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Evaluation of Automotive Lenses for Forensic Applications by FTIR, PGC, and Raman Spectroscopy†

ABSTRACT

Hit and run type accidents often result in trace evidence, such as broken fragments of automotive lenses, to be left behind at the scene of the accident. In an attempt to determine the evidentiary value of automotive lenses, this study examined a large number of polymer lenses by a variety of analytical methods. Fourier Transform Infrared Spectroscopy (FTIR) (225 of 275 lenses), Pyrolysis Gas Chromatography (PGC) (152 of 275 lenses) and Raman Spectroscopy (101 of 275 lenses) were used to characterize and compare chemical characteristics of the lenses. The relative power of each of the techniques to discriminate between polymer lenses was determined by data treatment. Color and FTIR comparisons combined yielded 11 distinct groups. PGC and color combined yielded 34 distinct groups. Raman and color combined yielded 20 distinct groups. Ninety-six (96) of the different automotive lenses in the sample set were analyzed on all three instruments. Forty-six (46) of the 96 lenses could be distinguished by color and at least one of the instrumental methods, demonstrating the utility of these techniques for discriminating plastic automotive lenses in forensic casework.

Keywords: forensic science, plastics, taillights, automotive lenses

INTRODUCTION

Plastic automotive lenses can become physical evidence in a number of ways including when an automotive lens is broken during impact in a hit-and-run accident. Pieces of the broken lens may be left behind at the scene, on the victim, or embedded in a second automobile. There is also the potential that the perpetrator's vehicle will remove

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evidence from the scene, such as when a piece of lens from the victim's vehicle becomes embedded in the perpetrator's vehicle after contact. The potential exists for front, rear, and side light automotive lenses to become physical evidence. If the lens fragments are large enough, there is a possibility that a physical match may be made. When a physical match is not possible, the questions become: 1) are there measurable physical and/or chemical differences between automotive lenses from different sources, and 2) are forensic scientists able to determine and describe the differences between them so that they are able to articulate the associative value of indistinguishable lenses?

There have been a limited number of studies [1,2] evaluating automotive lenses for forensic applications. The purpose of this study was to determine the amount of variability in the chemical composition of automotive lenses from different sources. It is also important to determine the homogeneity of a number of fragments originating from a single lens source in order to evaluate the value of the comparison. To measure the differences and/or similarities, the lenses were analyzed by three instrumental techniques: Fourier Transform Infra-red Spectroscopy (FTIR), Pyrolysis Gas Chromatography (PGC) and Raman Spectroscopy.

MATERIALS BACKGROUND

Historically, taillight and headlamp lenses were all manufactured from borosilicate glass [3]. Industry trends in the USA, Europe and Japan have resulted in the use of polymers in the composition of automotive lenses by manufacturers [4]. The factors driving these trends include lower costs, weight savings and recyclability [4]. Polymer lenses weigh half as much as glass lenses, have a lower assembly cost and offer greater design flexibility, which is important for the automotive industry [5]. Other advantages of polymers over glass include: better impact strength, improved optics and integrated mounts [6]. The polymers used in automotive lenses have to meet particular specifications [5] dictated by the Federal Motor Vehicle Safety Standard 571.108 (FMVSS108) for vehicle lighting in the United States.

Three types of polymers, polymethylmethacrylate (PMMA), polycarbonate (PC) and a copolymer of styrene-acrylonitrile (SAN), were found in the composition of the automotive lenses examined in this study [7]. Kuptsov [1] has reported that polystyrene, methylmethacrylate, and a second copolymer of acrylonitrile with methylmethacrylate are also sometimes used in automotive lens production. Various resin companies supply the polymer (or resin) that is used to manufacture automotive lenses. The homogeneous resin is extruded into small cylindrical pellets approximately 0.1 inch in diameter and 0.14 inches in length (communications with Gary Robin, Manager, TriPlex). The polymer pellets are then supplied to the injection molding companies for the formation of the lenses. The most common processing

technique for converting resin into automotive lenses is injection molding [8]. The injection molding process is a method of forming the hard polymer by heating the resin until it can flow, followed by injecting the hot liquid polymer into a mold.

ANALYTICAL BACKGROUND

FTIR has been applied in the analysis of many types of trace evidence including paint, fibers, adhesives, rubber, body fillers, shoe soles and plastics. Suzuki [9–13] has reported on FTIR as a useful method to classify binders and identify pigments present in automotive topcoats. Massonett and Stoecklein [14] have also reported on the qualitative information obtained through FTIR analysis of pigments despite overlap from absorption bands due to the resin and other components. Tungol *et al.* [15,16] describe IR spectroscopy to be the best established technique for identifying polymeric fibers among the analytical techniques for forensic examinations of fibers. Noble *et al.* [17] utilized IR spectroscopy for the characterization of adhesives and were able to discriminate between similar adhesives. Cleverly [18] was able to identify the brand of body filler from its color and IR spectrum. Walsh *et al.* [19] analyzed 37 formulations of body fillers using three instrumental techniques (Scanning Electron Microscope/Energy Dispersive X-Ray, visible microspectrophotometry, and IR). Lennard and Margot [20] illustrated in a case report, the high discrimination power of IR combined with PGC in the analysis of shoe soles. Parybyk and Kobus [21] showed that IR was useful for characterizing bumper bar samples according to polymer class. PGC is also a well-established technique for the analysis of various trace evidence including paint, automobile rubber, body fillers and automobile bumper bars [22–27]. Different information is available from Raman spectroscopy that is either not available or hidden within IR spectra. Raman spectroscopy is a simple and non-destructive method of analysis that has also been applied to various areas of trace evidence including explosives, fibers, paints and automotive lenses [1, 28–32].

METHODS

Sample Selection and Descriptions

Autobody shops and junk yards in the St. Paul, Minnesota area were contacted to obtain a representative cross-section of automotive lenses that might be expected to be found at a crime scene. Vehicles ranging from model years 1983 through 2000 were sampled. The make, model, year and location of the lens samples were recorded when available (see Appendix 1). The Vehicle Identification Number (VIN) was also recorded and verified to ensure the correct vehicle was reported. Both American and foreign vehicles were included in this sample set. Two hundred seventy-five (275) automotive lens samples were collected. These samples included a representation of 13 different American makes consisting of 52 models and 13 different foreign makes consisting of 29 different models. Color determination was made by a macroscopic examination.

The colors of automotive lenses collected were red, dark red, amber, clear, smoke grey and black. In order to remove environmental contamination on the surface of the lens, samples were washed in hot water and allowed to air-dry overnight.

Standards

Polymer standards of polymethylmethacrylate (PMMA), polycarbonate (PC), and styrene-acrylonitrile copolymer were received from Scientific Polymers (Ontario, NY). Resin standards were received from two of the resin supply companies. Atofina, formerly Elf Atochem, (Highland, MI) supplied 12 different standards: 1 clear, 3 amber, 3 red, 2 smoke gray, 1 black and 2 dark red. Plaskolite, formerly Continental Acrylics, (Long Beach, CA) supplied 2 red standards.

Fourier Transform Infrared Spectroscopy

The instrument utilized for this study was the Perkin-Elmer Spectrum BX FT-IR with the AutoImage Accessory. The AutoImage Accessory is a microscope attachment that allows for Attenuated Total Reflectance (ATR). Operating parameters for the instrument are as follows:

Crystal	Germanium
Source	mid-infrared (MIR)
Range	700 cm ⁻¹ to 4000 cm ⁻¹
Number of scans	16
Interval	2 cm ⁻¹
Resolution	4 cm ⁻¹
Apodization	strong
Gain	1.0
OPD Velocity	1.5 cm/s
APV Filter	out
Aperture size	100 μm x 100 μm
Single Beam	

In utilizing infrared spectroscopy, normal transmission and attenuated total reflectance were tried on two different lens samples. The normal transmission sample appeared overloaded with very broad flat peaks. The use of ATR resulted in better quality spectra for the same samples. A background spectrum was collected every day that data was collected for the samples on the surface of the gold mirror sample holder, and with the same aperture that was used for the samples. Sample preparation consisted of thinly slicing the lens sample with a scalpel blade and mounting it on the surface of the gold mirror sample holder with a small piece of tape covering a minimal area of the sample. The tape facilitated the viewing of the sample with the video camera and it diminished the possibility of the sample sticking to the crystal after contact.

Pyrolysis Gas Chromatography

The instrumentation utilized for this portion of the study consisted of a CDS 120 pyroprobe interfaced with a Hewlett Packard 5890 GC with an FID detector. The pyrolysis parameters included heating to 700° C for 5 seconds during the pyrolysis cycle and using a GC interface temperature of 275° C. Certified Grade Helium was used as the carrier gas.

A 50 m length HP Ultra 2 crosslinked 5% PH ME Siloxane column with a film thickness of 0.52 μm and a 0.32 mm internal diameter was used for the PGC studies.

The temperature program and parameters of the GC were:

Split mode:	10:1
Injector Temperature:	275° C
Detector Temperature:	310° C
Initial Temperature:	50° C
Initial Time:	3 minutes
Rate A:	20° / minute
Final Temperature A:	200° C (no hold at this temperature)
Rate B:	15° / minute
Final Temperature B:	300° C
Final Time B:	10 minutes
Total Run Time:	27.16 minutes

The pyroprobe was cleaned after each sample by heating the pyrolysis unit to 990° C for 5 seconds two times. The column temperature was kept at 300° C and the column effluent was monitored on a strip chart for 15 minutes. A blank was analyzed between different samples. A blank consisted of glass wool in the quartz tube using the same operating parameters as for the samples.

