



Elemental Profiling of Car Paint Residues for Forensic Discrimination Using XRF and EDX

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Abstract

Automotive paint chips represent one of the most frequently encountered forms of trace evidence in vehicular collisions, particularly in hit-and-run cases. Their multilayered structure, distinctive colour formulations and manufacturer-specific compositions make them valuable indicators for associating a suspect vehicle with a crime. The present work focuses on the systematic examination of paint samples collected from the Maruti Suzuki Swift Dzire model car, a vehicle that dominates the Indian automotive market and are therefore commonly implicated in road-traffic incidents. The primary objective is to evaluate the physical appearance of the collected paint samples, investigate the relationship between colour characteristics and elemental composition, analyse the multilayer architecture of the coatings, and estimate the distribution of major inorganic constituents across different layers.

A multi-analytical forensic approach is employed for systematic examination of paint samples. Visual and microscopic observations provided preliminary differentiation of colour, texture and layer thickness. X-ray fluorescence (XRF) spectroscopy enabled rapid, non-destructive elemental profiling, allowing comparison of inorganic pigments and extenders associated with different layers. Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) offered high-resolution cross-sectional imaging and precise elemental mapping of each coating layer, including electrocoat, primer surfacer, basecoat and clearcoat.

Integration of the spectral and structural data revealed significant variations in elemental markers such as Ti, Fe, Zn, Al, Si and Ba, which aided in discriminating between models and even similar colour shades. The results demonstrate the strong evidentiary value of combined physical, microscopic and spectroscopic analyses in characterising automotive paints. The methodology enhances the ability to match questioned paint fragments with known vehicle samples, thereby strengthening forensic reconstruction in hit-and-run investigations. The study reinforces that multi-modal analytical protocols provide robust, reproducible and legally defensible conclusions in forensic paint examinations.

Keywords: X-Ray Fluorescence Spectroscopy, Car Paint Residue, Energy Dispersive X-Ray Spectrometry, Elemental analysis

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1. Introduction

Recent studies indicate a steady rise in vehicular accidents and automobile-related crimes ([National Crime Records Bureau \[NCRB\], 2023](#)). In many such incidents, paint smears or microscopic chips collected from the crime scene serve as critical trace evidence that can be compared with control samples from suspected vehicles. The investigative process is often supported by additional inputs, including CCTV footage, eyewitness accounts, and other physical evidence ([Sinisa, 2023](#)).

Automotive paint systems typically exhibit a multilayer structure—commonly consisting of undercoats, a topcoat, and a clearcoat—each containing pigments, binders, and various additives ([Wontor et al., 2018](#)). While the number of layers and their composition vary across manufacturers, considerable overlap in their chemical makeup frequently complicates the process of discriminating between samples ([Ilicheva et al., 2019](#)). Consequently, analytical techniques such as FT-IR spectroscopy, Raman spectroscopy, SEM-EDS, and pyrolysis-GC/MS have become essential for forensic characterization and individualization of automotive paints ([Edelman et al., 2012](#), [Wilson & Judd, 2019](#)). Recent advances, including the use of prefilters in infrared spectral searches of clearcoat layers, have significantly increased the speed and accuracy of automotive paint identification ([Zieba-Palus et al., 2013](#), [Nishiwaki & Ishi, 2020](#)).

The primary scientific objective of forensic paint analysis is to either corroborate or exclude the involvement of a suspected vehicle in a criminal incident. The physical and chemical characteristics of recovered paint chips provide information about the multilayer paint system of a vehicle, which can be individualistic in nature ([Palmer & Peters, 2014](#); [Wontor et al., 2018](#)). Recently, Kaur and colleagues employed ATR-FTIR spectroscopy to characterize and discriminate automotive paints produced by major Indian manufacturers. Their study followed a systematic procedure for paint identification beginning with preliminary examinations, including optical inspection to assess color, texture, and surface irregularities, followed by solubility tests and spectroscopic analysis ([Kaur et al., 2022](#)).

