters [22] [2]:

- distance travelled by the vehicle fitted with the air filter (measured in thousands of km or miles).
- The operation period of the air filter (measured in months & years).
- Reaching a limit value of restriction or pressure drop specified by the manufacturer.

The first two parameters are the most commonly used among drivers. However, they are not very reliable methods for determining the filter element lifetime.

Usually for identifying the moment when the air filter should be changed, it is referred to as the total restriction of the filter (to prevent clogging) and the increase of restriction level from the initial restriction of the new filter. Overall restriction values are set by the engine manufacturer depending on engine type, which is commonly 2.5 kpa above the initial restriction level [22].

The test was conducted on several stages. Firstly, five new filters were weighted before inspecting each of them into the car and the initial restriction level was measured for all filter elements at the laboratory. In addition, the lab recorded the date when the new filter element was inspected into the car.

After inspection of the filter element into the car, the car was sent out to be used by the customer. When the customer arrives for his/her regular maintenance at the service shop, the lab recorded the date of arrival in order to know the period for how long the filter has been used.

Then the used filter element was weighted again in order to compare the difference in masses (between new & used filter) and know how much dust has been stored in each filter.

Finally, filter elements were sent to the lab again in order to measure the final restriction value reached by each used filter and compare the pressure drop between the new and the used filters to determine if the air filters were changed prematurely.

5.2 Results and discussion

Weighting of the filter

The air filters were weighted in order to measure the dust stored in the filter. Firstly, the filter was measured in the new state, and then after it was used.

In order to measure the dust already stored in the used filters, first in the lab, the new filters were dried to remove any moisture and weighted with the mass noted with (M_N). And then, the laboratory measured the used filter mass when the customer arrived for his/her regular maintenance at the service shop noted with (M_U).

The dust mass (M_D) was calculated as the difference between the used filter mass (M_U) and the new filter mass (M_N).

Table 1 summarizes the values for the masses of new and used filters with specific dates for giving and receiving the filter from the customer's car.

	New Filter Mass (M_N) [g]	Used Filter Mass (M_U) [g]	Mass Difference (M_D) [g]	Given date	Received date
FE1	359	379	20	18.09.2015	6.02.2017
FE2	362	385	23	18.09.2015	6.02.2017
FE3	358	375	17	18.09.2015	6.02.2017
FE4	354	364	10	03.2017	21.05.2019
FE5	354	386	32	02.2018	21.05.2019

Table 1.

After that, the filter elements went under another test to investigate the pressure drop against different flowrates.

Pressure drop Vs Airflow

In table 2, it shows the measurements for pressure drop at different flowrates; this numerical data is used in order to illustrate a graphical relationship between the pressure drops and the airflow rate as shown in figure 14.

Further, with this data we were able to create a chart to compare the pressure drops between the used and new filter at a specific flowrate as shown in figure 15 in next section.

Pressure drop on filter element (FE) [mbar] at different flow rates [kg/h]										
flow through the FE [kg/h]		**42**	**106**	**212**	**354**	**472**	**607**	**702**	**759**	**850**
New	FE1	0.087	0.286	0.674	1.30	1.92	2.73	3.37	3.78	4.48
	FE2	0.098	0.312	0.720	1.37	2.00	2.82	3.46	3.87	4.56
	FE3	0.098	0.307	0.711	1.35	1.98	2.79	3.44	3.84	4.53
	FE4	0.087	0.277	0.645	1.24	1.83	2.60	3.20	3.59	4.25
	FE5	0.113	0.357	0.827	1.57	2.30	3.25	3.99	4.46	5.27
Used	FE1	0.182	0.486	1.069	1.99	2.89	4.06	4.97	5.55	6.54
	FE2	0.150	0.409	0.912	1.72	2.52	3.56	4.39	4.91	5.80
	FE3	0.171	0.486	1.081	2.01	2.90	4.05	4.94	5.50	6.46
	FE4	0.104	0.331	0.773	1.48	2.18	3.10	3.83	4.29	5.07
	FE5	0.179	0.530	1.227	2.37	3.51	5.03	6.23	7.00	8.32

Table 2. Measurements of pressure drop at different flowrates

Figure 14, shows the pressure drops against the flowrate. It shows how each filter (New and used) responded to a steadily increasing airflow for up to 850 kg/h.