Samples were prepared by cutting small rectangular pieces of the lens sample with a scalpel blade. Samples were approximately 1/2 mm x 1 mm and weighed approximately 0.1 mg. Samples were placed inside the quartz tube with glass wool placed on both sides of the sample. The sample, quartz tube and glass wool were handled with forceps to minimize the opportunity for any contamination.

Raman Spectroscopy

The instruments utilized for this study were the Dilor Instruments SA 'Lab Ram' Raman Spectrometer and the Kaiser HoloSpec 5000 Imaging Raman Spectrograph. Operating parameters for the Dilor Instruments SA Raman are as follows:

Source:	HeNe laser (632.8 nm)
Spectral Range:	450 cm ⁻¹ to 4000 cm ⁻¹
Resolution:	4 cm ⁻¹
Filter:	none
Slit:	300 microns
Hole:	800 microns
Grating:	1800 grooves per millimeter
Accumulation time:	Varies per sample
Microscope:	Olympus BX40 with 100x objective
Detector:	Thermoelectrically cooled CCD

Operating parameters for the Kaiser HoloSpec Imaging Raman Spectrograph are as follows:

Source:	near-infrared (NIR) 785 nm diode laser
Spectral Range:	250 cm ⁻¹ to 3500 cm ⁻¹
Resolution	4 cm ⁻¹
Accumulation time:	Varied per sample
Focal distance:	18 millimeters
Probe:	Fiber optic probe
Detector:	CCD

The CCD detector was optimized for both systems by comparing the signal from a well-characterized sample and making mathematical adjustments using a software program. A specially cut silicon wafer (Si 100) was analyzed on both systems before any samples were analyzed. The Kaiser Optical Systems Raman spectrometer also used a vial of high purity isopropanol to ensure that the fiber optic probe head was properly calibrated. The Raman shift was corrected using the silicon wafer and its reference Raman shift photon band of 520 Rcm⁻¹. No additional sample preparation was necessary other than the original sample preparation of washing the samples and fracturing the lenses.

RESULTS and DISCUSSION

Reproducibility

The reproducibility of each instrument was evaluated by analyzing five samples from one lens. The instruments were continuously monitored for their reproducibility as each sample was analyzed in triplicate.

Homogeneity Study

The homogeneity of several automotive lenses was determined by chemical analysis. One PMMA lens sample was fractured and sampled from ten different areas and analyzed on all three instruments to determine the homogeneity of the sample. The ten

samples from the same lens were found to be indistinguishable using a match criterion based on the instrumental limitations. For verification, a second PMMA lens sample was also fractured and analyzed from ten different areas, with similar results. Large differences within a sample and small differences between two different samples would render the comparison between different lenses useless or of very limited forensic use. The combination of lens homogeneity and variation in chemical properties between different lenses would suggest that lens comparisons could have utility in forensic comparisons.

Fourier Transform Infrared Spectroscopy

The three polymer standards from Scientific Polymers were analyzed in triplicate and their respective infrared spectra are shown in Figure 1. Each of the polymers gave distinctly different spectra and were easily differentiated. Two co-polymers of styrene-acrylonitrile with varying percentages (75% styrene/25% acrylonitrile and 68% styrene/32% acrylonitrile) were analyzed but could not be differentiated from each other by FTIR.

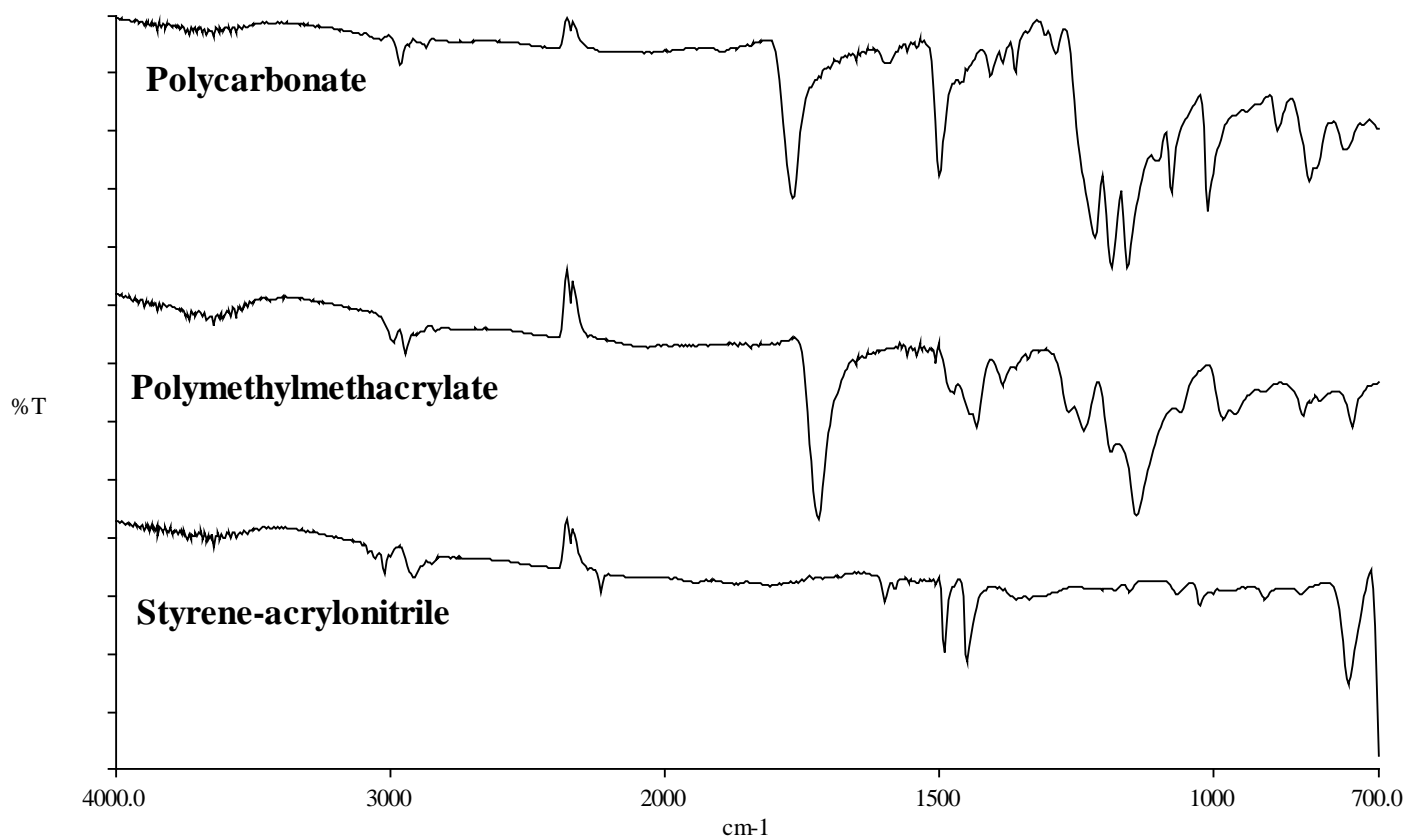


Figure 1: FTIR spectra of polycarbonate, polymethylmethacrylate, and styrene-acrylonitrile standards from Scientific Polymer.

The twelve standards from Atochem and the two standards from Continental Acrylics were analyzed in triplicate. All 14 of the resin standards were categorized as PMMA but were not further differentiated.

Two hundred twenty-five (225) lens samples were analyzed with the ATR accessory on the FTIR. The polymer type was identified for each sample but no additional differentiation between the samples was possible. Two hundred and three (203) samples were identified as PMMA, 21 samples were identified as PC and one sample was a co-polymer of styrene-acrylonitrile. Samples of different color were not differentiated further by FTIR. One possible reason for this may be that the overwhelming polymer bands mask any FTIR absorptions by the small amount of dye in the sample.

Pyrolysis Gas Chromatography

The three polymer standards from Scientific Polymers were analyzed and their respective pyrograms are shown in Figure 2. Similar to the FTIR results, each of the polymer standards resulted in distinctly different pyrograms and were easily differentiated. One hundred fifty-two (152) lens samples were analyzed by PGC. All of the samples analyzed were composed of one of the three polymer types of PC, PMMA or the copolymer of styrene-acrylonitrile.

Additional discrimination of the polymer type was possible for the PMMA samples. The PMMA samples could be further classified into three categories by characteristic peaks in their pyrograms. The pyrograms of category A, B and C PMMA samples are shown in Figure 3. The PMMA-C type was differentiated from the A and B categories due to a large peak at approximately 8 minutes and four additional peaks between 21 and 23 minutes. PMMA categories A and B were differentiated by two groups of peaks at approximately 4 and 5 minutes. PMMA category A had a set of doublet peaks at approximately 4 minutes and a triplet set of peaks at approximately 5 minutes. PMMA category B had a single peak at approximately 4 minutes while it had a set of doublet peaks at approximately 5 minutes.

The A category could be further differentiated into two sub-groups. Sub-group A1 was differentiated from sub-group A2 because of an additional peak at approximately 19 minutes. Figure 4 illustrates the two sub-groups of category A. To verify these were real peaks from the sample and not due to laboratory environment or contamination, two sets of samples were re-analyzed 11 months later. The peak at approximately 19 minutes was reproducible in the samples from sub-group A2.

