

Characterization of Properties for Thermoplastic Alternatives to Glass and its Use within Automotive Industry

by

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Abstract

The aim of this thesis work is to evaluate the feasibility and capability of utilization of plastic glazing instead of current heavy materials in exterior parts, focusing on glass parts in passenger cars. Trending usage of such materials in car industries has tempted car manufacturers such as Volvo Cars to investigate whether implementation of them are efficient or not. Much development work have been done and there have been some distinct breakthrough with regards to that. To follow-up on these, several tests have been performed in order to ensure in a realistic manner that potential materials have the ability to perform satisfactorily in such automotive applications.

Different material configurations from different car manufactures have been tested. The thesis also contains a literature study with the aim to summarize what other manufactures have done so far. The tests performed include: Scratch resistance, long-term heat exposure, resistance to UV-light, resistance against chemicals, light transmission measurements (evaluation of transmittance) and aging in humidity, which are all described further in the thesis.

The results show that polycarbonates potentially have the ability to be used in automotive glazing parts; however an adequate consideration of tooling, machining and coating of the samples is needed in order to satisfy the requirements. Since there were only few samples of poly(methyl methacrylate) (PMMA) to test, the reliability of the test results is lowered since the tested samples exhibited inferior properties opposing expectations from PMMA. Possible reasons for this are discussed.

Keywords: Plastic glazing, polymers, polycarbonate, transmittance, UV-resistance, heat exposure, scratch resistance

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1 Introduction

Volvo Car Corporation (VCC) provides luxurious cars with the following body types: Sedans, Sport wagons, Cross country vehicles, and SUV. Considering the volume of production, VCC is categorized as a small car manufacturer with global sales of 421,951 cars in 2012, having the biggest markets in US, Sweden, China, and Germany. The corporate's brand strategy is "Designed Around You".

In automotive industries, processing simplicity and lightweight make polymers a growing material in terms of utilization. These two factors associate either directly or indirectly with environment with less fuel consumption and lower emission of hazardous substances. During the infancy era of commercialization of polymers in auto industries, they were firstly brought into service in the interior of cars. For instance, polymers contribute to passive safety by covering edges, corners, and surfaces in the passenger compartment with shock absorbing polymers. On the other hand, they have been employed as improvements of handling characteristics such as front air dams and rear spoilers.

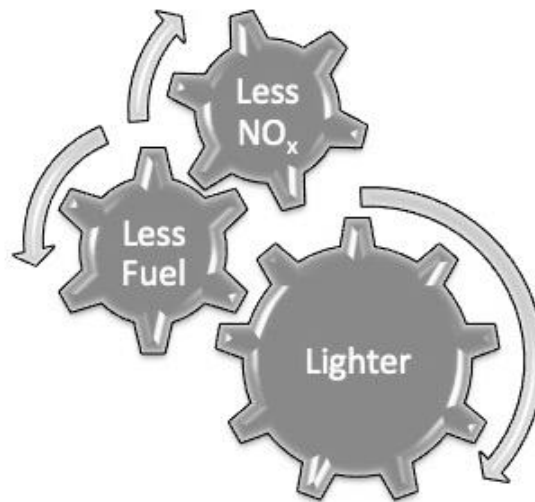


Figure 1- Schematic impacts of utilization of lightweight materials in the automotive industry.

When it comes to lightweight materials, polymers act as a promising material for different applications. One of the most important characteristics of polymers is their rather high capacity and freedom in styling compared to metals. Also being lightweight is an additional reason for introduction of polymer materials into the car industry.

Most plastics used in car industry are based on thermoplastic polymers. They are categorized into three different groups:

- Commodity plastics (polyethylene, polypropylene, polystyrene, and poly(vinyl chloride)), which are mass-produced and cheap enough to get a great attention in the passenger car industry.
- Engineering thermoplastics (poly(methyl methacrylate), polyamide, polyoxymethylene, etc.), which aim high quality, while being slightly more costly.
- Specialty plastics

Although significant inroads in use of plastics in the automotive industry are governed by engineering thermoplastics, commodity thermoplastics are eroding the market of engineering thermoplastics. This is encouraged whilst cost issues and improvements in end-use performance of cars are taken into account. Undoubtedly, in regard to this, polypropylene can be mentioned as a starred polymer.

2 Literature review

This chapter aims to give a clear and short survey of basic information needed to understand the materials used in this work. This includes a short review of properties of polymers and their structure as well as a literature review of previous related works.

2.1 Basics of polymers

This part will describe polymers and their characteristics in order to provide a good understanding of these materials.

2.1.1 What is a polymer?

Polymers are based on the connection of chains of carbons connected to each other by stiff covalent bonds. The terminology of polymers originates from the repeatable units. These units are called monomer units. There are vast different possible configurations of atoms or groups in the chains, which will result in a large range of polymeric materials with different properties. Usually, oxygen, nitrogen, and/or hydrogen are present in polymers. It is not just the difference between atoms, which make different polymers, even different morphology, symmetry, configuration and formation of monomers with the same atoms can result in varying properties (Tadmor & Gogos, 2006).

Polymer molecules are comparatively large and their structure is not always uniform. For example and expressed in a simplified manner, the structure can, for some polymers, be regarded as mixtures of ordered and crystalline parts with non-crystalline amorphous parts. Such polymers are called (semi)crystalline. Polymers without any crystalline regions are called amorphous. The fraction of crystallinity is measured by the degree of crystallinity; the greater this fraction is, the higher the rigidity of the polymer (Landel & Nielsen, 1993). This degree of crystallinity thus highly influences the properties of the polymer. The specific volume of a semi crystalline polymer is composed of the specific volumes of the crystalline part and the amorphous part (1):

$$v = (1-x) v_a + x v_c \quad (1)$$

Where x stands for the degree of crystallinity of the polymer, and v_a and v_c for the specific volumes of the amorphous and crystalline part, respectively. Specific volume is also the inverse of density.

To distinguish between a crystalline and an amorphous polymer, molecular regularity should be referred. The crystallization process of a polymer starts when the temperature comes down to the melting temperature. Then, some nuclei would be the source of spherulite formation. These spherulites grow larger at a constant rate if the temperature is constant until they fill the whole material. This will be the end of the primary crystallization stage. Between the crystallized

macromolecules, there will be some trapped portions of amorphous parts, which can start secondary crystallization when the primary crystallization is finished. The rates of nucleation and crystal growth lead to the rate of crystallization. These also affect the size of the spherulite, i.e. a rapid solidification gives a smaller spherulite. This is obvious since the time of growth is limited.

Plastics are generally categorized into two groups:

- Thermoplastics- They have two stages upon exposure to heat. They melt when the temperature passes the critical transition point, e. g. the melting point. Chains in this category of polymers are either linear or branched.
- Thermosets- They do not melt and cannot transform to the liquid phase. The way to keep molecules together relies on crosslinking.

Formation of polymers is either toward addition polymerization or condensation polymerization depending on the mechanism of polymerization. In addition polymers, unsaturated monomers are attached to the chain and this will continue until the chain gets a specific size, which will satisfy the application aims.



In condensation formation of polymers, as it is understandable from its name, reaction of two monomers makes the final polymer. Usually water is split off from this type of reaction. These polymers can have a higher tendency to crystallize because of the higher regularity they are benefitting from (Ravve, 2012).

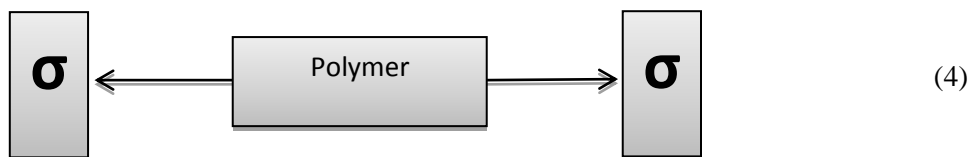


2.2 Properties of polymers

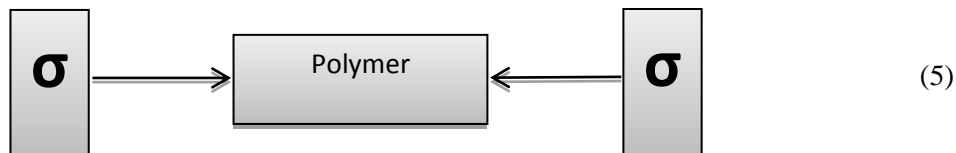
The properties of polymers vary a lot depending on different factors. The most important factors are: The length of the molecule, which is proportional to the size of the molecule known as relative molecular mass, and the shape of the molecule. Other factors that also can determine the properties of polymers include: Side groups, symmetry of branches, and crosslinking. In some cases and for certain application, introduction of additives to alter the properties is proposed. Crystallinity is another vital factor for the properties of a polymer.