It can be seen that the pressure drop is proportional to the flowrate. By increasing the flowrate, pressure drop was increasing as well. The rate of augmentation of pressure drop is highest in the case of FE5 reaching around 8.3 mbar, as this filter seems to run under dustier environmental conditions because it showed a higher mass difference of 32g in a shorter period compared to the other filters that ran for 2 years.

Therefore, we conclude that the lifetime of a filter element doesn't depend on the operation period, as most drivers (around 15%) believe in replacing their air filter after one year [21]. However, the restriction rise is not proportional to operation period because vehicles are operating under different environmental conditions where the dust has different concentrations and particle size distribution.

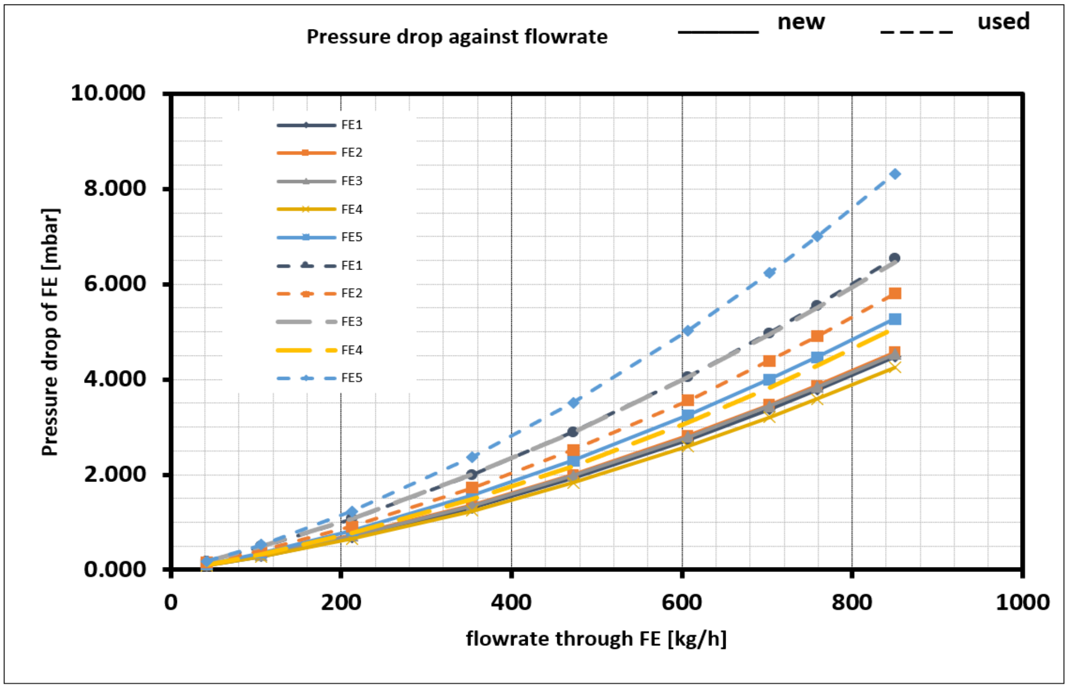

Figure 14. pressure drops against flowrate

Pressure Drop

Here in this section we will discuss the pressure drop at two different flowrates. maximum airflow (Q_{max}= 850kg/h) and for normal airflow ($Q_{50\%}$ = 425kg/h).

It is shown that the used filters produced a final restriction/pressure drop higher than the new filters at both flow rates (Q_{max} & $Q_{50\%}$).

The increase of the restriction for the used filters at Q_{max} is 2 mbar for FE1 & FE3, and 3 mbar for FE5 (the highest-pressure drop measured). This increase is insignificant comparing to the engineering recommendations aforementioned of 2.5 kpa, which is equivalent to 25 mbar.