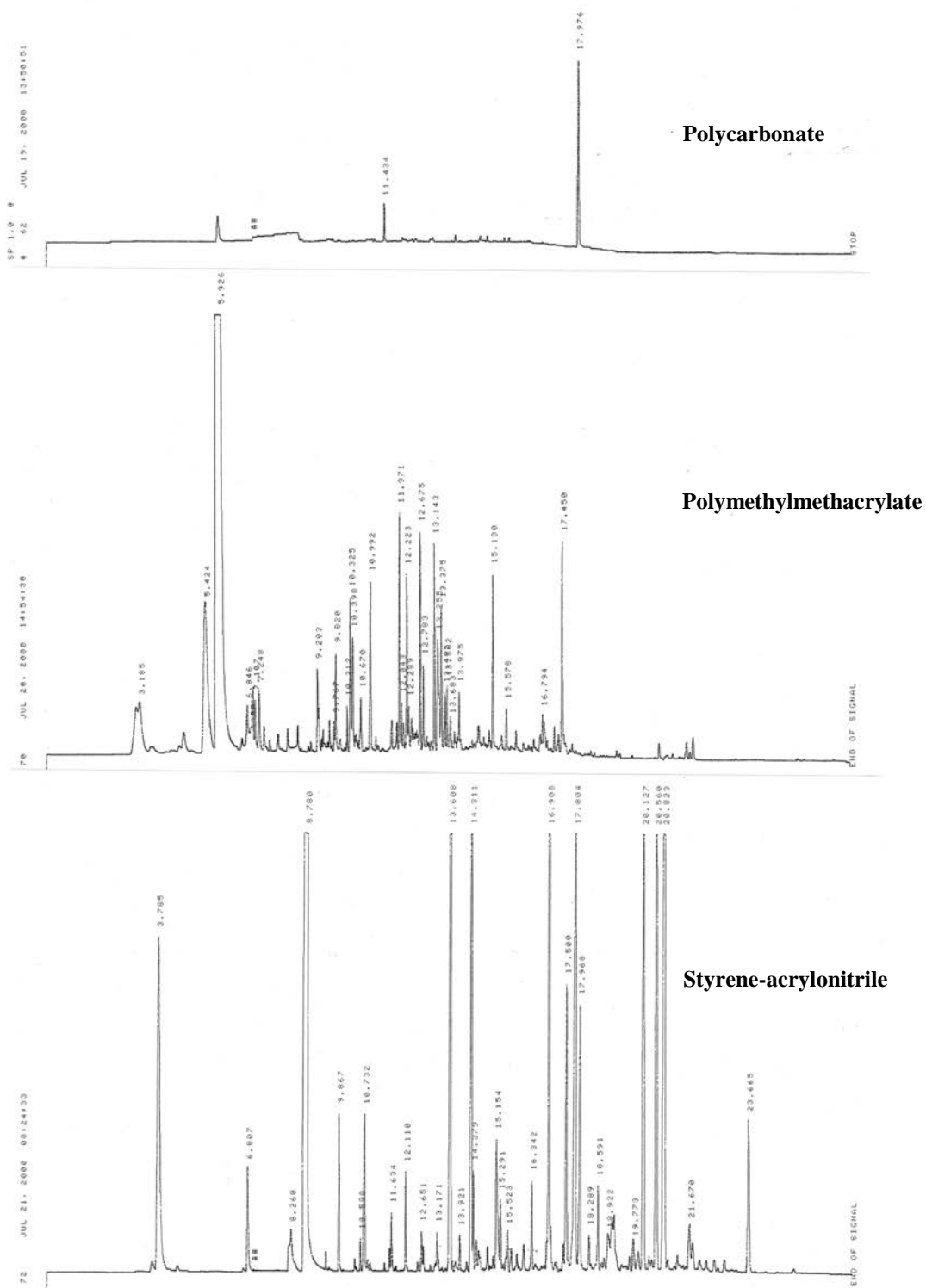


Figure 2: Pyrograms of the three polymer types: polycarbonate, polymethylmethacrylate, and styrene-acrylonitrile. Standards from Scientific Polymer.

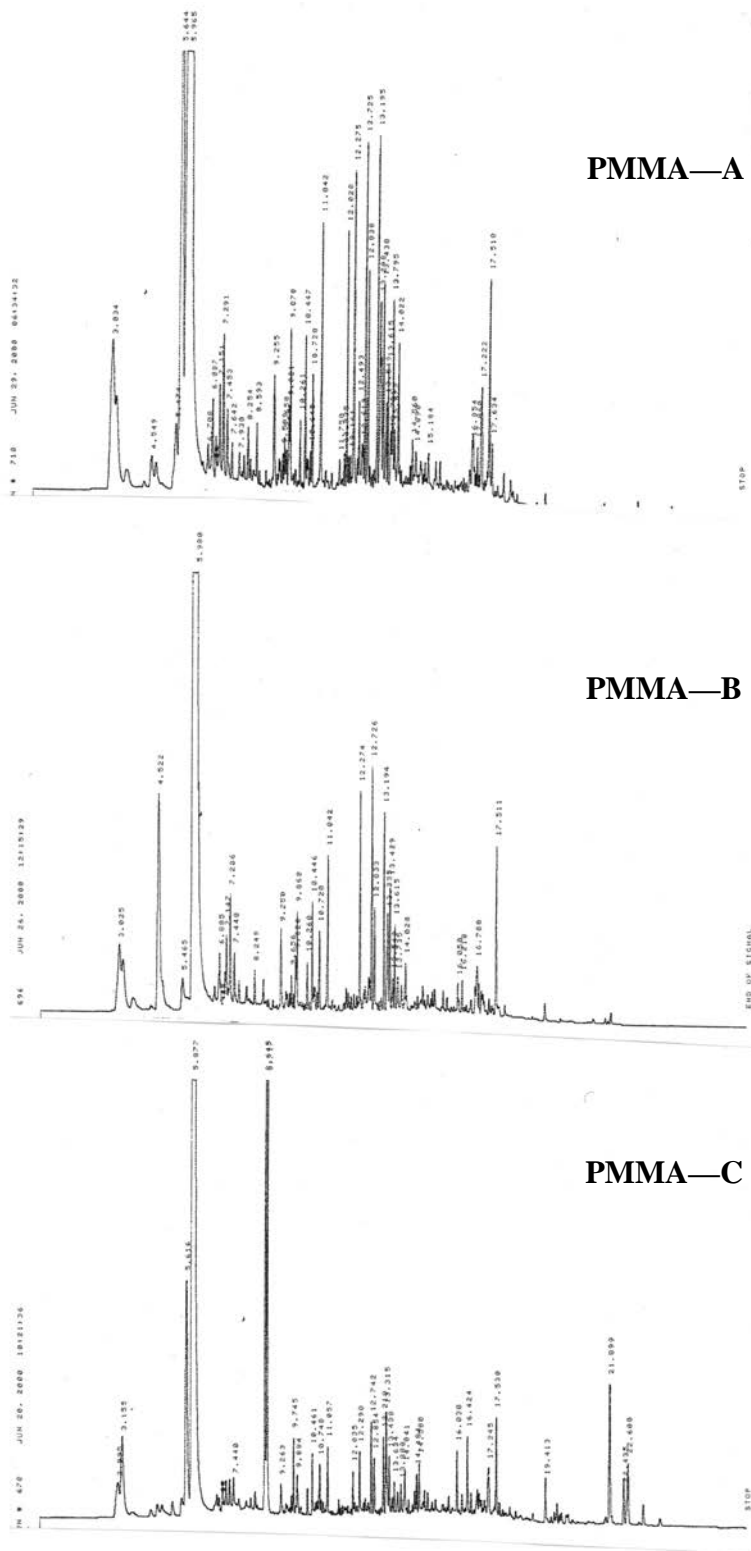


Figure 3: PGC pyrograms of three different categories of PMMA (A, B, and C).

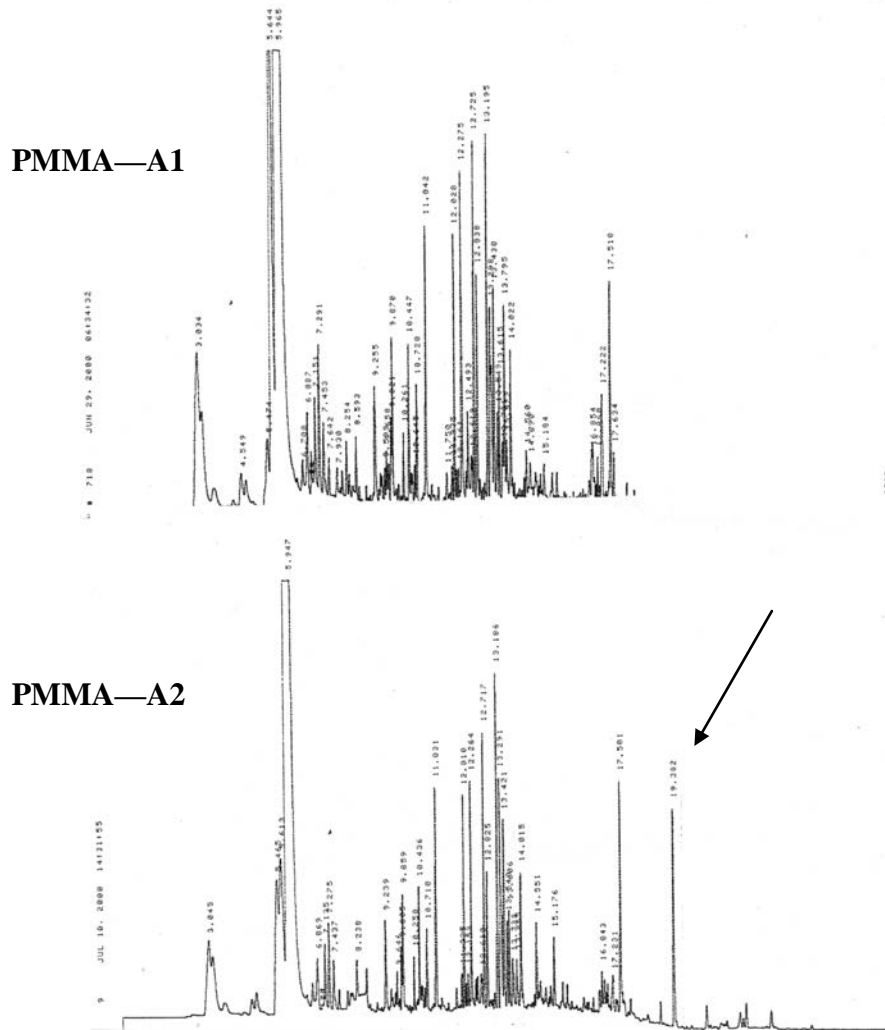


Figure 4: PGC pyrograms of two different PMMA-A samples (A1 and A2). Distinguishable due to an additional peak at approximately 19 minutes in A2.