2.2.1 Mechanical properties

The most important term regarding mechanical properties is strength (in addition to stiffness). This term is sometimes misunderstood with being “strong” or not. There are several types of strength; among which tensile strength is the most important one due to high number of applications imposing tensional stresses to the material.



In compression, compression strength comes out. It is hard to measure compression strength since the starting point of failure is vague.



When an applied stress is flexural, flexural strength is taken into account.

Now the question would be which polymer is called a “strong”, tough or soft polymer. Stress-strain curves between polymers are often compared to those of other materials like metals and ceramics. To be brief, polymers like polystyrene and polycarbonate can withstand a relatively high stress, although the elongation at break is too low to call them tough materials and that is because of the small area under their stress-strain curve. On the other hand, polyethylene acts in the opposite way. To optimize the behavior of polymers in order to have a tougher material some additives can be used. They are called plasticizers. Adding a plasticizer to PVC can alter it from a rigid material used in water pipes to a flexible swimming pool toy. (Polymer Science Learning Center, 2005)

2.2.2 Optical properties

Optical properties are of immense importance for automotive applications where aesthetics of the parts should also be maintained. Very few polymers can be used in applications where optical properties are crucial compared to the most attractive optical material, i. e. glass. This is because many of them are mostly translucent or semitransparent which gives an opaque appearance. However, in certain applications where density is important it is a better choice to opt for polymers. With some few exceptions, most of the polymeric optics is implemented in thermoplastic materials. Note that only amorphous polymers are transparent, thus the crystalline are of limited interest in many applications.

For evaluating the optical properties, refractive indices, transmission spectra and dispersion of light can be measured. (Sultanova, Kasarova, & Nikolov, 2012) The primary optical polymers (OP) are poly(methyl methacrylate) (PMMA), polystyrene (PS), polycarbonate (PC), methyl methacrylate-styrene copolymer, styrene-acrylonitrile copolymer (SAN) and polymethylpentene (Horne, 1983)

In this study, the amorphous polymers PMMA and PC, which are mostly employed for automotive optical applications, are used.

2.2.3 Thermal properties

When thermal properties of polymers are discussed, transition temperatures are addressed in order to avoid failure in certain applications. In polymers, one of them is the melting point T_m which is relevant only for the crystalline polymers.

In amorphous polymers with chains arranged in a disordered manner, there is another transition influencing the properties, T_g , the glass transition temperature. As the temperature is lowered below T_g the polymer becomes brittle. When the temperature becomes higher than T_g , the increase in structural mobility leads to a rubber-like behavior. T_g is obtained experimentally by cooling down the specimen at a fixed rate, and measuring the specific volume versus the temperature. There would be a slope change as the material passes T_g defining the transition (Figure 2).

Note that even crystalline polymers have some fraction of amorphous phase. Polymers with both amorphous and crystalline phases are, as mentioned earlier, called semi-crystalline polymers. This makes semi-crystalline polymers exhibiting both melting and glass transition temperatures. (Mississippi, 2005)

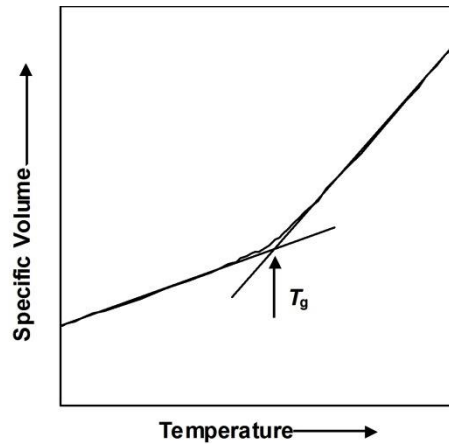


Figure 2- Experimental determination of the glass transition temperature

Empirically the ratio of T_g to T_m is: (McCrum, Bucknall, & Buckly, 1997)

$$T_g / T_m = 0.6 \quad (6)$$

Table 1- Glass transition temperatures and melting temperatures of some common polymers (Kubat & Klason, 1995)

Material	T_g (°C)	T_m (°C)
Polycarbonate (PC)	150	amorphous
Poly(ethylene terephthalate) (PET)	70	265
Nylon 6.6 (PA6.6)	50	265
Poly(methylmethacrylate) (PMMA)	105	amorphous
Polypropylene (PP)	-10	165
Poly(vinyl chloride) (PVC)	80	amorphous
Polyoxymethylene (POM)	-85	175
Polystyrene (PS)	100	amorphous
High density polyethylene (HDPE)	-120	115-140
Low density polyethylene (LDPE)	-120	105-125

Exposing a polymer to heat can lead to molecular rearrangement due to e. g. oxidation. This may cause scission of molecules at high temperatures. The service properties may alter and thermal degradation commences. Consequently, altering of the molecular weight is anticipated, leading to significant changes in physical, optical, and mechanical properties, such as embrittlement, color changes, reduction of density, and so on.

2.2.4 Chemical properties

Aggressive chemical environments are able to change the properties of polymers by either dissolving or chemical reaction. Dissolving of the polymer involves absorption of the chemical and no chemical change of the material is expected. Chemical reaction occurs when some changes take place in the chemical structure of the molecular polymer chain. Parameters like temperature and stress state can affect the chemical degradation as well as the moisture content. (Lyondell Chemical)

2.3 Polymers in focus in this work

It is obvious that plastic glazing can be a breakthrough in the future passenger cars and this has been explored by plastic experts during the last four decades. The use of plastics will allow for a higher degree of freedom in shaping and design of the glazing materials. Promising attributes that make these materials a first class alternative for transparent applications in the automotive industries are high robustness, low density, and superior physical properties like beneficial interactions with ultraviolet and infrared range wavelengths. (Beecham, 2008)

Polymers that potentially will satisfy the optical requirements for transparent applications include poly(methyl methacrylate) (PMMA) and polycarbonate (PC). PMMA is a transparent thermoplastic often denoted acrylic glass although from a chemical point of view it is not a glass. The first launch of PMMA was in acrylic safety glass in 1936. During World War II acrylic safety glass was used in submarines and airplanes. Thereafter, it has been utilized in many other applications, like constructing residential, commercial aquariums, spectator protection in ice hockey rinks, police vehicles for riot control, etc. In the automotive industry, PMMA is already used in rear lamps, exterior lights, etc.

Polycarbonate is one of the main materials of interest to the automotive glazing market. With regard to opportunities of PC-glazing in the automotive industries, panoramic sunroofs, tailgates and backlights are examples that already have been implemented. Low weight, high robustness, and interesting optical properties in the ultraviolet and infrared wavelength regions are the key factors to widening usage of polymer glazing in automotive industries. On the flipside, in automotive industries cost is a challenging issue to address. Though there might be a considerable difference between the price of PC and tempered glass, a slight difference between PC and laminated glass is reckoned to tempt automaker to introduce PC in their products. The primary advantage of PC is its lower weight compared to glass, styling freedom and simpler functional integration.

The main focus in this work will be on fixed side windows, whereas moveable side windows are not taken into account. The drawback of usage of PC in moveable side windows is its (in some respects) inferior Young's modulus and scratch resistance. In countries where impact on the environment is of significant concern, PC is a good alternative since it is environmental friendly with its low weight and can be recycled.

Condensation polymerization is the route to produce PC. Reaction of bisphenol-A and phosgene alongside with a catalyst at temperatures range of 25 to 35 °C is the most common way to polymerize PC (Figure 3).

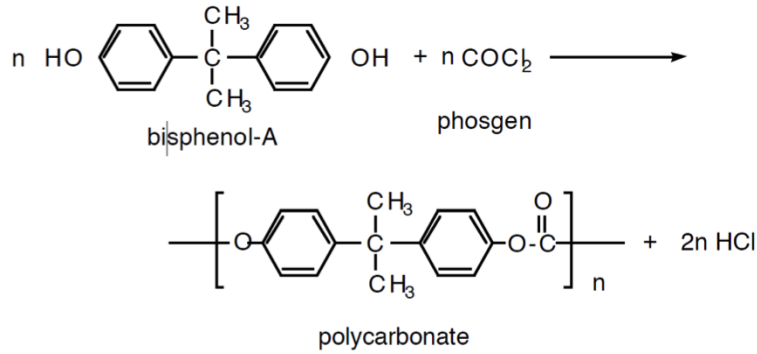


Figure 3- An example of making PC as a result from reacting bisphenol-A with phosgene

Bisphenol-A is responsible for high stiff backbones of PC due to its two aromatic rings. This part also contributes to transparency of PC since it keeps PC invulnerable to crystallization. The molecular rotation around the bonds is not considerable, leading to a high glass transition temperature for PC (Rodriguez, 2003).