Filters with the lowest quantity of dust, namely the used FE4 with M_D = 10g produced the lowest restriction difference of 0.8 mbar. On the other hand, the highest restriction was produced by FE5, that has the highest dust mass difference of M_D = 32g. This is accounted for the fact that dust particle size and weight influence the air restriction, So, it may differ the environmental conditions where the air filter is used and the type of dust getting into the filter, as dust particles are having a different structure size, and composition.

So, it is observed that all the filters that were changed, were changed prematurely before reaching their full capacity of utilization.

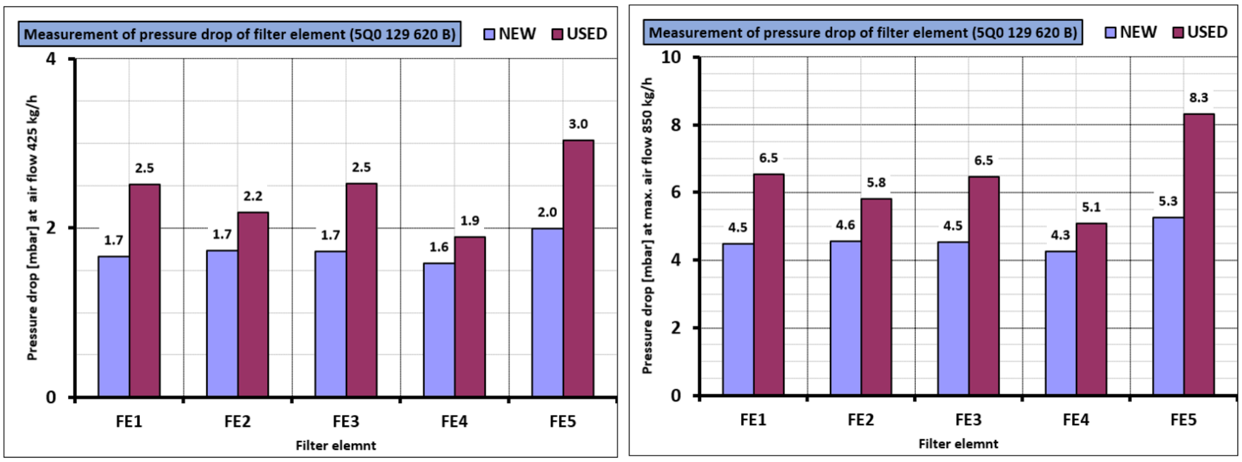

Figure 15. pressure drop generated by air filters

Service shops are changing filters as manufacturer specifications or if the client asks for it. However, based on the statistical data gathered and the surveys conducted on drivers to know their perception about when to replace their vehicle's air filter, it showed that a high percentage of drivers (48%) would change their air filters based on covering a specific distance [26], which is not true as it has been proven that the distance travelled by the vehicle is not dependent on the restriction rise [22]. Therefore, air filters should be replaced based on reaching a limit value of restriction; This limit value could be emphasized with a specialized transducer calibrated according to the type of engine.

6. conclusion

The main objective of this research was to determine the parameters affecting the filter element lifetime. Due to the mechanics of filtration, the air filter service life can be divided into three parts, the initial phase where the efficiency is low, the main phase where dust is accumulated in the filter and the efficiency is reaching its final specification. Then, Toward the end of life phase, then the differential pressure drop will rise due to the accumulated amount of dust in the filter element. At this point with more dust accumulated, a formation of cake layer will accumulate on the surface media resulting in reaching a clogging point. As a result, the pressure drop will instantly increase, and this affect the output power of the motor.

Nowadays, there are a variety of filters available in the market. Most are produced with different features as some are treated, others are pleated or embossed, which their manufacturers claim makes them more efficient at trapping impurities and increase lifespan.

Engine air filter performance are affected by several parameters, such as critical face velocity determined by the manufacturer that has to be kept and not exceed a specific value to avoid re-entrainment and bouncing of particles in the filter media. Type and size of filter media also plays a role in regard with initial efficiency and dust holding capacity respectively.

If the air filter is not serviced at appropriate intervals for the conditions in which it must operate, it will become restricted and prevent an adequate air supply for complete combustion from reaching the cylinders. Incomplete combustion results in carbon deposits on valves, rings, and pistons, which in turn cause engine wear and oil consumption problems.