The group B category could be broken down into four additional sub-groups due to the presence or absence of three peaks at approximately 12, 18 and 20 minutes. Two peaks at approximately 12 and 20 minutes were absent while a peak at approximately 18 minutes was present in sub-group B1. In the sub-group B2, the peak at 12 minutes was present while the peaks at 18 and 20 minutes were absent. Sub-group B3 had peaks at 12 and 20 minutes present while the peak at 18 minutes was absent. Sub-group B4 did not have any of the three peaks present. Figure 5 illustrates the different pyrograms for the four sub-groups of group B. A set of samples was re-analyzed at a later time which verified that these were real peaks from the sample and not due to laboratory environment or contamination.

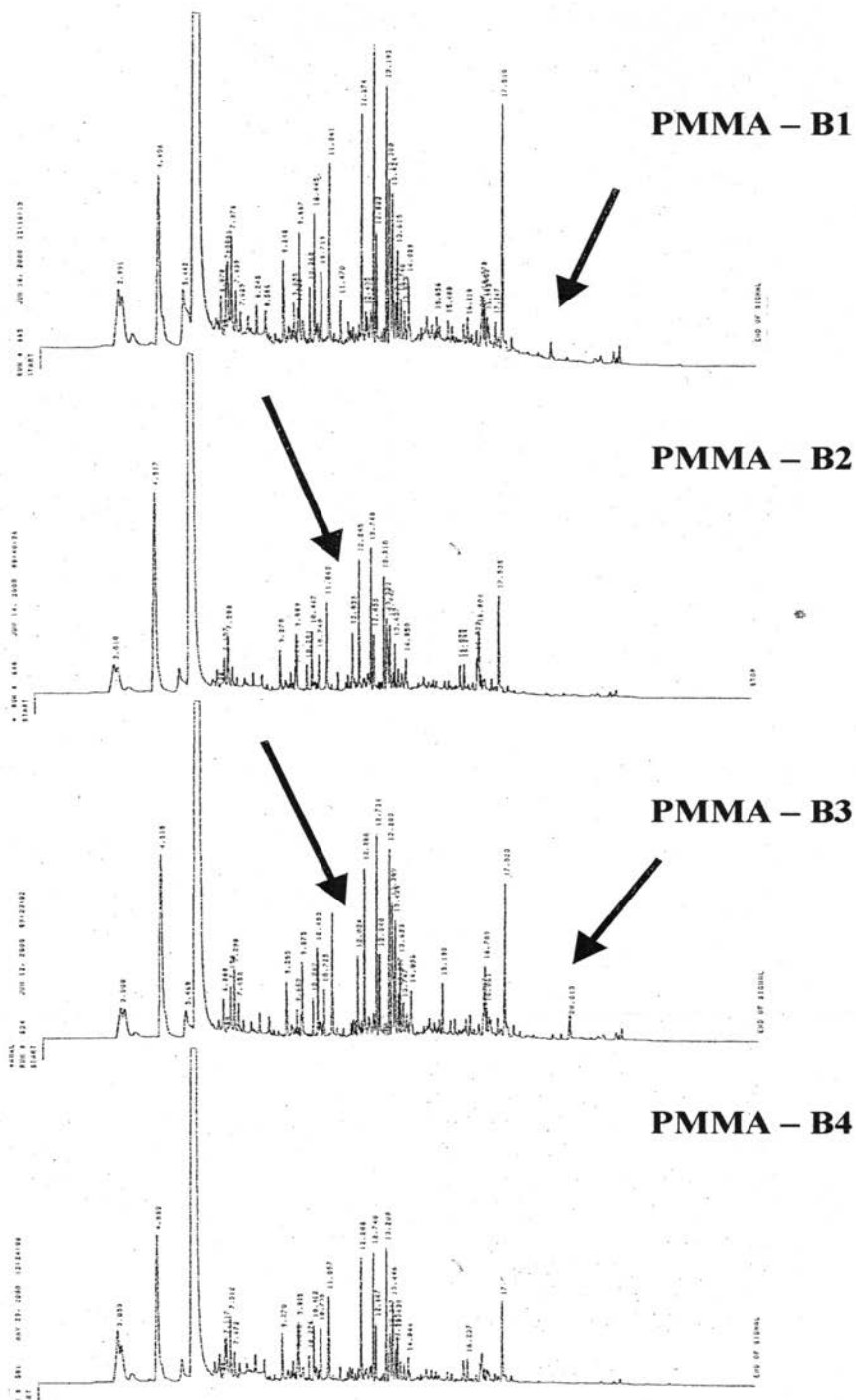


Figure 5: PGC pyrograms of four different PMMA-B samples (B1, B2, B3 and B4). Distinguishable due to the presence or absence of peaks at approximately 12, 18 and 20 minutes.

The PMMA-C category could not be further differentiated by PGC but one noteworthy observation was PMMA-C samples contained only American vehicle lenses. The polycarbonate samples could not be further differentiated into additional categories.

Raman Spectroscopy

Raman spectra easily differentiated the three different polymer types as shown in Figure 6. Similarly to the FTIR and PGC techniques, each of the polymers gave distinctly different spectra and were easily differentiated.

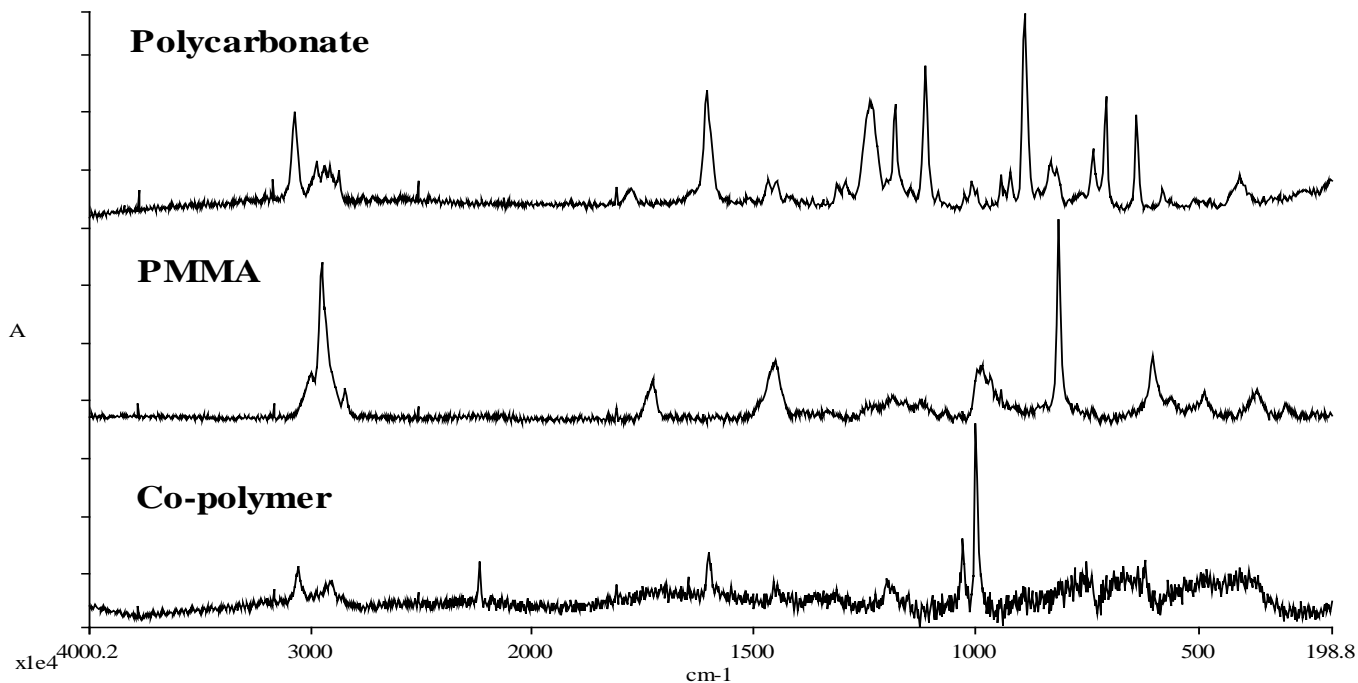


Figure 6: Raman spectra of three polymer types: polycarbonate, polymethylmethacrylate, and co-polymer of styrene-acrylonitrile.