2.4 Test specimens

The test specimens for this project were taken from three different auto brands, which have implemented plastic glazing in their products, mostly PC. Quarter glass pieces of Citroen DS5, 2014 Fiat 500L, Seat Leon were used. For PSA Peugeot-Citroen, Teijin Chemicals developed glazing jointly with Freeglass GmbH. The material supplier for Fiat and Seat Leon was SABIC innovative plastics (SABIC, 2012). The material supplier of the PMMA test samples was Evonic.

Transparent oxides are coated on the polycarbonate samples in order to reduce moisture adsorption on the surface. Some coatings are based on a silicon oxide film which will enhance the scratch resistance. The thickness of the coatings is of great importance when mechanical forces are applied (Boentoro, Pflug, & Szyszka, 2008). Hwang et al. applied a transparent UV-protective coating on polycarbonate. They used acetyl acetone chelated silanes and 3-glycidoxypopyl-trimethoxysilane (GPTMS) modified nano-titania sols. No crack formation was seen after UV exposure, and the adhesion between the coating and the polycarbonate was sustained (Hwang & Moon, 2003).

A coating of high hardness should not be applied on a relatively soft polycarbonate substrate since this will lead to the so-called “eggshell” effect. To describe it briefly, the soft substrate would deform easier than the hard coat and this can lead to a delamination. To avoid this, a proper adjustment of mechanical properties should be considered. This can mean that there can be variation of coating properties, composition and microstructure from the surface to substrate. (Piegari & Flory, 2013)

3 Methodology

3.1 Experimental setup

In order to evaluate the materials properties, several tests have been performed according to Volvo Cars test plans. These tests are categorized in five groups:

- Aging in humidity
- Resistance against UV-light
- Light exposure (Sun simulation)
- Scratch resistance
- Chemical resistance

3.1.1 Aging in humidity

Variation in different regional locations requires a thorough investigation in order to guarantee no changes in properties for different applications. Humidity is a representative factor of climate which should be studied. For this, some samples were exposed to high humidity ($95\pm 5\%$ relative humidity) and a temperature of $38\pm 2^\circ\text{C}$ for 1000 hours.

3.1.2 Resistance against UV-light

Polycarbonate is a commonly used thermoplastic material with desirable mechanical, electrical, optical, and thermal properties. However, its vulnerability to degradation upon exposure to ultra-violet light is a tough aspect, which should be further investigated by the industries utilizing it. A way to shield it from the most common UV attack, sunlight, is to apply a coating on its surface, although interaction with sunlight during a long period of time can lead to a degradation of the coating. Nevertheless, application of coatings on a PC-substrate is also a way to improve the scratch resistance.

To follow this, samples were placed in a weather-ometer equipment according to VCS 1027,3379 for 2000 hours. This test corresponds to ISO 4892. The equipment contained a water-cooled xenon lamp. This light source had external and internal filters in order to obtain a spectral distribution similar to natural sunlight. The irradiation from the source had an intensity of 550 W/m^2 at 340 nm. The temperature and relative humidity during the tests were $65 \pm 3^\circ\text{C}$ and $50\% \pm 5\%$. Two samples for each part with the size of $10\times 10\text{ cm}^2$ were chosen for a better comparison by introducing some intervals before the completion of the test. This is to ascertain how soon the material will fail and to have a better overview of the test by recording the changes in color and gloss. After the test, the samples are washed lightly with sponge and then inspections shall start with checking the gloss and color changes of the test samples and a reference part. Requirements to be fulfilled at this test are:

- No visible cracks or deformations
- No visible surfaces that have become blotchy
- No significant color change according to Volvo STD 1026,8201

Specimens subjected to this test were not used when evaluating the light transmittance ability (described later in the text).

3.1.3 Light exposure and heat ageing

The test standard is technically similar to SAE J1960 (2004), SAE J2527 (2004), ISO 4892-2 (2006), and ASTM G155-05a. This test is a development of another Volvo test (VCS 1027,3379, issue 2), which can still be used for certain applications. This method is intended for use as an artificial accelerated weathering test for exterior painted surfaces and for plastics. In a laboratory test chamber, the test pieces are exposed to an artificial light source in order to obtain accelerated degradation. The irradiation from the light source had an intensity corresponding to 0.5 W/m^2 in the wavelength range $290 \text{ nm} \leq \lambda \leq 800 \text{ nm}$.

The material should sustain its properties even after an exposure of a temperature of 80°C for 1000 hours as used in this study. Assessments should be done after the samples are removed from the oven and after they are cooled down to room temperature.

It is important to note that the correlation between test results from accelerated weathering and outdoor exposure is not exact, and is only valid for specific types of material and for specific properties, where such a correlation is based on known experience. The correlation factors for accelerated weathering tests could very well be different for different types of coatings or plastics foils. The test chamber should be provided with an artificial light source. It must be possible to automatically control the humidity, light intensity and temperature, and to spray the test pieces with water. The test chamber shall have a turntable with holders for the test pieces. This will rotate around the light source during exposure.

Since the degradation of polymeric materials is affected by temperature, it is important that the temperature is carefully controlled during testing. The temperature is controlled by means of a black-standard thermometer mounted on the rotating test-piece holder so that it is exposed in the same way as the test pieces. The temperature indicated by the black-standard thermometer corresponds to the temperature of a dark test surface of poor thermal conductivity.

The black-standard thermometer consists of a stainless steel plate of approximately 1 mm thickness. An even black coating of good ageing resistance covers the plate surface facing the light source. The black-painted surface shall absorb at least 95 % of all irradiation from the light source, up to 2500 nm (wavelength). The surface temperature is measured with a platinum resistance sensor. The steel plate shall be insulated with a 5 mm thick poly(vinylidene fluoride) (PVDF) backing plate. In some standards, a non-insulated black-panel thermometer is specified. A non-insulated black panel shows typically 5°C lower temperature than an insulated black-

standard panel. This panel sensor can only be used after agreement with the responsible testing department at Volvo Cars.

The air temperature in the chamber shall be measured and controlled. The temperature sensor shall be shielded from the light source and the water spray. The relative humidity of the air in the test chamber shall be measured and controlled at the set value. The sensor, which measures relative humidity, shall be shielded from the light emitted by the lamp.

The test chamber shall have spray nozzles, which permit evenly distributed wetting on both the front and the back of the panels. The water must not leave patches or residues on the surface. The water shall have conductivity lower than 5 $\mu\text{S}/\text{cm}$ and shall not have more than 1 ppm of solids content. The level content of silica in the water shall not exceed 0.2 ppm. This water quality can be obtained by distillation or a combination of deionization and reverse osmosis.

The test pieces should be representative of the whole sample. The samples were delivered to the cutting laboratory and the size of test pieces was 10 x 10 cm^2 .

3.1.4 Scratch resistance

This standard is technically similar to ISO 20566 but with further specifications. This test method is used to assess the resistance of topcoats against scratching which occurs in automatic car washes using brushes and is caused by abrasive particles (dirt). The method is aimed at simulating this effect using a laboratory-scale car wash and standardized dirt (quartz powder). The equipment for this is a Laboratory-scale AMTEC-Kistler car wash with brushes. Further specifications of the equipment are addressed below:

- Diameter of brush (roller): 1000 ± 10 mm
- Width of brush (roller): 400 ± 5 mm
- Material: Polyethylene brush profile, X-shaped
- Greater diameter of brush bristles: 0.8 mm
- Depth of depression: 100 ± 5 mm

Two stainless steel nozzles are located at two sides of the roller, see Figure 5. Tap water, free from particles, is sprayed through the nozzles at a the flow rate of 1.6 ± 0.1 L/min with a temperature of 22 ± 3 °C and pressure of 3 ± 0.2 bar. The nozzles spray one at a time on the side towards which the test bench is moving, with an impact point in the brush about 5 cm above the test bench. The jet shall impact the entire width of the test bench (Figure 5).

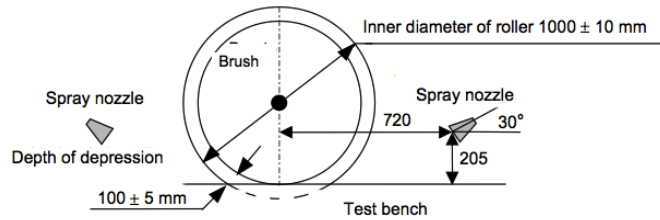


Figure 4- Schematic picture of the washing equipment

In order to avoid unnecessary wear on the brush bristles, the edges of the test bench shall be covered with protective tape (Figure 6).