Among the various analytical tools available, FT-IR and Raman spectroscopy are the most commonly used techniques in forensic paint analysis. Spectral data obtained from different paint layers can be compared with reference samples and archived in databases to generate fingerprint libraries for identification ([Harris et al., 2019](#)). One such global resource is the Paint Data Query (PDQ), maintained by the [Royal Canadian Mounted Police](#) (RCMP), which contains nearly 23,000 OEM automotive paint systems and continues to expand as new entries are added ([Doucet & Foran, 2018](#); RCMP, 2023). These databases assist examiners in comparing questioned paint samples with known standards to establish potential manufacturer and model information.

Similarly, a recent study by [Dawood et al. \(2022\)](#) utilized a combination of FT-IR, Raman spectroscopy, and SEM-EDX to perform a comprehensive multilayer analysis of paint samples from three different automobiles, demonstrating the complementary nature of these techniques in achieving robust discrimination. However, within the Indian context, there remains a notable gap: no extensive forensic database or systematic multilayer characterization study has yet been developed specifically for paints from Indian automotive manufacturers.

Thus, when comparing a questioned paint sample with a control sample, forensic scientists rely heavily on analytical instrumentation to achieve accurate identification. Among these tools,

Fourier Transform Infrared Spectroscopy (FT-IR) and Raman spectroscopy are most frequently employed because they require minimal sample preparation and provide rapid, reproducible results ([Wontor et al., 2018](#); [Zieba-Palus et al., 2013](#)). However, combining these spectroscopic methods with additional analytical techniques can enhance precision and discriminatory power.

Pyrolysis–Gas Chromatography–Mass Spectrometry (Py-GC/MS) is another powerful technique for automotive paint examination, offering high discriminating capability and the ability to differentiate acrylic–melamine topcoats across manufacturing years ([Zieba-Palus et al. 2008](#),). The limitation of this method, however, is its destructive nature.

Conversely, Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM–EDS) and X-ray Fluorescence (XRF) are well-established for high-magnification morphological observation and elemental characterization of paint layers ([Bhoir et al., 2024](#)). Elemental composition obtained from these techniques can be used in chemometric analyses to estimate the likely chemical constituents and improve discrimination between multilayered paint systems ([Duarte et al, 2020](#); [Bhoir et al, 2024](#), [Jha, 2016](#)).

Maruti Suzuki is the largest automobile manufacturer in India and produces several high-demand models, including the Swift, Alto, WagonR, S-Presso, Eeco, Ertiga, Celerio, and Ciaz. In line with the selected journal article, the objective of the present study was to examine the physical appearance of the collected automotive paint samples and to investigate the relationship between color, elemental composition, and layer structure. The study further aimed to characterize the multilayer paint system and estimate the compounds present in each layer through instrumental analysis ([He Jun et al, 2013](#)). Such a scientific approach holds significant potential for establishing the involvement of vehicles in hit-and-run incidents by enabling the depiction of the physical and chemical attributes of automotive paint chips recovered as trace evidence.

2. Materials and method

2.1 Sample collection methodology

Paint chip samples from a Maruti Suzuki Swift Dzire automobile were collected from a local garage in Gandhinagar, Gujarat (India). The collection procedure began with confirming the precise sampling locations on the vehicle surface, followed by cleaning each area with alcohol using sterile cotton to remove surface contaminants. Surgical blades and razor blades were then employed to carefully cut and peel the paint chips without altering their structural integrity. Each collected sample was appropriately numbered, placed in labelled zip-lock bags, and handled with additional care to prevent any further breakage or damage.

A preliminary physical examination of the samples was conducted with the naked eye to document color, surface texture, and the appearance of individual layers. A stereo microscope was also utilized to identify fine structural features and layer morphology.

X-ray Fluorescence (XRF) spectroscopy, a widely used non-destructive elemental analysis method in forensic science, was applied to characterize the inorganic elemental composition of the paint samples. XRF aids in identifying specific elements present in automotive coatings, which is crucial for correlating a questioned paint trace from a crime scene—such as in hit-and-run cases—with a known control sample. The technique functions by irradiating the

sample with X-rays, inducing the emission of characteristic secondary X-rays unique to the constituent elements. This provides an elemental “fingerprint” reflecting the inorganic pigments and fillers. Commonly detected elements in automotive paints include titanium (Ti), barium (Ba), iron (Fe), zinc (Zn), lead (Pb), silicon (Si), and calcium (Ca).