Eighty-two (82) samples were analyzed with the Dilor Instruments SA Raman Spectrometer with the HeNe 633 nm laser. Twenty-seven (27) of these samples fluoresced and little information was obtained from their spectra. Of the 27 samples that fluoresced, 15 were red, seven were smoke gray, two were black, and three were dark red. Even though the spectra of these samples did not provide any information about the sample, they were differentiated from the other samples that did not fluoresce. The authors were unable to determine the cause of the fluorescence in these samples with this laser. None of the amber or clear samples analyzed fluoresced with this laser. The remaining 55 samples analyzed with the Dilor instrument all fit into one of the three polymer types of PC, PMMA or the copolymer of styrene-acrylonitrile. The PC samples could not be further differentiated and there was only one copolymer sample analyzed.

Additional discrimination of the polymer type was possible for the PMMA samples. The PMMA samples could be further classified into four categories by characteristic peaks in the spectra. The Raman spectra of new categories a, b, c and d are shown in Figure 7.

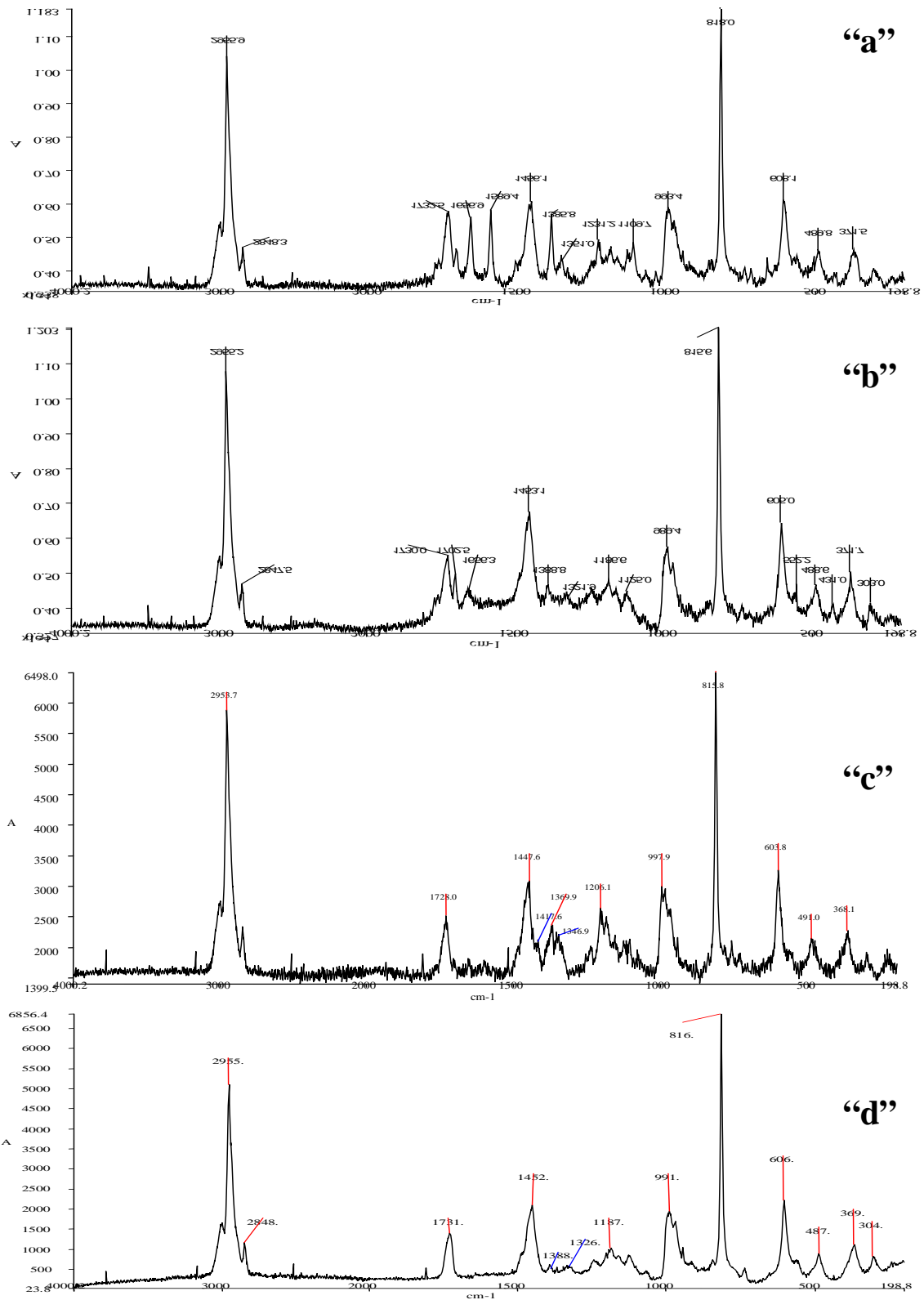


Figure 7: Raman spectra illustrating the four PMMA categories "a", "b", "c", and "d".

The differences appear in the Raman shift region between 2000 Rcm⁻¹ and 1000 Rcm⁻¹. Category “a” contains peaks at 1706, 1656, 1589, 1385, and 1352 Rcm⁻¹. Category “b” contains three similar peaks that are also in category “a” at 1702, 1657, and 1388 Rcm⁻¹, but lacks the peaks at 1589 and 1352 Rcm⁻¹. Category “c” lacks the above-mentioned peaks in “a” and “b” except for the peak at 1354 Rcm⁻¹. Category “c” contains additional peaks at 1419 and 1374 Rcm⁻¹ that are not found in either “a” nor “b”. Category “d” differs only from category “b” in that it lacks the two peaks at 1702 and 1657 Rcm⁻¹. Figure 8 shows this area of the spectrum enlarged for the four different PMMA samples with the peaks of interest labeled.

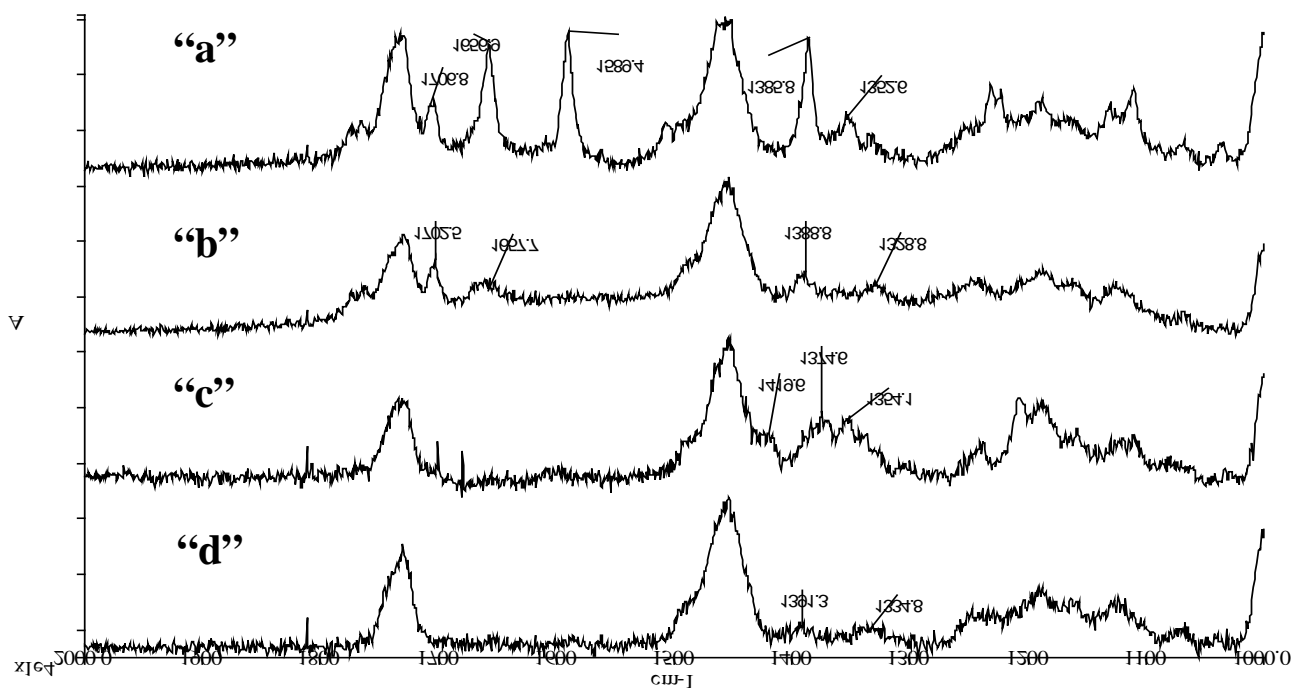


Figure 8: Enlarged area of Raman spectra illustrating different PMMA categories “a”, “b”, “c”, and “d”.

The Kaiser HoloSpec Imaging Raman Spectrograph with the longer wavelength laser of 785 nm was utilized for the analysis of 61 samples. These samples included 23 of the original 27 samples that fluoresced, 19 samples that did not fluoresce, and 19 red samples which were not previously analyzed with the 633 nm laser. Analysis of the 19 non-fluorescing samples was explored to compare the different lasers as well as to see if additional information could be obtained. No additional differentiation was achieved with the longer wavelength laser, but useful spectra from all of the red and smoke gray samples were obtained without any interference from fluorescence. Figure 9 is an example of the interference from the fluorescence when utilizing the shorter wavelength laser and the useful spectrum of the same red sample utilizing the longer wavelength

laser. Even with the longer wavelength laser, two of the three dark red samples continued to have interference from fluorescence and a useful spectrum was not obtained from these samples. One possible explanation is the darker dye could give rise to fluorescence even at the longer wavelength.