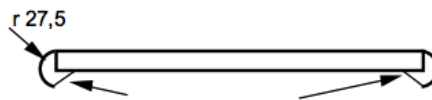


Figure 5- Tape to protect against unnecessary wear of brushes

The speed settings for the brush and test bench were 120 rpm and 0.05 m/s, respectively.

An abrasive fluid is prepared in the mixing vessel after the vessel; the pump and the hose system have been rinsed with clean tap water. 1.5 grams of quartz powder shall be added for each liter of water. It is important to have an even distribution of abrasive fluid. An even level of moisture and an even coating of dirt are achieved during the conditioning process of the equipment, which shall be run before the tests.

The test pieces were cut into 10 x 10 cm² samples and placed on the test panel of the equipment. The test pieces are held flat and in contact with the test surface, either by a magnetic coating on the test bench or by taping them in position. If tape is used, only the edges shall be taped and not the parts of the sample which are to be evaluated. Scratched test samples are rinsed in lukewarm water (< 35 °C) and wiped dry with, e.g., a microfiber cloth of polyester lightly moistened with for example a mixture of household detergent and low-aromatic white spirit.

The washing solution must not damage the paint film and should not contribute to “healing” of scratches due to swelling. Drying shall be done so that the film of brush material on the surface of the test sample is removed but no further scratching is caused. If rinsing is required to remove the washing solution, this shall be done with cold (< 20 °C) water, after which the test sample is wiped clean and dried with a microfiber cloth to remove water spots or traces of washing solution.

After scratching and cleaning have been carried out, gloss measurements can be made as in the preparation of test samples (equipment according to VCS 1026,52729). No gloss measurements were however performed in the present study.

3.1.5 Chemical resistance

Each part used in automobiles must have good resistance to obstacles it might face during use. In order to fulfill this requirement, some different solutions are applied to clarify if the material can sustain its properties or not, after application of the solutions. Fluids used in this test are:

- Solvent 98310 according to VCS 1283,19
- Degreaser, Volvo part no. 1161450
- Alkaline car wash detergent, part no. 8707102, 10% solution
- Concentrated and diluted washer fluid, 10% and 33% solution

3.2 Light transmission

The aim of this test is to ascertain significant differences in light transmission between different polycarbonate samples. The measurements were carried out on specimens that were subjected to the humidity exposure and the heat ageing as well as non-treated samples (references). A quick comparison of the light transmission of the best polycarbonate test piece and a sample from the current Volvo V70 glass is discussed later. Note that transmission stands for the physical transmission of light through the sample, whereas the term “transmittance” stands for the mathematical quantity, which is given below.

In optics, transmittance is the fraction of the incident light, which can pass the sample at a certain wavelength. The transmittance of a spectrum at the wavelength λ is given by:

$$T_{\lambda} = \frac{I}{I_0} \quad (7)$$

Where I is the intensity of transmitted light, and I_0 is the intensity of incident light. Note that transmittance of a sample depends on the wavelength.

The equipment used for the transmittance measurements was Avantes, containing entrance slit, collimator, dispersive element, detector, and focusing optics, Figure 7. Any dust or similar obstacle should be avoided since it may influence the test results. The specimens were exposed to light wavelengths ranging from 280 to 1100 nm. The transmitted light is shown as a function of the wavelength.

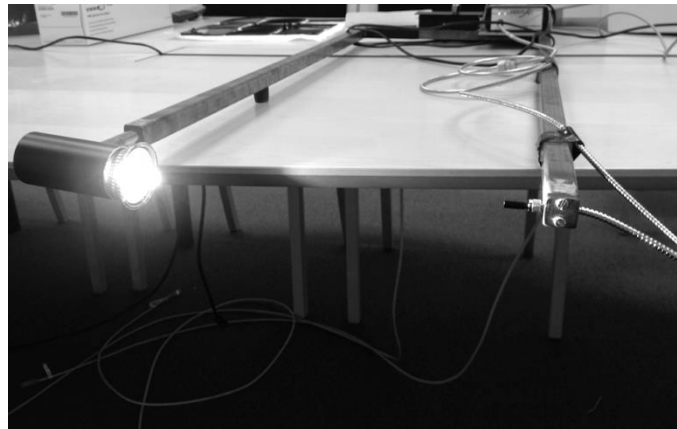


Figure 6- The Avantes instrument used for the light transmission evaluation. The samples were fixed at a proper distance between the light source and the detector.

Note that the spectral range included the ultraviolet region from 280 to 380 nm. The visible range extends roughly from 350 to 650 nm, and the infrared region is above that. However, the most interesting region in this study is the visible range 420-580 nm.

4 Results

4.1 Visual evaluation

For evaluation of color differences between the specimens, the gray scale standard has been used. The total perceived color difference between two non-self luminous specimens depends on the uniformity of them and the sharpness of the dividing line between them. These dividing lines are physically sharp borders between colors. Based on ASTM 2616-12 the color difference between the tested samples was evaluated for some of the specimens in the color matching cabinet. The scale of the color change consist of numbers from 1 to 5; i.e. 1 showing the greatest contrast and when there is no change in the color of the specimen it is graded 5. For each of these gray scale numbers, specific tolerance and color difference ranges are given.

Designation	Color Difference	Tolerance(\pm)
5.0	0.0	0.2
4.5	0.8	0.2
4.0	1.7	0.3
3.5	2.5	0.3
3.0	3.4	0.4
2.5	4.8	0.5
2.0	6.8	0.6
1.5	9.6	0.7
1.0	13.6	1.0

4.1.1 Aging in humidity

Except for the PMMA, there was no perceived difference in color and contrast between the samples based on gray scale test, see Table 2.

Table 2-Results from the gray scale color test for samples aged in humidity

Specimen	Gray scale	Color difference (ΔE)	Tolerance (\pm)
PC-Fiat	5	0.0	0.2
PC-SEAT	5	0.0	0.2
PC-Citroen	5	0.0	0.2
PMMA	4.5	0.8	0.2

4.1.2 Resistance against UV-light

Many natural and synthetic polymers are vulnerable to ultraviolet radiation. The effect can be crack initiation and propagation, change in appearance or disintegration. As observed visually, the polycarbonate samples resisted the ultraviolet radiation, but the PMMA sample did not fulfill the requirements and some deterioration in transmittance and color change could be seen. The color change is in the form of blotchy areas near the edges. This opposes the expectations of PMMA under UV-exposure. As blotchy areas are seen near the edges only, it can be some heterogeneous areas of coating. Due to the lack of sufficient number of samples, there might be a low reliability of the test and no conclusion was made regarding the behavior of PMMA under UV exposure.

4.1.3 Light exposure

Light exposure under 1000 hours and temperature of 80 °C has been done in the test chamber. The artificially aged samples were compared with their respective reference samples in the color matching cabinet. PMMA did not fulfill the test requirements, which could be a result of the lower glass transition temperature of PMMA compared to polycarbonate. However, the limited number of PMMA-specimens did not allow for a solid conclusion about this. Some stains were seen on the polycarbonate sample from the SEAT, which was due to inferior coating of the sample. However, the other samples passed the test successfully according to visual examinations. Results from transmittance difference between the reference sample and the tested ones are shown in section 4.2.

4.1.4 Scratch resistance

Since there were few PMMA samples and failure of the polymer during previous tests we have disregarded it from other tests. There are however good reasons for Volvo Cars to perform further testing of PMMA in the future.

After the test, the samples were compared with the reference samples. Probably, due to the poor coating of PC-SEAT some cracks could be seen with the optical microscopy and also even by naked eye (Figures 8 and 9).



Figure 7- Scratch checking with the optical microscopy



Figure 8- Scratches on the polycarbonate samples; Fiat (Left), Citroen (Right) and SEAT (center)

The other samples met this test and no considerable cracks could be seen on them. This is directly related to the superior coating of the samples.

4.1.4 Resistance against chemicals

None of the chemicals stated in the previous chapter were able to visually affect the materials. No stains, cracks, or any other changes were seen on the samples (Figure 10). Note that as mentioned before, the inferior performance in previous tests and the few available PMMA-samples made us disregard it from this test.