Energy Dispersive X-ray Spectrometry (EDX), a highly informative microanalytical technique, was also employed. EDX combined with Scanning Electron Microscopy enables morphological visualization and elemental identification of micrometer-sized paint fragments with submicron resolution. In the present study, cross-sectional analysis was performed on the selected Maruti paint samples. For this purpose, the samples were embedded in epoxy resin to facilitate precise cross-sectional examination and to allow detailed characterization of individual paint layers.

3. Results and Discussion

3.1 X-Ray Fluorescence (XRF) Data for elemental composition:

The elemental composition of the outer layer of the car paint samples is presented in Table 1 for channel Al-U and the data is plotted in the graph shown in Fig 1(a) and Fig 1(b). For the same sample with channel Na-Sc the elemental composition is presented in Table 2 and the data is plotted in Fig 2.

Table 1: Elemental composition of outer car paint layer (Al-U channel)

Channel	Line	KeV	Net Int.(cps/uA)
Al-U	ZrLa	2.02	0.5842
Al-U	S Ka	2.32	1.7269
Al-U	RhLa	2.74	18.0094
Al-U	TiKaESC	2.78	20.0806
Al-U	RhLb2	2.96	8.8181
Al-U	TiKbESC	3.18	2.3339
Al-U	CaKa	3.7	4.0176
Al-U	CaKb	3.98	0.5625
Al-U	I La	3.98	0.9698
Al-U	TiKa	4.52	1742.2733
Al-U	TiKb	4.94	266.4698
Al-U	PrLa	5.04	1.5584
Al-U	PrLb1	5.52	0.7523
Al-U	PrLb2	5.82	1.0708
Al-U	FeKa	6.4	2.1759
Al-U	CuKa	8.04	0.9249
Al-U	ZnKa	8.62	1.3924
Al-U	CuKb	8.9	0.1533
Al-U	TiKaSUM	9.02	11.2288
Al-U	Ti SUM	9.46	4.0598
Al-U	ZnKb	9.58	0.2089
Al-U	BiLa	10.86	1.5919
Al-U	BiLb1	13	1.1462
Al-U	ThLa	13	0.5224
Al-U	SrKa	14.16	7.6389
Al-U	ZrKa	15.76	63.2021

Al-U	SrKb	15.84	1.2929
Al-U	NbKa	16.6	7.2186
Al-U	ZrKb	17.66	10.9047
Al-U	RhKaC	19.14	35.4926
Al-U	RhKa	20.18	26.2576
Al-U	RhKbC	21.44	6.0067
Al-U	RhKb	22.72	3.2849
Al-U	BaKa2	31.8	2.8057
Al-U	BaKa1	32.2	5.4787
Al-U	BaKb	36.34	0.9891

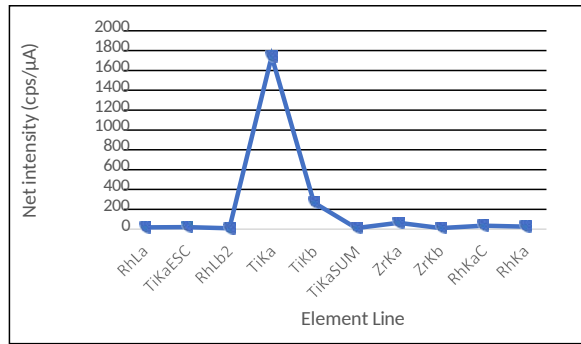


Fig 1(a): Elemental composition of outer car paint layer (Al-U channel) (part 1)

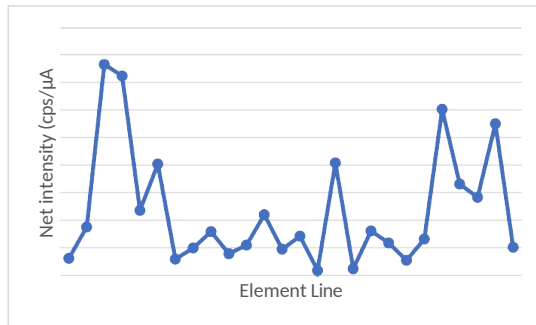


Fig 1(b): Elemental composition of outer car paint layer (Al-U channel) (part 2)

Table 2: Elemental composition of outer car paint layer (Na-Sc channel)