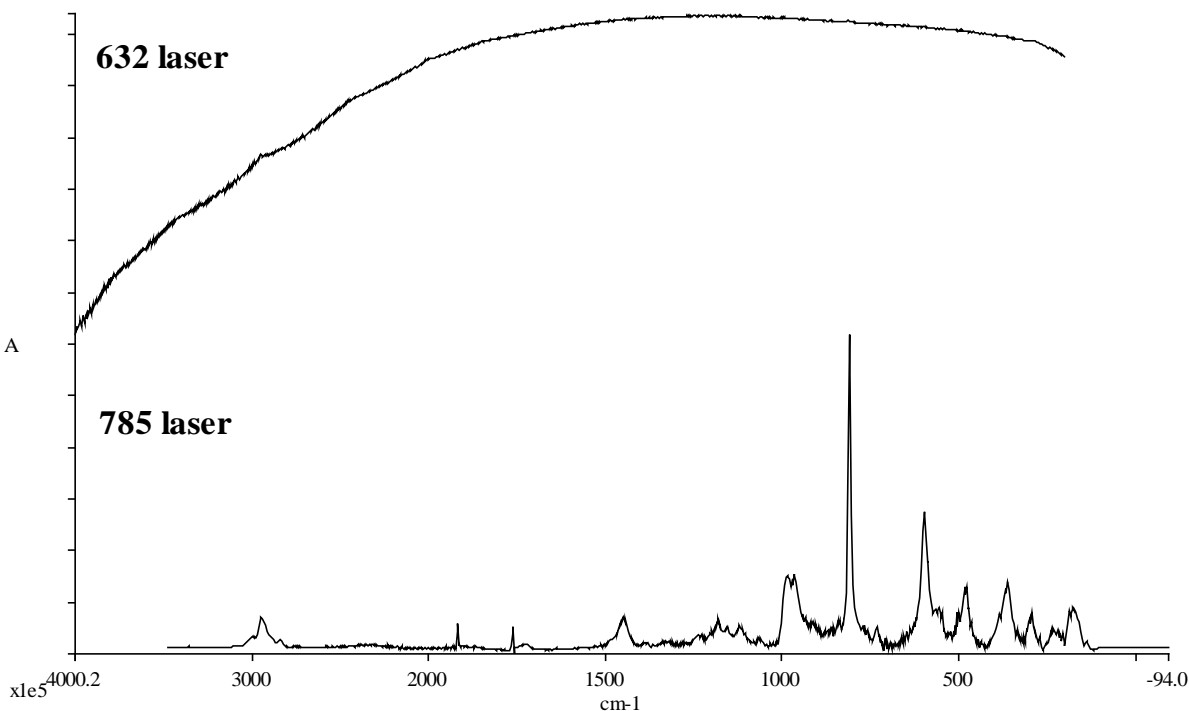


Figure 9: Red sample (#92) analyzed on two Raman instruments with different lasers (633 nm and 785 nm laser).

Within the 19 non-fluorescing samples analyzed using both laser wavelengths, greater efficiency was achieved using the 633 nm laser. Figure 10 illustrates a comparison between two spectra of one polycarbonate sample analyzed on both instruments. The efficiency of the 633 nm laser compared to the 785 nm laser in these spectra is illustrated by the intensity of the peaks in the sample analyzed with the 633 nm laser. Both of the Raman spectroscopy instruments provided useful information but fluorescence prevented the use of the more efficient, shorter wavelength, in some cases.

Discussion

The variation within a single automotive lens was determined and the within-item variations were used to set the criteria to determine any between-item differences. The results show that within-item homogeneity is sufficient to yield useful comparison criteria. It has also been shown that the differences between groups of automotive lenses are large enough to yield good discrimination between the different lenses. These two conditions allow for the analysis of automotive lenses for forensic work.

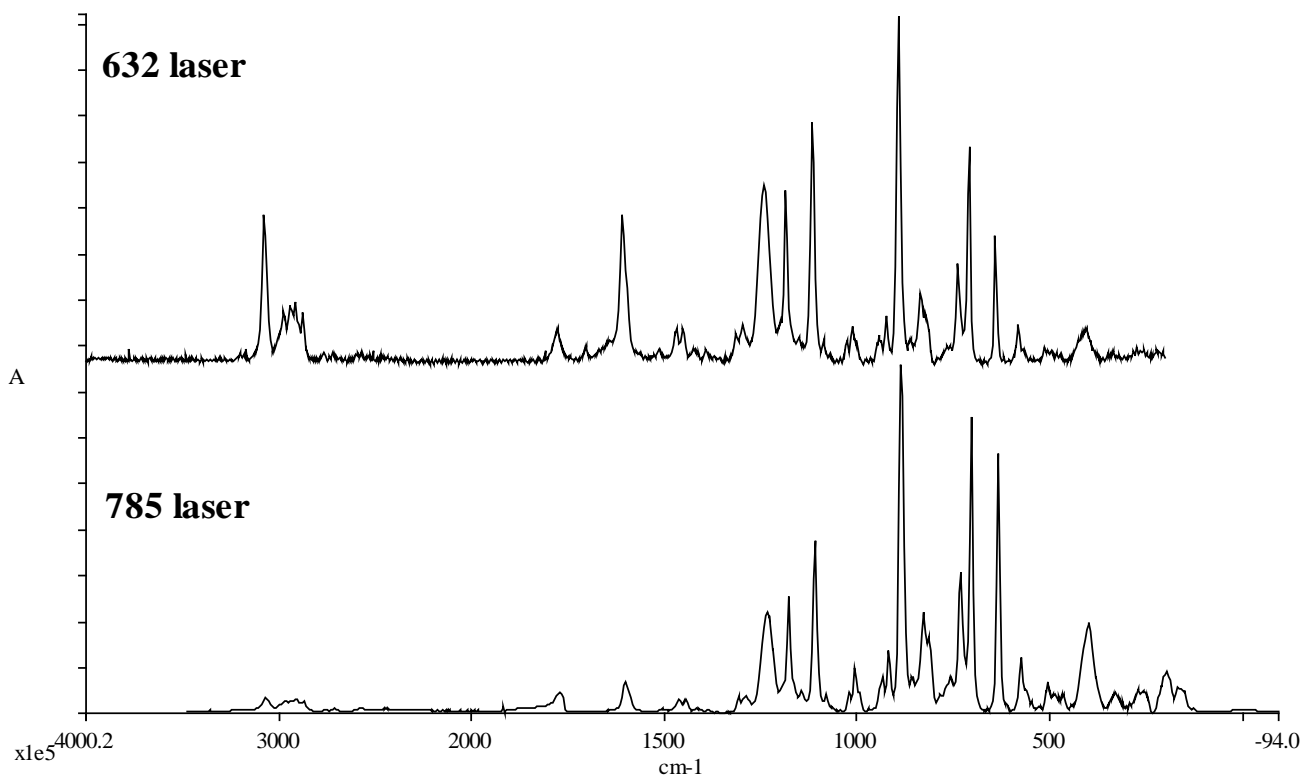


Figure 10: Sample #60 (polycarbonate sample) analyzed with the 633 nm laser and the 785 nm laser.

An analytical technique utilized in forensic work must include the following characteristics in order to be effective and useful: reliability, reproducibility, instrument availability, sensitivity, high selectivity, and sample preservation. Three techniques were employed to determine the homogeneity within a single lens sample and to determine the variations between different lenses. Each of the techniques used exhibited at least some of the above-mentioned characteristics.

FTIR with an ATR attachment is a reliable and reproducible technique in addition to being non-destructive. FTIR spectrometers are found in most forensic laboratories so the availability of the instrument is an advantage of this technique along with the ease of use and short analysis time. The three polymer types of polycarbonate, polymethyl-methacrylate, and a copolymer of styrene-acrylonitrile were differentiated by IR. However, IR could not further differentiate polymers of the same general class. The 225 samples analyzed by IR alone could only be classified into three distinct groups. Utilizing color and FTIR, one could classify the 225 samples into 11 groups.

PGC provided further discrimination in addition to the polymer type. Similar to IR, this analytical method is typically available in forensic laboratories. This technique has been proven to be reliable and reproducible in many different types of analysis, as well as in

this study. The technique is very sensitive and requires a very small sample for analysis. The disadvantage to this technique is the destruction of the sample during analysis. PGC was able to differentiate the samples into the three polymer types and to further differentiate the PMMA samples into seven distinct groups. The 152 samples analyzed by this technique alone could be separated into nine distinct groups. Utilizing color and PGC results, one could classify the 152 samples into 34 groups.

Raman Spectroscopy has become more widely accepted in the forensic community and more available to forensic scientists. It is a very reliable and reproducible technique. The analysis is fast, with little or no sample preparation needed and the sample is not consumed in the analysis. Raman analysis provided not only polymer information, but also further classification of one of the polymer types into additional groups. Raman was not as selective as PGC, but some samples that were not differentiated by PGC or IR could be differentiated by Raman. The Raman technique, by itself, could categorize the samples into the three polymer types and classify the PMMA samples into four additional groups. The 101 samples analyzed by this technique alone could be classified into six distinct groups. Utilizing color and Raman results, one could classify the 101 samples into 20 groups.

By combining the different techniques, there is additional discrimination between the automotive lenses. Since IR did not give any added discrimination compared to PGC or Raman spectroscopy, it was not included in the combination of techniques. Table 1 shows the number of distinct groups each method, along with color, could differentiate the samples into, and the associated fraction of samples that were distinguishable. The number of samples analyzed by each technique is also listed. Time and personnel limitations prevented the application of all the instrumental techniques to all the samples. The sample set for each instrumental technique was determined by selecting representative samples of each polymer type, as well as other properties including color. The table illustrates that IR had the least amount of discrimination while PGC had the most amount of discrimination.