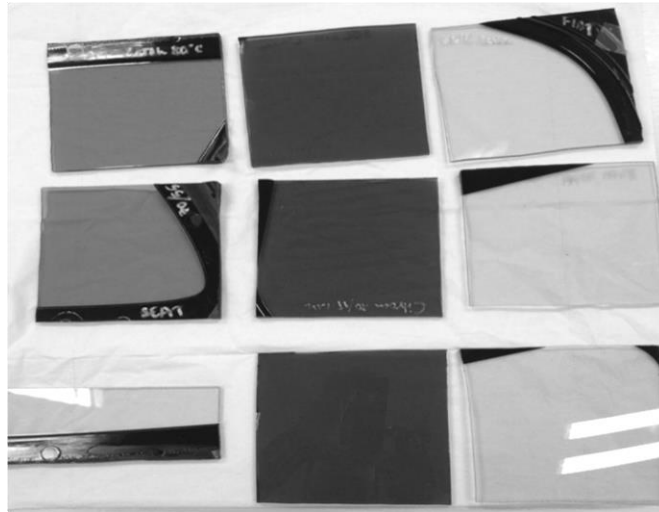


Figure 9- No signs of chemical degradation between some of the tested samples and the reference specimens. Fiat samples (Right), Citroen (Middle) and SEAT (Left)

4.2 Light transmission

The measuring equipment used gives the transmittance in percent on the y-axis as a function of the wavelength on the x-axis. However, as discussed before, it is the wavelengths in the visible range are of primary interest in this project. Furthermore, a comparison between the different samples was carried out. The PMMA-samples as discussed before are not a part of evaluation of this test.

The transmittance of the Citroën reference sample was quite low in the visible range, 32% at most at 540 nm (Figure 11). This is because of the tinting of the polycarbonates. Tinting can control heat gain by absorbing some fraction of sun light and can provide a variety of privacy matters. Tinted glazing will reduce the amount of visible light passing the PC.

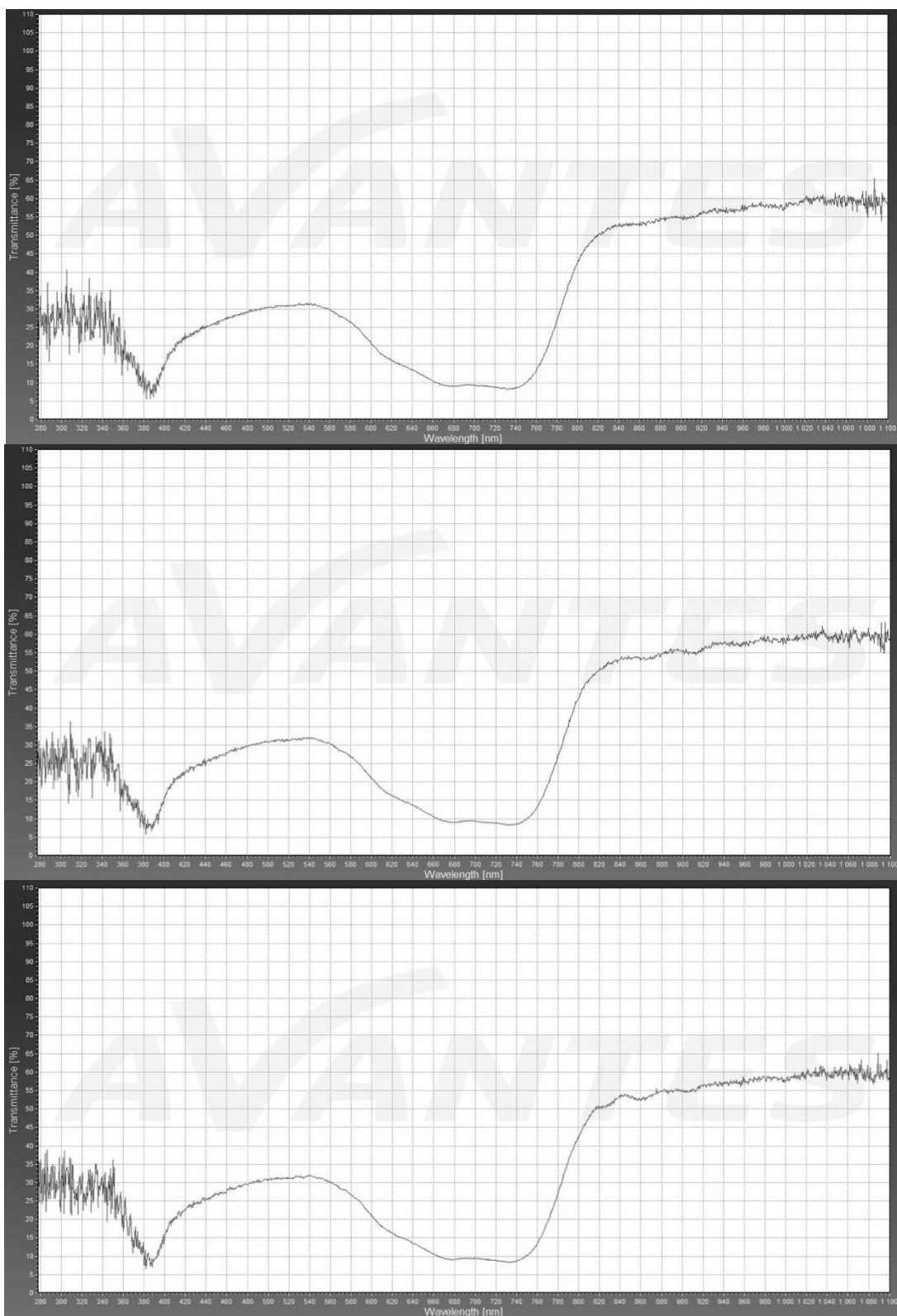


Figure 10- Transmittance as a function of the wavelength for the samples from Citroen; Reference (top), heat aged (middle) and humidity aged (bottom)

The samples from the heat aging and humidity tests exhibited small differences when compared with the reference sample having a very low transmittance, which was caused by tinting as discussed previously, see Figure 11. This difference, which is of the order of a percent increase, could be a result of either experimental scatter or degradation of the tinted layer caused by the heat cycling and the humidity exposure.

The transmittance of the SEAT reference sample showed a higher transmittance than the glass in V70 Volvo Cars (Figures 12 and 13).

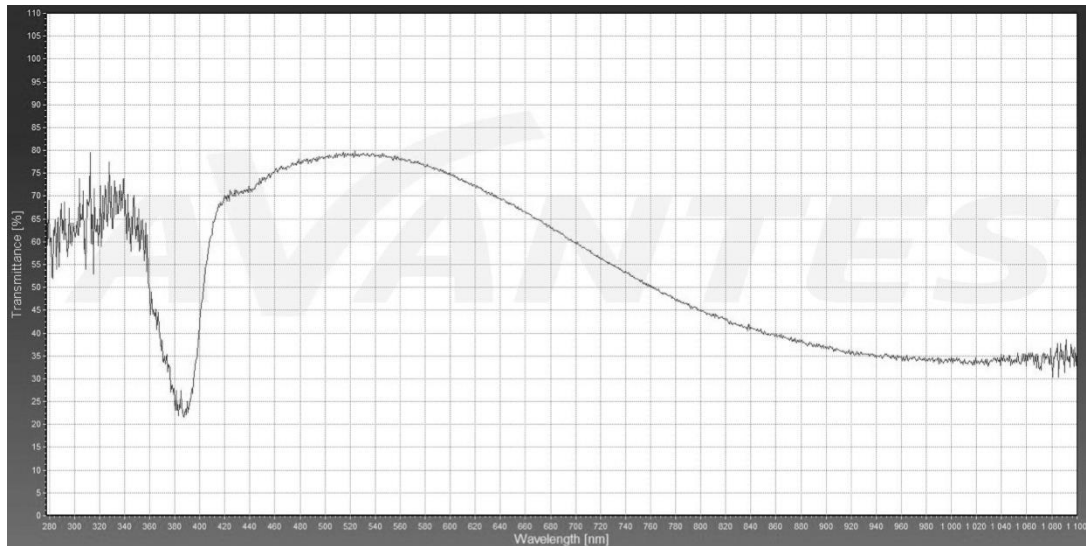


Figure 11- Transmittance as a function of the wavelength for Volvo V70 glass.

However, perhaps due to the adopted coating procedure and/or the type of base polycarbonate, the transmittance decreased after the heat aging and humidity exposure and this difference was of the order of 30 percent (Figure 13).