To sum up, the service life of air filters for internal combustion engines of vehicles is usually defined among drivers as the distance travelled by the vehicle fitted with the air filter or as the operation period, but this will eventually lead to premature replacement.

On the other hand, in engineering terms the moment of air filter replacement is determined by measuring the total restriction of the clogged filter, or the increase of restriction with respect to the initial restriction of a new filter. The restriction limits are set by the engine manufacturer, which recommends the total restrictions values, depending on the engine type (usually 2.5kpa above the initial restriction value). Moreover, restriction rise is not proportional to the distance travelled by vehicles due to operation under different environmental conditions. As if the vehicle is operating on a high dusty road, the possibility of the filter getting clogged earlier.

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Appendix I

Database

surer	filter element (FE)				new FE				used FE						pressure drop at flow:		800 kg/h		weight	
č.	Part No.		new	used	trendline coefficients			weight	trendline coefficients			weight	lenght km	car (VDS)	new	used	delta		delta	
[-]	product	secondary	given	received	a	b	c	g	a	b	c	g	km		mbar	mbar	mbar	%	g	
0.174	5Q0.129.620.B	001	2012-09-13		0.01510000	0.2065000	-0.054	356							3.99					0
0.175	5Q0.129.620.B	002	2012-09-13	2017-02-06	0.00000298	0.0029163	-0.043	359	0.00000395	0.003210	-0.018	358		SK 372 3 0034	4.20	5.08	0.88	20.9	-1	1
0.176	5Q0.129.620.B	003	2012-09-13		0.01500000	0.2047000	-0.039	356							3.98					0
0.177	5Q0.129.620.B	004	2012-09-13		0.01520000	0.2052000	-0.035	359							4.01					0
0.178	5Q0.129.620.B	005	2012-09-13		0.01550000	0.2060000	-0.037	357							4.05					0
0.179	5Q0.129.620.B	13-001VV1			0.01550000	0.1968000	-0.031	357							3.96					0
0.180	5Q0.129.620.B	13-001VV2			0.01600000	0.2023000	-0.027	358							4.08					0
0.181	5Q0.129.620.B	13-001z			0.01940000	0.2575000	-0.019					376			5.09					0
0.182	5Q0.129.620.B	13-002	2013-04-19	2017-02-06	0.00000298	0.0025553	0.037	351	0.00000364	0.003208	0.012	366		SK481 4 0056	3.99	4.91	0.92	23.1	15	1
0.183	5Q0.129.620.B	13-003	2013-04-19		0.01480000	0.1900000	-0.043	347							3.79					0
0.184	5Q0.129.620.B	13-004	2013-04-19		0.01500000	0.1829000	-0.015	349							3.76					0
0.185	5Q0.129.620.B	13-005	2013-04-19		0.01460000	0.1888000	-0.038	347							3.76					0
0.186	5Q0.129.620.B	13-006	2013-04-19		0.01480000	0.1830000	-0.032	345							3.72					0
0.187	5Q0.129.620.B	13-007	2013-04-19		0.01460000	0.1849000	-0.030	348							3.72					0
0.188	5Q0.129.620.B	13-008	2013-04-19		0.01460000	0.1836000	-0.033	358							3.70					0
0.189	5Q0.129.620.B	13-009	2013-05-14		0.01490000	0.1814000	-0.038	349							3.71					0
0.190	5Q0.129.620.B	13-010	2013-05-14		0.01490000	0.1845000	-0.030	353							3.75					0
0.191	5Q0.129.620.B	13-011	2013-05-14		0.01530000	0.1836000	-0.025	354							3.80					0
0.192	5Q0.129.620.B	13-012	2013-05-14		0.01540000	0.1955000	-0.022	354							3.94					0
0.193	5Q0.129.620.B	13-013	2013-05-14		0.01480000	0.1843000	-0.034	346							3.73					0
0.194	5Q0.129.620.B	14-001	2014-04-17		0.01490000	0.1985000	-0.030	361							3.91					0
0.195	5Q0.129.620.B	14-002	2014-04-17		0.01410000	0.1890000	-0.033	361							3.70					0
0.196	5Q0.129.620.B	14-003	2014-04-17		0.01400000	0.1858000	-0.032	360							3.66					0