The discrimination power of PGC and Raman in combination is shown in Table 2. The number of samples and the associated fraction of the total that were distinguishable is also listed in Table 2. Ninety-six (96) samples were separated by color and analyzed by both techniques and these samples could be classified into 46 distinct groups. Forty-eight percent (48%) of the samples were distinguishable when analyzed by the combination of PGC, Raman and color. From these results, it is evident that combining the techniques increases the discrimination substantially.

Table 1: Discrimination of the different techniques used to analyze the different colored automotive lens samples.

	Red	Amber	Clear	Sm. Grey	Black	Dk. Red	Totals
IR	2/76	3/73	2/56	2/14	1/3	1/3	11/225
	2.6%	3.9%	3.6%	14.3%	33.3%	33.3%	4.9%
PGC	8/61	9/51	7/20	5/14	2/3	3/3	34/152
	13.1%	17.6%	35.0%	35.7%	66.6%	100%	22.3%
Raman	4/39	5/31	5/15	2/10	2/3	2/3	20/101
	10.2%	16.1%	33.3%	20.0%	66.6%	66.6%	19.8%

Table 2: Discrimination power of combined techniques of PGC and Raman used to analyze the different colored automotive lens samples.

	Red	Amber	Clear	Sm. Grey	Black	Dk. Red	Totals
PGC and Raman	14/37	14/30	8/13	4/10	3/3	3/3	46/96
	37.8%	46.6%	61.5%	40.0%	100%	100%	47.9%

Resin companies provide their product to numerous molding companies. Molding companies can receive the resin from multiple resin companies and they can mold lenses for different vehicle manufacturers. There can be an overlap such as two Jeep Cherokee lenses produced from resin from two different companies. Therefore, no information is available on make, model or year of the vehicle such as with original equipment manufacturer (OEM) paints. There is potential to differentiate some American vehicle lenses from foreign vehicles lenses, however. The PGC polymethylmethacrylate category “C” samples consisted of American made vehicles only. There was a limited number of samples in this study for a definitive determination of country of origin, but this may be of investigative value in identifying an unknown vehicle. Furthermore, Kuptsov [1] reported the co-polymer type of methylmethacrylate with anhydride units to be found in foreign made vehicles only. Kirkwood and Isaacs [2] also report finding polystyrene in foreign vehicles. Neither of these two types of polymers were found in the 225 samples analyzed for this study. Finding one of these polymer types may indicate the lens is from a foreign vehicle.

CONCLUSIONS

Prior to this study, very little research had been conducted on the analysis of automotive lenses for forensic applications. No information was available on the homogeneity of a single lens sample and very little information was available on the variability of a population of lens samples. The results have shown that the measured homogeneity within a single lens and the observed variations between different lenses for the characteristics considered produce excellent means of discriminating between samples. The results have also brought about many additional questions and further research opportunities.

This study characterized a large and diverse set of lens samples by FTIR, PGC and Raman Spectroscopy. Ninety-six samples were separated by color and analyzed using the three techniques and classified into 46 distinct groups.

While the investigative information may be limited, the comparison of a lens sample retrieved from a known source to a recovered lens sample found at a crime scene can be useful forensic evidence, even when no differences are found in physical characteristics and polymer type.

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Appendix 1. All of the samples utilized in this project.

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
1	1988	Buick	Reatta	amber	A1	PMMA	d	
2	1999-2000	Buick	Century	amber	PC	PC	PC	
3	1992-1996	Buick	LeSabre	red	A1	PMMA		d
4	1993-1998	Jeep	Grand Cherokee	amber	B3	PMMA	a	a
5	1993-1998	Jeep	Grand Cherokee	red	C	PMMA		d
6	1999	Jeep	Grand Cherokee	amber	C	PMMA	a	
7	1999	Jeep	Grand Cherokee	amber	C	PMMA	a	
8	1998	Buick	Park Avenue	red	PC	PC		PC
9	1998	Buick	Park Avenue	red	PC	PC		PC
10	1999	Buick	Regal	amber	PC	PC	PC	
11	1999	Buick	LeSabre	clear	PC	PC		
12	1998	Ford	Escort	clear		PMMA		
13	1999	Jeep	Cherokee	amber	C	PMMA	a	a
14	1999	Jeep	Cherokee	red	C	PMMA		a
15	1998	Buick	Riviera	amber	B2	PMMA		
16	1993	Ford	Ranger	red	A1	PMMA	Fluoresced	d
17	1993	Ford	Ranger	amber	C	PMMA	d	
18	1993	Ford	Ranger	clear	C	PMMA	b	b
19	1997	Saturn	SL2	red	A1	PMMA	Fluoresced	d
20	1997	Saturn	SL2	amber	B1	PMMA	a	a
21	1997	Saturn	SL2	clear	PC	PC	PC	
22	1997	Saturn	SL2	amber	B1	PMMA		
23	1999	Ford	Escort SE Wagon	amber	A2	PMMA		
24	2000	Ford	Ranger XL	clear		PMMA		
25	1993	Ford	Base Ranger	amber	A1	PMMA	b	b
26	1999	Chevrolet	Prizm	amber	A2	PMMA	a	a
27	1999	Chevrolet	Prizm	red	B3	PMMA	Fluoresced	
28	1999	Chevrolet	Prizm	clear		PMMA		
29	1999	Toyota	Camry	clear		PC		
30	1999	Ford	Escort Wagon	clear		PC		
31	1993	Ford	Tempo GL	red	A1	PMMA		
32	1983	Ford	Ranger	amber	A1	PMMA	d	
33	1999	Chevrolet	Prizm	amber	A2	PMMA	a	a
34	1999	Chevrolet	Prizm	red	B3	PMMA		
35	2000	Ford	Ranger XL	amber		PMMA		
36	1997	Mercury	Grand Marquis	red	C	PMMA		

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
37	1996	Volkswagen	Golf GTI	red	B4	PMMA		
38	1996	Volkswagen	Golf GTI	amber	B4	PMMA	d	d
39	1996	Volkswagen	Golf GTI	clear	B4	PMMA	Fluoresced	d
40	1999-2000	Jeep	Grand Cherokee	amber		PMMA		
41	1999-2000	Jeep	Grand Cherokee	amber		PMMA		
42	1988	Toyota	Camry LE	red	B4	PMMA		a
43	1988	Toyota	Camry LE	amber	B4	PMMA	a	a
44	1988	Toyota	Camry LE	clear	B4	PMMA	d	
45	1998	Ford	Taurus	red	C	PMMA		a
46	1995	Ford	Explorer XL	red	B2	PMMA		
47	1995	Ford	Explorer XL	amber	B2	PMMA	d	
48	1995	Ford	Explorer XL	clear		PMMA		
49	1999	Toyota	Solara	red	A2	PMMA		a
50	1994	Toyota	Corolla	clear		PMMA		
51	1996	Saturn	SCL	red	B3	PMMA		d
52	1996	Saturn	SCL	amber		PMMA		
53	1993	Honda	Civic	amber	B2	PMMA		
54	1993	Honda	Civic	clear	B2	PMMA	d	
55	1988	Toyota	Camry LE	red	B4	PMMA		
56	1988	Toyota	Camry LE	amber	B3	PMMA	a	a
57	2000	Suzuki	Grand Vitara	amber	B4	PMMA		
58	2000	Chrysler	Cirrus LX	amber	A2	PMMA	a	a
59	1993	Honda	Accord	amber		PMMA		
60	1999	Buick	Century	amber	PC	PC	PC	PC
61	1999	Buick	Century	clear		PC		
62	1993	Ford	Tempo GL	black	A1	PMMA	Fluoresced	
63	1994	Chevrolet	Cavalier	amber	B2	PMMA		
64	1994	Chevrolet	Cavalier	clear		PMMA		
65	Unknown	Audi	5000 C5	red	B2	PMMA	Fluoresced	d
66	Unknown	Audi	5000 C5	amber		PMMA		
67	Unknown	Audi	5000 C5	clear	B2	PMMA	d	
68	Unknown	Audi	5000 C5	red	B2	PMMA	Fluoresced	d
69	Unknown	Audi	5000 C5	amber		PMMA		
70	1986	Toyota	4 Runner	amber	B4	PMMA	b	b
71	1985	Honda	Accord	amber		PMMA		
72	1986	Toyota	4 Runner	red	B1	PMMA		d
73	1986	Toyota	4 Runner	amber	SAN	SAN	SAN	
74	1986	Toyota	4 Runner	clear	B4	PMMA	d	
75	1990	Geo	Prizm	red	A2	PMMA		d