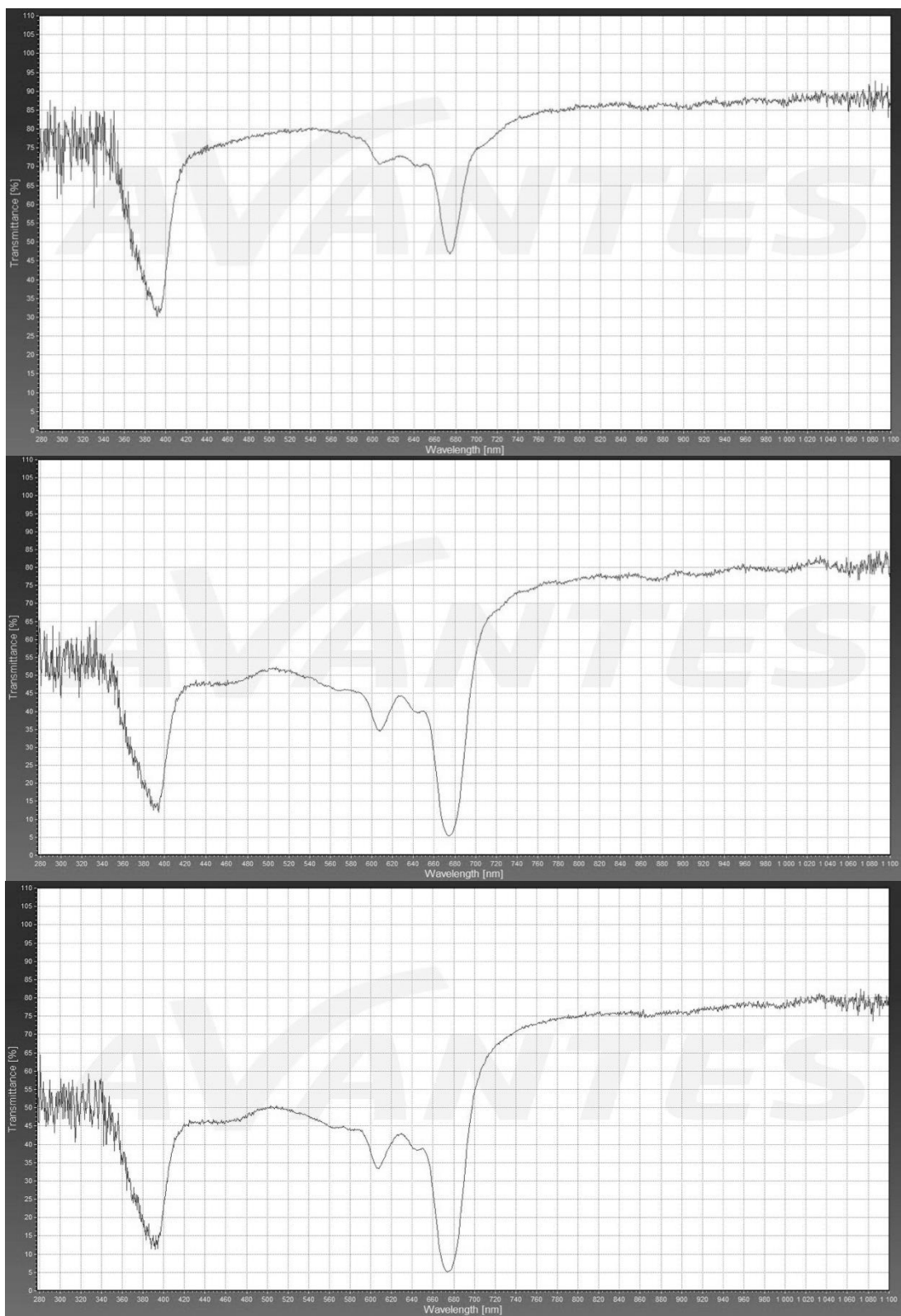


Figure 12- Transmittance as a function of the wavelength for samples from Seat; Reference (top), heat aged (middle) and humidity aged (bottom)

The samples from Fiat showed the best results among our test species since the reference PC-sample had a high transmittance, which remained even after heat aging and humidity exposure with a small change (Figure 14).

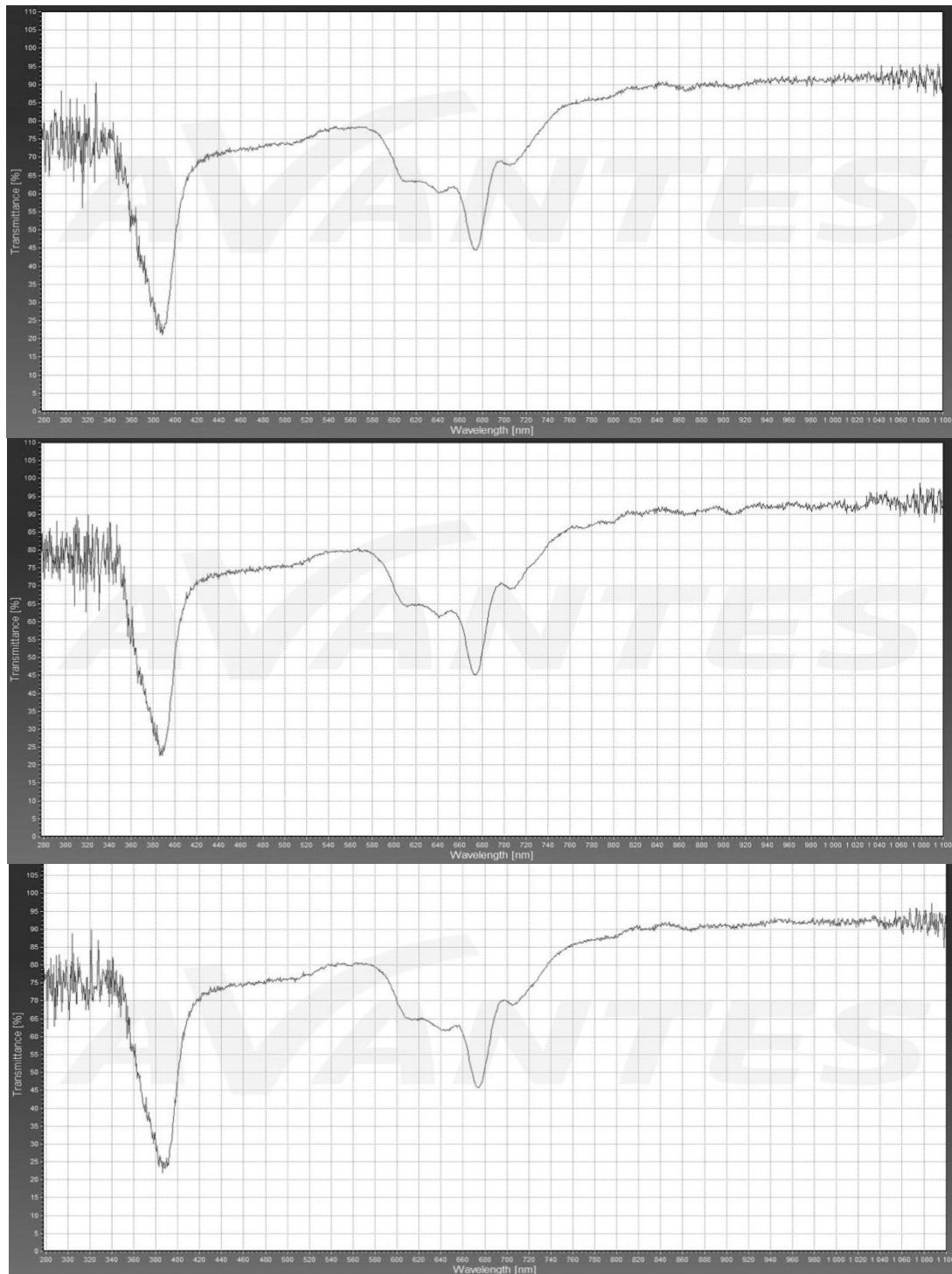


Figure 13- Transmittance as a function of the wavelength for samples from Fiat; Reference (top), heat aged (middle) and humidity aged (bottom).

The results for all specimens are shown in Table 3 below.

Table 3- The transmittance (in %) of the samples at different wavelengths within the visual range. The indices denote the wavelength.