0.197	5Q0.129.620.B	14-004	2014-04-17		0.01470000	0.1965000	-0.031	358							3.86					0
0.198	5Q0.129.620.B	14-005	2014-04-17		0.01440000	0.1858000	-0.026	361							3.71					0
0.199	5Q0.129.620.B	14-z							0.01920000	0.210900	-0.012	376				4.57				0
0.200	5Q0.129.620.B	14-006			0.01610000	0.1901000	-0.030	355							3.96					0
0.201	5Q0.129.620.B	14-007			0.01590000	0.1921000	-0.022	355							3.96					0
0.202	5Q0.129.620.B	14-008			0.01590000	0.1940000	-0.021	358							3.98					0
0.203	5Q0.129.620.B	14-009		2017-02-06	0.00000320	0.0026971	-0.032	358	0.00000439	0.004083	-0.004	382		SK 3761 6-0007	4.17	6.07	1.90	45.6	24	1
0.204	5Q0.129.620.B	14-010		2017-02-06	0.00000311	0.0026596	-0.032	356	0.00000369	0.003417	-0.020	363		SK 371 6-0112	4.09	5.07	0.99	24.1	7	1
0.205	5Q0.129.620.B	14-011		2019-05-21	0.00000308	0.0027274	-0.032	356	0.00000647	0.008303	-0.001	372			4.12	10.78	6.66	**161.6**	16	1
0.206	5Q0.129.620.B	15-001	2015-09-04	2019-05-21	0.00000316	0.0028492	0.002	356	0.00000366	0.003927	-0.022	374		SK3717-0014	4.30	5.46	1.15	26.8	18	1
0.207	5Q0.129.620.B	15-002	2015-09-04		0.01460000	0.1999000	-0.018	358							3.90					0
0.208	5Q0.129.620.B	15-003	2015-09-18	2017-02-06	0.00000311	0.0026596	-0.032	359	0.00000418	0.004147	-0.001	379		SK 481 7-0005	4.09	5.99	1.91	46.6	20	1
0.209	5Q0.129.620.B	15-004	2015-09-18	2017-02-06	0.00000300	0.0028279	-0.036	358	0.00000398	0.003518	-0.011	373		SK482 7 0006	4.15	5.35	1.20	29.0	15	1
0.210	5Q0.129.620.B	15-005	2015-09-18	2017-02-06	0.00000296	0.0028526	-0.029	362	0.00000383	0.004374	-0.022	385		SK326 6 0041	4.15	5.93	1.78	42.9	23	1
0.211	5Q0.129.620.B	15-006	2015-09-18	2017-02-06	0.00000294	0.0029059	-0.030	358	0.00000395	0.003478	-0.005	375		SK 326/1 6 0002	4.18	5.30	1.13	27.0	17	1
0.212	5Q0.129.620.B	15-007	2015-09-18	2017-02-06	0.00000298	0.0028324	-0.027	357	0.00000443	0.003757	-0.007	370		SK 4820 7 0039	4.14	5.83	1.69	40.7	13	1
1	5Q0.129.620.B	17-001	2017-03	2019-05-21	0.00000294	0.0025330	-0.026	354	0.00000349	0.003040	-0.031	364		SK3720 8 0030	3.88	4.63	0.75	19.4	10	1
2	5Q0.129.620.B	17-002	2017-03	2019-05-21	0.00000295	0.0025335	-0.011	352	0.00000356	0.003129	-0.010	364		SK3720 8 0034	3.90	4.77	0.87	22.2	12	1
3	5Q0.129.620.B	17-003	2017-03		0.00000301	0.0025366	-0.012	354							3.94					1
4	5Q0.129.620.B	17-004	2017-03	2019-05-21	0.00000299	0.0024655	-0.004	352	0.00000403	0.003409	-0.025	370		SK3720 9 0018	3.88	5.28	1.40	36.0	18	1
5	5Q0.129.620.B	17-005	2017-03		0.00000301	0.0025537	-0.043	351							3.93					1
6	5Q0.129.620.B	17-006	2017-03	2019-05-21	0.00000301	0.0026097	0.011	354							4.02					1
7	5Q0.129.620.B	není		2017-02-06					0.0000047	0.008601	-0.015	483				9.88				1
8	5Q0.129.620.B	není		2017-02-06					0.0000069	0.005872	-0.070	594				9.06				1
9	5Q0.129.620.B	není		2017-02-06					0.0000040	0.003701	-0.028	363				5.46				1
10	5Q0.129.620.B	není		2017-02-06					0.0000065	0.008301	-0.193	669				10.59				1
15	5Q0.129.620.B	17-005			0.0000033	0.0032682	-0.043	358							4.67					1
16	5Q0.129.620.B	17-006x		2019-05-21	0.0000037	0.0033795	-0.032	356	0.0000044	0.003453	-0.048	367		SK3710 9 0052	5.04	5.52	0.48	9.6	11	1
17	5Q0.129.620.B	17-007		2019-05-21	0.0000034	0.0032726	-0.043	356	0.0000045	0.003738	-0.020	372		SK3720 9 0047	4.74	5.88	1.14	24.1	16	1
18	5Q0.129.620.B	17-008			0.0000036	0.0035260	-0.049	360							5.05					1
30	5Q0.129.620.B	17-009	2017-12		0.0000032	0.0030097	-0.014	354							4.44					1