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
76	1990	Geo	Prizm	clear	A1	PMMA		
77	1991	Buick	Regal Limited	red	B3	PMMA		
78	1992	Ford	Crown Victoria	red	C	PMMA		
79	1992	Ford	Crown Victoria	red	C	PMMA		
80	1992	Ford	Crown Victoria	clear		PMMA		
81	1991	Ford	Escort	red	B3	PMMA		
82	1991	Ford	Escort	amber		PMMA		
83	1991	Ford	Escort	clear		PMMA		
84	1990	Geo	Storm	red	B1	PMMA		a
85	1990	Geo	Storm	amber	B3	PMMA	a	
86	1990	Geo	Storm	clear	B4	PMMA	Fluoresced	d
87	1992	Ford	Tempo	red	B3	PMMA		
88	1992	Ford	Tempo	amber		PMMA		
89	1992	Ford	Tempo	clear		PMMA		
90	1990	Acura	Integra	red	B1	PMMA		
91	1990	Acura	Integra	clear		PMMA		
92	1987	Volkswagen	Jetta	red	B2	PMMA	Fluoresced	d
93	1987	Volkswagen	Jetta	amber		PMMA		
94	1987	Volkswagen	Jetta	clear		PMMA		
95	1985	Lincoln	Towncar	red	A1	PMMA		d
96	1991	Saab	900 S	amber	B4	PMMA	a	a
97	1991	Saab	900 S	clear	B4	PMMA	d	
98	1991	Geo	Storm	red	B1	PMMA		
99	1991	Geo	Storm	amber	B3	PMMA	a	
100	1997?	Mercury	Grand Marquis	clear		PMMA		
101	1996	Volkswagen	Golf GTI	black	B2	PMMA	Fluoresced	
102	1991	Geo	Storm	clear	B4	PMMA		
103	1988	Lincoln	Towncar	red	A1	PMMA		d
104	1995	Pontiac	Sunfire	red	A1	PMMA		
105	1999-2000	Jeep	Grand Cherokee	clear		PC		
106	1999-2000	Jeep	Grand Cherokee	clear		PC		
107	1988	Buick	Reatta	clear	PC	PC	PC	PC
108	1998	Buick	Park Avenue	clear		PMMA		
109	1993-1998	Jeep	Grand Cherokee	clear		PMMA		
110	1993-1998	Jeep	Grand Cherokee	amber	C	PMMA	a	a
111	1993-1998	Jeep	Grand Cherokee	clear	C	PMMA		
112	1998	Buick	Park Avenue	clear		PC		
113	1998	Buick	Park Avenue	red		PMMA		

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
114	1999	Buick	Regal	clear		PC		
115	1999	Jeep	Cherokee	clear		PMMA		
116	1993	Honda	Accord	clear	A2	PMMA	d	
117	1993	Honda	Civic	red	A2	PMMA		
118	1993	Honda	Civic	amber	A2	PMMA		
119	1993	Honda	Civic	red	A2	PMMA	Fluoresced	d
120	1993	Honda	Civic	amber	A2	PMMA		
121	1990	Toyota	Celica	amber	B3	PMMA	a	a
122	1990	Toyota	Celica	clear		PMMA		
123	1989	Mercedes	300SE	red	B3	PMMA		
124	1994	Toyota	Corolla	clear	B4	PMMA	a	
125	1989	Mercedes	300SE	amber	B2	PMMA	d	
126	1989	Mercedes	300SE	clear		PC		
127	1999	Mercedes	E430	red	B4	PMMA	c	
128	1998	Chevrolet	Prizm	red	B3	PMMA	c	
129	1998	Chevrolet	Prizm	amber		PMMA		
130	1999	Acura	3.2TL	red	A1	PMMA		
131	1999	Acura	3.2TL	amber	A1	PMMA		
132	1998	Chevrolet	Prizm	red	B3	PMMA	c	
133	1998	Chevrolet	Prizm	amber		PMMA		
134	1998	Chevrolet	Prizm	clear		PMMA		
135	1999	Dodge	Intrepid	red	C	PMMA	Fluoresced	d
136	1999	Dodge	Intrepid	amber	C	PMMA		
137	1999	Dodge	Intrepid	clear		PMMA		
138	1999	Mercury	Mountaineer	red	B3	PMMA	c	
139	1999	Mercury	Mountaineer	amber	B2	PMMA	a	
140	1999	Mercury	Mountaineer	clear	B2	PMMA		
141	1998	Ford	Ranger	red	B3	PMMA	c	
142	1998	Ford	Ranger	amber		PMMA		
143	1998	Ford	Ranger	clear		PMMA		
144	1999	Acura	3.2TL	clear	B1	PMMA		
145	1989	Mercedes	300SE	red	B1	PMMA	Fluoresced	a
146	1999	Dodge	Intrepid	dk. red	C	PMMA	Fluoresced	Fluoresced
147	1999	Mercury	Mountaineer	dk. red	B3	PMMA	Fluoresced	Fluoresced
148	1989	Toyota	Camry	red		PMMA		
149	1989	Toyota	Camry	amber		PMMA		
150	1989	Toyota	Camry	clear		PMMA		
151	1989	Toyota	Camry	red	A1	PMMA		
152	1989	Toyota	Camry	amber	A1	PMMA		
153	1991	Honda	Civic DX	red		PMMA		

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
154	1991	Honda	Civic DX	amber		PMMA		
155	1994	Geo	Metro	red		PMMA		
156	1994	Geo	Metro	clear	PC	PC		
157	1994	Nissan	Sentra	red	A1	PMMA	Fluoresced	d
158	1994	Nissan	Sentra	amber	A1	PMMA		
159	1994	Nissan	Sentra	clear		PMMA		
160	1997	Geo	Metro	red		PMMA		
161	1997	Geo	Metro	clear		PC		
162	1988	Chevrolet	Sprint	red		PMMA		
163	1988	Chevrolet	Sprint	amber	B4	PMMA		
164	1988	Chevrolet	Sprint	clear	B4	PMMA		
165	1992	Mazda	Protégé SE	red	B4	PMMA		
166	1992	Mazda	Protégé SE	amber		PMMA		
167	1992	Mazda	Protégé SE	clear		PC		
168	1992	Mazda	Protégé SE	amber	B4	PMMA	a	a
169	1990	Toyota	Camry Deluxe/MR2	red		PMMA		
170	1990	Toyota	Camry Deluxe/MR2	amber		PMMA		
171	1988	Mazda	626	red		PMMA		
172	1988	Mazda	626	clear	B4	PMMA		
173	1988	Mazda	626	red		PMMA		
174	1997	Mazda	626	red		PMMA		
175	1997	Mazda	626	clear		PMMA		
176	1991	Honda	Civic CRX Si	red		PMMA		
177	1991	Honda	Civic CRX Si	amber		PMMA		
178	1990	Toyota	Corolla	red	A2	PMMA		
179	1990	Toyota	Corolla	clear		PMMA		
180	1991	Toyota	Corolla	red	A1	PMMA		
181	1991	Toyota	Corolla	clear		PMMA		
182	1988	Acura	Integra	red		PMMA		
183	1988	Acura	Integra	amber	B4	PMMA		
184	1988	Acura	Integra	clear		PMMA		
185	1996	Nissan	Sentra/200X	red		PMMA		
186	1996	Nissan	Sentra/200X	amber		PMMA		
187	1988	Nissan	Pulsar	red		PMMA		
188	1988	Nissan	Pulsar	amber	B4	PMMA		
191	1993	Volkswagen	Fox	amber			a	
192	1993	Volkswagen	Fox	clear			d	
193	1990	Dodge	Colt	red		PMMA		
194	1990	Dodge	Colt	amber	B4	PMMA		
196	1988	Mazda	929 Sedan	amber	B4	PMMA		

No.	YEAR	MAKE	MODEL	COLOR	PGC Group	IR	RAMAN	
							633	785
197	1988	Mazda	929 Sedan	dk. red	B4	PMMA	Fluoresced	a
200	1992	Isuzu	4 Dr Rodeo	amber	B2	PMMA		
201	1992	Isuzu	4 Dr Rodeo	clear	B4	PMMA	d	
202	1992	Isuzu	4 Dr Rodeo	amber	B4	PMMA		
203	1988	Volkswagen	Quantum	red		PMMA		
204	1988	Volkswagen	Quantum	amber		PMMA		
205	1988	Volkswagen	Quantum	clear		PMMA		
206	1992	Toyota	Corolla	red	B3	PMMA		
209	1989	Dodge	Daytona	sm grey	A1	PMMA	Fluoresced	d
210	1993	Plymouth	Laser	red	B2	PMMA	Fluoresced	d
212	1992	Dodge	Shadow	clear	A1	PMMA	d	
215	1994	Plymouth	Sundance	clear	C	PMMA	c	
217	1992	Chrysler	LeBaron	red	B2	PMMA	Fluoresced	d
218	1997	Dodge	Neon	red	C	PMMA	Fluoresced	a
220	1991	Dodge	Dynasty	red				d
223	1991	Lincoln	Towncar	red	A1			d
224	1988	Lincoln	Towncar	red	A2			d
229	1989	Ford	Mustang	red		PMMA		
230	1989	Ford	Mustang	amber	B4	PMMA		
231	1989	Ford	Mustang	clear	B2	PMMA	b	b
236	1994	Chevrolet	Caprice	sm grey	PC	PC	PC	
239	1990	Buick	LaSabre	red	A1	PMMA		
242	1989	Buick	Electra Park Ave Ultra	sm grey	A1	PMMA	d	
243	1989	GM	Cadillac	red			Fluoresced	
244	1995	Buick	Century Special	red		PMMA		
245	1995	Buick	Century Special	sm grey	A1	PMMA	Fluoresced	d
246	1994	Oldsmobile	Cultass Ciera S	red	A1	PMMA	Fluoresced	d
249	1989	Chevrolet	Celebrity	sm grey	B2	PMMA	Fluoresced	d
250	1998	Pontiac	Grand Am	red	A1	PMMA		a
251	1998	Pontiac	Grand Am	amber	B2	PMMA	a	
252	1998	Pontiac	Grand Am	clear	B2	PMMA	Fluoresced	d
254	1994	Chevrolet	Lumina	black	B2	PMMA	c	
258	1995	Pontiac	Grand Prix	clear	A1	PMMA	Fluoresced	d
259	1993	Pontiac	Sunbird	red	A2	PMMA		
260	1993	Pontiac	Sunbird	amber	A1	PMMA		
263	1995	Saturn	SC2 Coupe/SL1 Sedan	clear	PC	PC	PC	
269	1995	Volvo	850 Turbo	amber		PMMA		
270	1995	Volvo	850 Turbo	clear	B4	PMMA		
274	1998	Toyota	Avalon XLS	red	B3			c