Specimen	Status	T₄₄₀	T₄₈₀	T₅₂₀	T₅₆₀
PC-Citroen	Reference	25	28	32	29
	Heat aged	25	29	33	30
	Humidity aged	26	29	32	30
PC-SEAT	Reference	76	78	80	80
	Heat aged	47	49	52	49
	Humidity aged	46	47	49	50
PC-Fiat	Reference	76	77	78	78
	Heat aged	76	78	78	79
	Humidity aged	77	78	78	79
Glass-V70	Reference	70	76	79	74

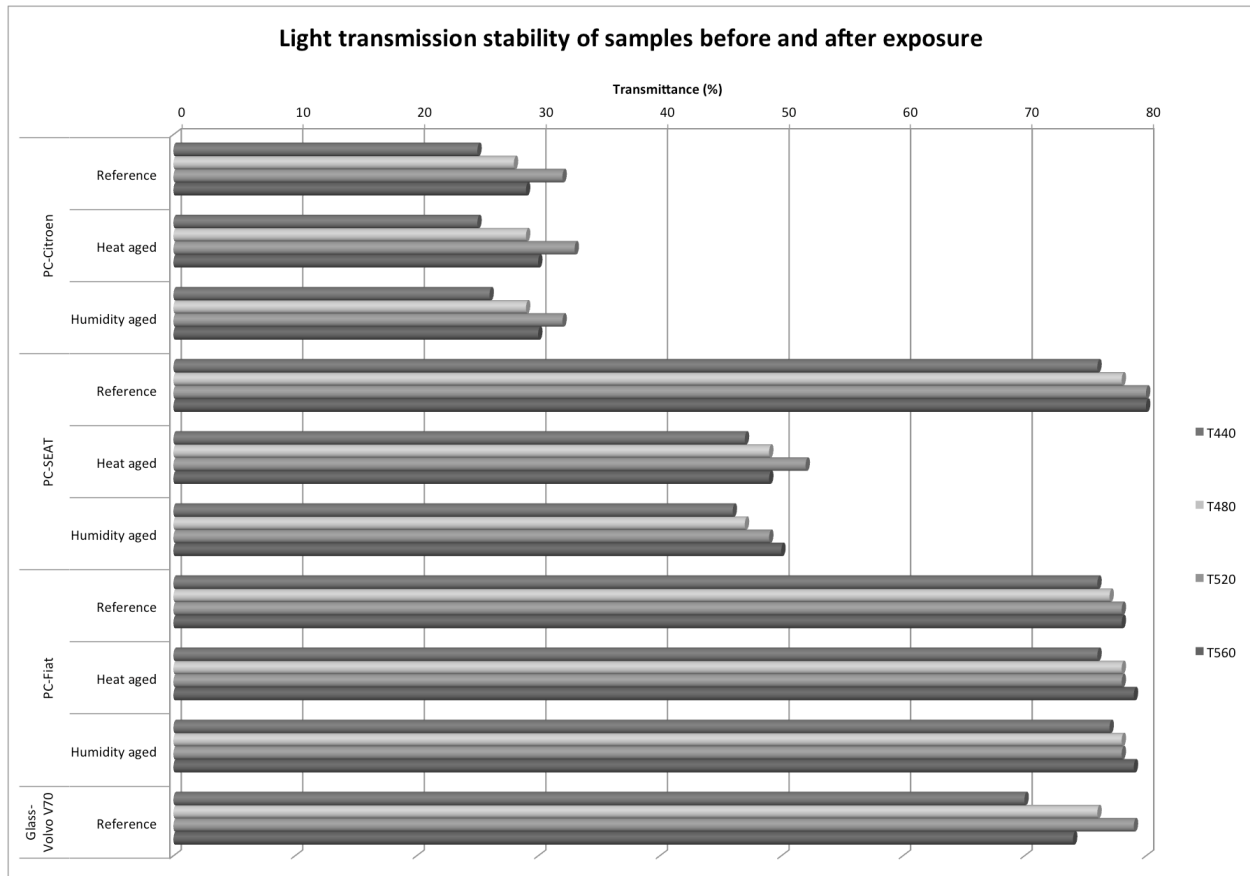


Figure 14- Light transmission of the samples before and after exposure/ageing.

From Figure 15 above it can be concluded that the most stable sample was from FIAT, which did not exhibit significant changes due to the heat and humidity exposures. The most substantial change between the tested and the reference sample was noted with the Citroen sample (Figure 15).

Appendix 3 includes a comparison of the different PC-specimens after the same treatment. This is to give a better overview of certain samples.

5 Conclusions and discussion

As expressed in the previous chapter, the test samples showed that it is potentially possible to use polycarbonate glazing in the fixed side glass of cars due to their adequate-properties. However, PMMA did not show any significant advantage compared to the glass and nearly did not fulfill the requirements of the tests. This was not up to the expectations and thus surprising; this might be because of the limited number of PMMA samples available.

As discussed before, the investigated samples differed in different aspects such as base material, coating procedure, design, etc. Among the samples that were tested, the sample from FIAT showed a better performance with the least deviation in transmittance of samples before and after exposure to heat and humidity. It also showed good performance when exposed to mechanical forces.

An important factor in this context is the coating material and the related processing. Even the strength of the interface layer (glue) between the coating and the base material is of considerable importance and it can influence the performance the whole component especially when it interacts with aggressive environments like UV-light at elevated temperatures. This can also be further enhanced, when mechanical forces are applied on the samples. The most common mechanical force to be considered is scratch.

To sum up, with an appropriate consideration of quality of the material and coating and choosing a competitive supplier that can fulfill requirements of Volvo Cars, implementation of plastic glazing can, by reducing weight and fuel consumption, reduce the environmental impact and offer ease of some preproduction approaches. Among those, the most important one can be the styling freedom it offers.

It is believed that challenging and tough environmental considerations from the European Union within the coming decades, use of plastic glazing would be of great interest for automotive industry.

6 Recommendations and future work

There has been a good advance in the use of plastic materials in vehicles. But now, advances in materials, machinery and tooling make it much easier to surpass limitations and restrictions in order to utilize plastics for example in rear screens, panorama roof and fixed side glasses. As a recommendation, Volvo Cars should take action in use of polycarbonate glazing in exterior parts. The results from the range of tests show that they possess an interesting potential to be implemented in cars.

A survey on the possible use of PMMA is recommended in future studies. In this study, PC received more attention and due to the limited number of PMMA samples, authenticity of their test results is in doubt. Future developments in coating technology are of great interest. For example, use of electro-chromatic elements in the coating to give the option to the driver to change and control the amount of light entering the vehicle.