31	5Q0.129.620.B	17-010	2017-12		0.0000033	0.0031875	-0.046	357							4.60					1
32	5Q0.129.620.B	17-011	2017-12		0.0000032	0.0032110	-0.050	353							4.55					1
33	5Q0.129.620.B	17-012	2017-12		0.0000033	0.0031318	-0.045	357							4.55					1
34	5Q0.129.620.B	17-013	2017-12		0.0000035	0.0038056	-0.046	358							5.24					1
35	5Q0.129.620.B	17-014	2017-12		0.0000031	0.0029340	-0.028	350							4.31					1
36	5Q0.129.620.B	18-001	2018-02	2019-05-21	0.0000034	0.0033245	-0.035	354	0.0000061	0.004606	-0.028	386		SK3206 9 0097	4.82	7.58	2.76	57.3	32	1
37	5Q0.129.620.B	18-002	2018-03		0.0000033	0.0030836	-0.021	346							4.58					1
38	5Q0.129.620.B	18-003	2018-03		0.0000035	0.0031727	-0.021	350							4.76					1
39	5Q0.129.620.B	18-004	2018-03		0.0000029	0.0028128	-0.018	350							4.11					1
40	5Q0.129.620.B	18-005	2018-03		0.0000031	0.0029649	-0.030	352							4.30					1
41	5Q0.129.620.B	18-006	2018-03		0.0000034	0.0036912	-0.037	356							5.11					1
42	5Q0.129.620.B	18-007	2018-03		0.0000032	0.0029893	-0.026	349							4.42					1
43	5Q0.129.620.B	18-008	2018-03		0.0000030	0.0028575	-0.031	350							4.15					1
44	5Q0.129.620.B	18-009	2018-03		0.0000030	0.0028375	-0.032	350							4.15					1
45	5Q0.129.620.B	18-010	2018-03		0.0000030	0.0030788	-0.053	359							4.33					1
46	5Q0.129.620.B	18-011	2018-03		0.0000034	0.0037761	-0.032	354							5.17					1
47	5Q0.129.620.B	18-012	2018-03		0.0000035	0.0037441	-0.036	358							5.20					1
48	5Q0.129.620.B	18-013	2018-03		0.0000030	0.0028482	-0.031	354							4.16					1
49	5Q0.129.620.B	18-014	2018-03		0.0000030	0.0030413	-0.033	353							4.34					1
50	5Q0.129.620.B	18-015	2018-03		0.0000034	0.0037831	-0.040	356							5.14					1
62	5Q0.129.620.B	19-002		2019-05-21					0.0000051	0.004685	-0.008	367		SK3714-0221		7.01				1
63	5Q0.129.620.B	19-003		2019-05-21					0.0000142	0.007424	-0.067	331		SK3722-0038		14.96				1