Channel	Line	KeV	Net Int.(cps/uA)
Na-Sc	NdMa	0.95	0.0037
	PrMa	0.95	0.0049
	SiKa	1.73	0.0844
	P Ka	2.01	0.2428
	S Ka	2.31	0.8193
	RhLa	2.71	6.4569
	TiKaESC	2.77	1.0085
	RhLb1	2.83	3.5798

ArKa	2.96	3.7031
TiKbESC	3.18	0.5804
CdLa	3.18	0.0078
CaKa	3.69	1.4481
CaKb	3.98	0.2027
ILa	3.98	0.1339

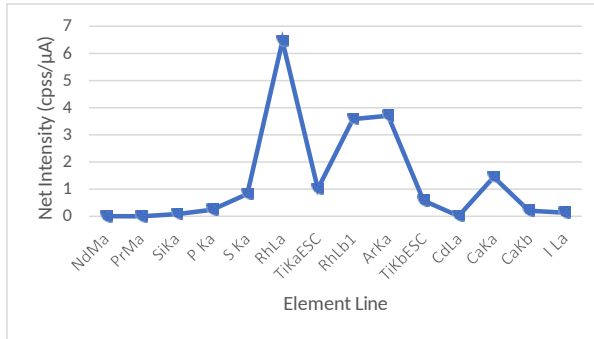


Fig 2: Elemental composition of outer car paint layer (Na-Sc channel)

The elemental composition of the base (inner) layer of the car paint samples is presented in Table 3 for channel AI-U and the data is plotted in the graph shown in Fig 3(a) and Fig 3(b). For the same sample with channel Na-Sc, the elemental composition is presented in table 4 and the data is plotted in Fig 4.

Table 3: Elemental composition of inner car paint layer by XRF (AI-U channel)

Channel	Line	keV	Net Int.(cps/uA)
AI-U	BrLa	1.48	0.0188
	AlKa	1.48	0.1202
	SrLa	1.74	0.1235
	SiKa	1.74	1.251
	ZrLa	2	0.1521
	CaKaESC	2	0.3449
	P Ka	2	0.2618
	PbMa	2.32	1.2726
	S Ka	2.32	0.2619
	RhLa	2.72	12.4073
	TiKaESC	2.78	12.0141
	RhLb2	2.96	7.6402
	K Ka	3.32	6.4269
	K Kb	3.58	0.8998
	CaKa	3.7	34.4907
	CaKb	4.02	5.218
	TiKa	4.52	942.4092
	TiKb	4.94	142.2565
	PrLa	5.04	1.9427
	PrLb1	5.54	0.9441

MnKa	5.9	1.9721
FeKa	6.4	111.9636
MnKb	6.5	0.2676
FeKb	7.06	17.1317
CuKa	8.04	1.6345
ZnKa	8.64	9.2289
CuKb	8.9	0.2582
TiKaSUM	9.04	5.253
PrLLSUM	9.04	0.2284
Ti SUM	9.52	1.6919
ZnKb	9.58	1.4578
PbLa	10.56	7.0764
BiLa	10.84	1.2571
Ti SUM	10.88	1.2453
BrKa	11.9	0.9391
PbLb1	12.64	5.3922
BiLb1	13.02	1.1062
BrKb	13.28	0.0715
RbKa	13.36	1.0026
SrKa	14.16	5.1783
ZrKa	15.76	8.1924
SrKb	15.76	0.8711
NbKa	16.56	1.3559
ZrKb	17.66	1.3342
RhKaC	19.16	13.8206
RhKa	20.2	8.538
RhKbC	21.42	1.944
RhKb	22.72	1.1138
BaKa2	31.84	0.9429
BaKa1	32.2	1.6552
BaKb	36.34	0.3827

Table 4: Elemental composition of inner car paint layer by XRF (Na-Sc Channel)

Channel	Line	keV	Net Int.(cps/uA)
Na-Sc	PrMa	0.95	0.0067
	NdMa	0.95	0.0564
	EuMa	1.09	0.036
	AlKa	1.48	0.0634
	SiKa	1.74	0.6537
	P Ka	2.01	0.2264
	CaKaESC	2.01	0.1217
	S Ka	2.31	0.727
	RhLa	2.7	4.9305
	TiKaESC	2.77	1.0131
	RhLb1	2.82	2.3732
	ArKa	2.96	3.525
	TiKbESC	3.17	0.3771
	CdLa	3.17	0.0523
	K Ka	3.32	2.0618
	CdLb1	3.32	0.0317