Appendix

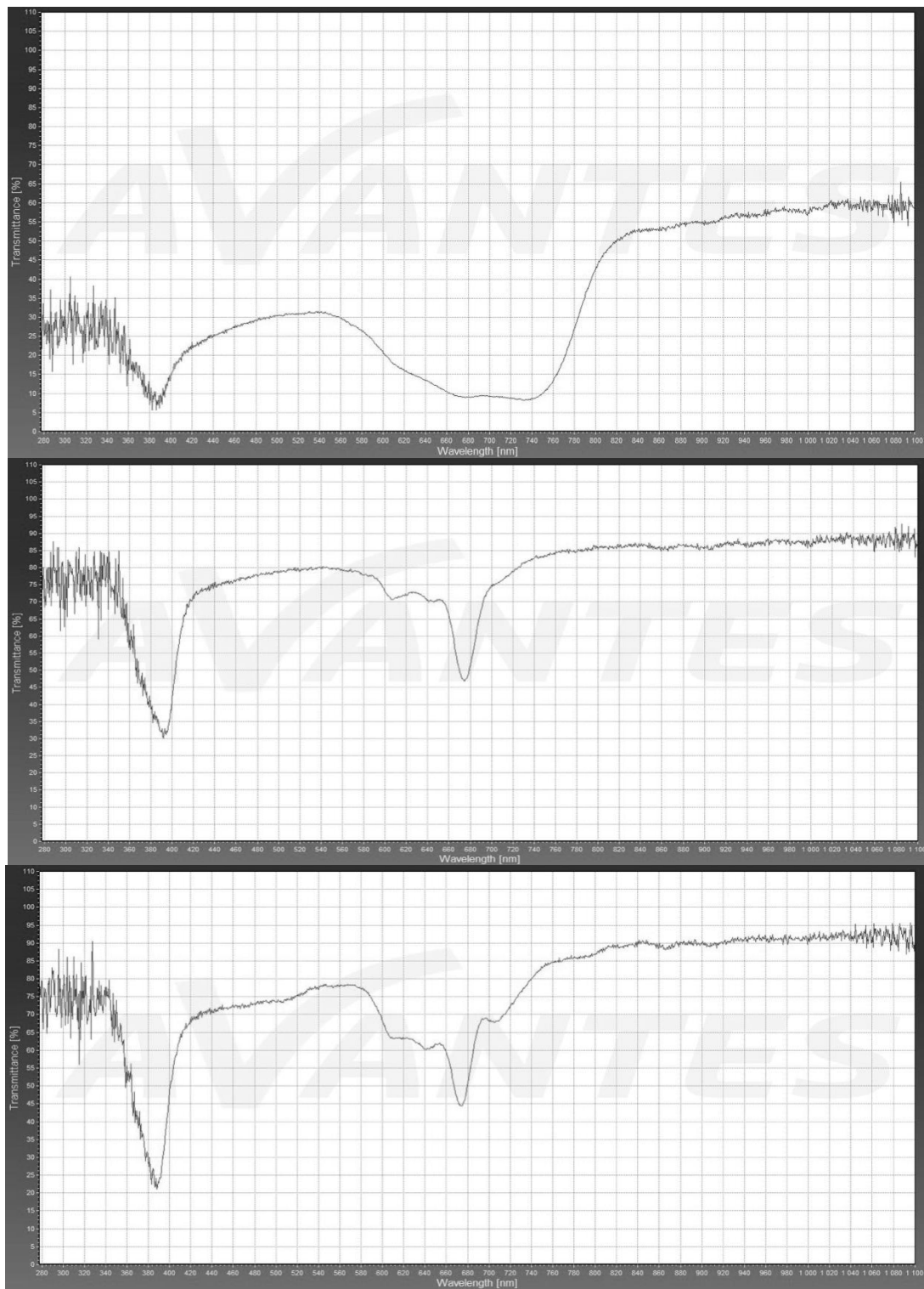
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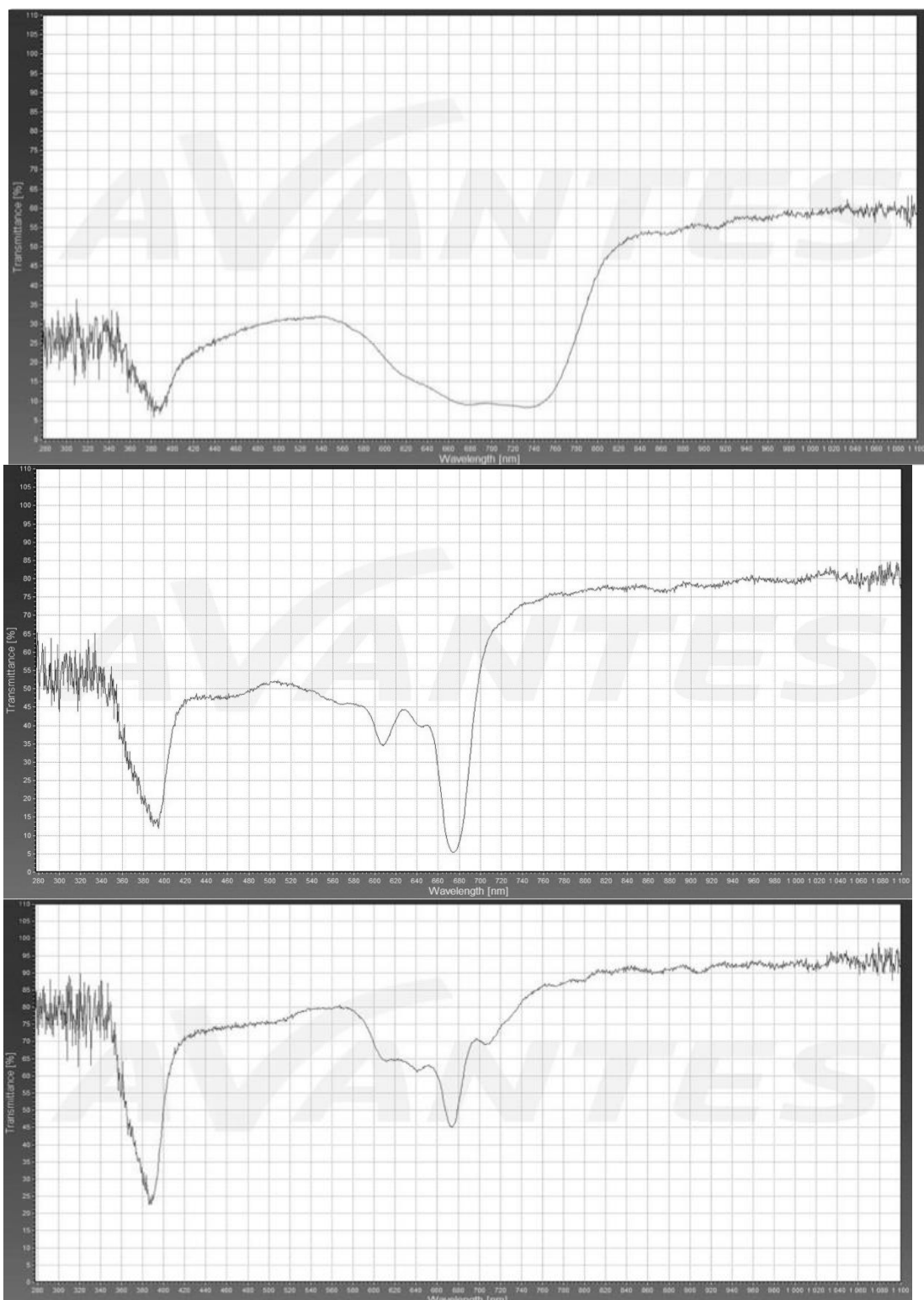
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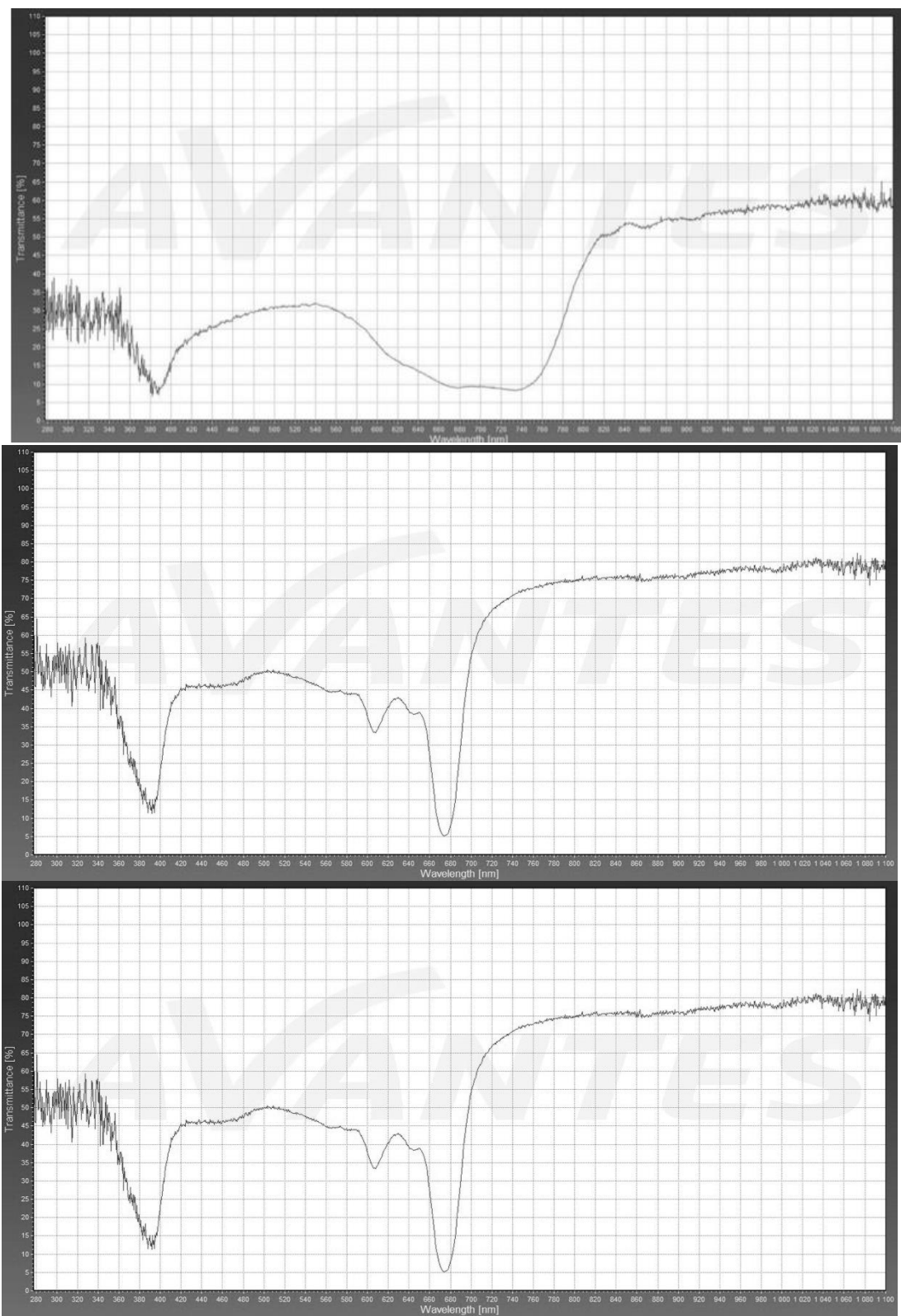
A.3 Transmittance results



A.3.1 Transmittance as a function of the wavelength for the reference samples from the different manufacturers; Citroen (top), Seat (middle) and Fiat (bottom)



A.3.2 Transmittance as a function of the wavelength for the heat-aged samples from the different manufacturers; Citroen (top), Seat (middle) and Fiat (bottom)



A.3.3 Transmittance as a function of the wavelength for the humidity-aged samples from the different manufacturers; Citroen (top), Seat (middle) and Fiat (bottom)

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