Appendix II

Media Face Velocity Graph

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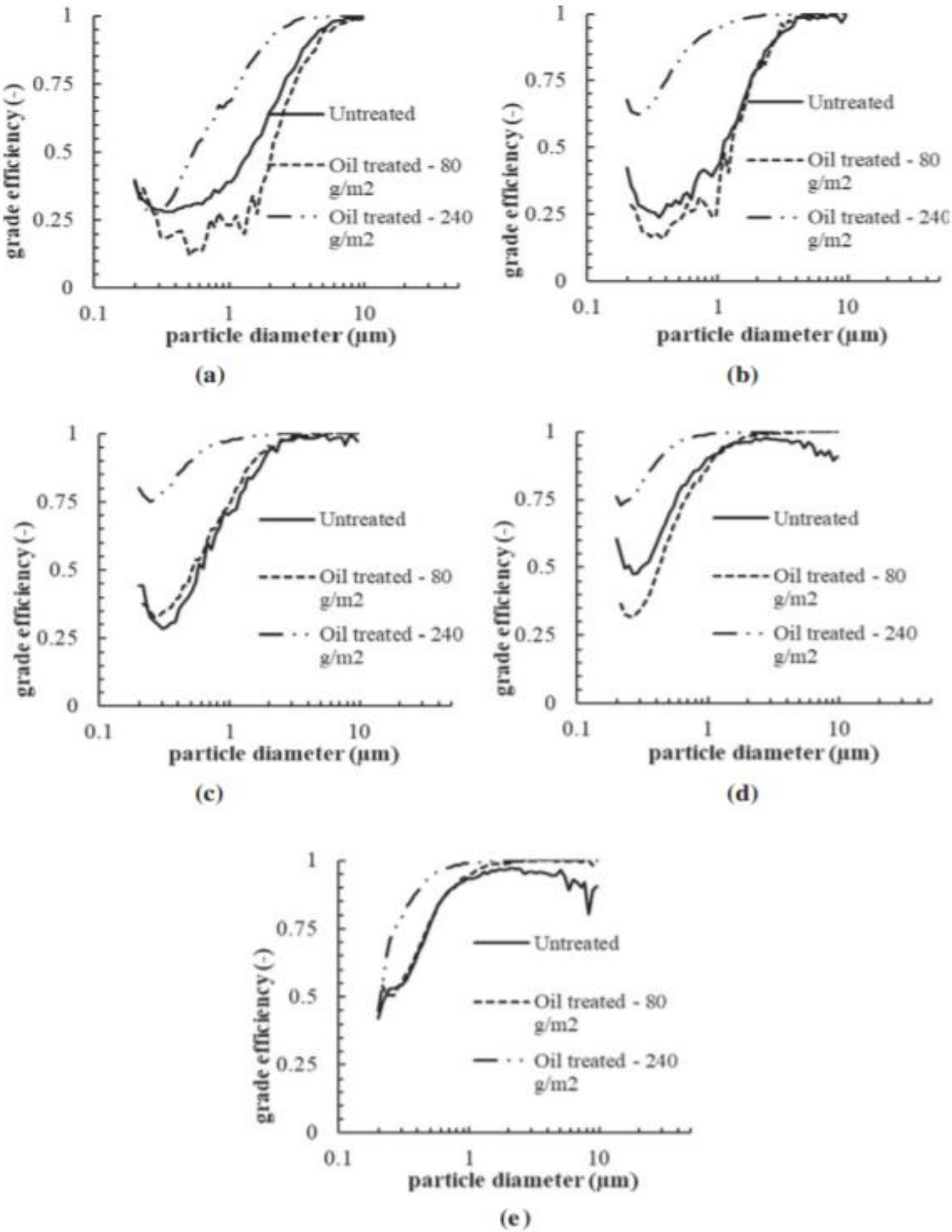

Fig. 5. Initial Grade efficiency at 0.1 m/s (a), 0.3 m/s (b), 0.5 m/s (c), 0.85 m/s (d), and 1.2 m/s (e).