K Kb	3.59	0.2886
CaKa	3.69	11.024
CaKb	4.02	1.5448

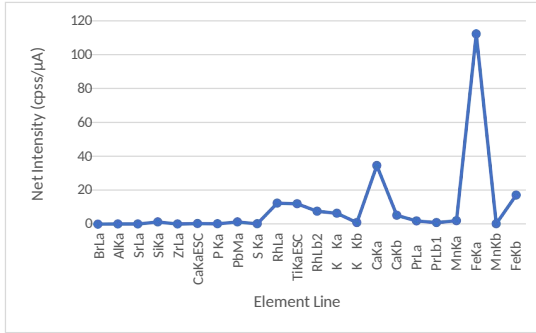


Fig 3(a): Elemental composition of inner car paint layer (AI-U channel) by XRF (Part 1)

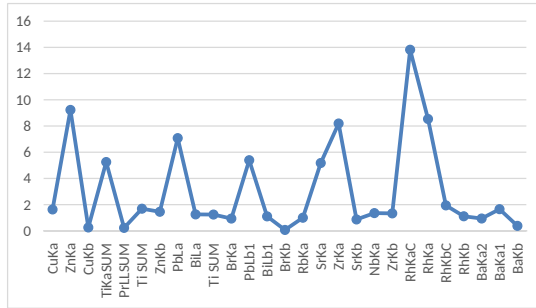


Fig 3(b): Elemental composition of inner car paint layer by (AI-U channel) by XRF (Part 2)

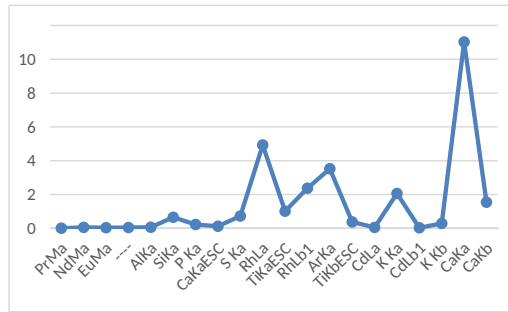


Fig 4: Elemental composition of inner car paint layer by (Na-Sc) channel by XRF

3.2 Elemental Composition from EDX data

The outer car paint residue and the inner car paint residue are also analyzed for the elemental composition through Energy Dispersive X Ray Spectrometry technique and the following plots are obtained for the observed data with respect to Al-U channel (Table 5 and Fig 5 for outer car paint residue, Table 7 and fig 7 for inner car paint residue) and Na-Sc channel (Table 6 and fig 6 for outer car paint residue, Table 8 and Fig 8 for inner car paint residue)

Table 5: Elemental composition of outer car paint layer (Al-U channel) by EDX

Channel	Line	keV	Net Int.(cps/uA)
Al-U	ZrLa	2.02	0.5438
	S Ka	2.32	1.5799
	RhLa	2.76	19.0185
	TiKaESC	2.78	21.1441
	RhLb2	2.96	8.4382
	TiKbESC	3.18	2.5106
	CaKa	3.7	3.931
	CaKb	3.96	0.5503
	I La	3.96	0.9968
	TiKa	4.52	1887.993
	TiKb	4.94	287.8717
	PrLa	5.04	2.1469
	PrLb1	5.54	1.0781
	PrLb2	5.82	1.1789
	FeKa	6.4	1.9752
	CuKa	8.04	1.4911
	CuKb	8.9	0.2472
	TiKaSUM	9.04	12.4317
	Ti SUM	9.44	4.1156
	BiLa	10.86	2.0191
	BiLb1	13.04	1.4538
	SrKa	14.16	7.6781
	ZrKa	15.76	64.953
	SrKb	15.84	1.3127

NbKa	16.6	7.3399
ZrKb	17.68	10.9707
RhKaC	19.14	35.5281
RhKa	20.2	26.3528
RhKbC	21.38	5.6178
RhKb	22.7	3.3297
BaKa2	31.82	2.5801
BaKa1	32.22	4.6574
BaKb	36.36	1.0711

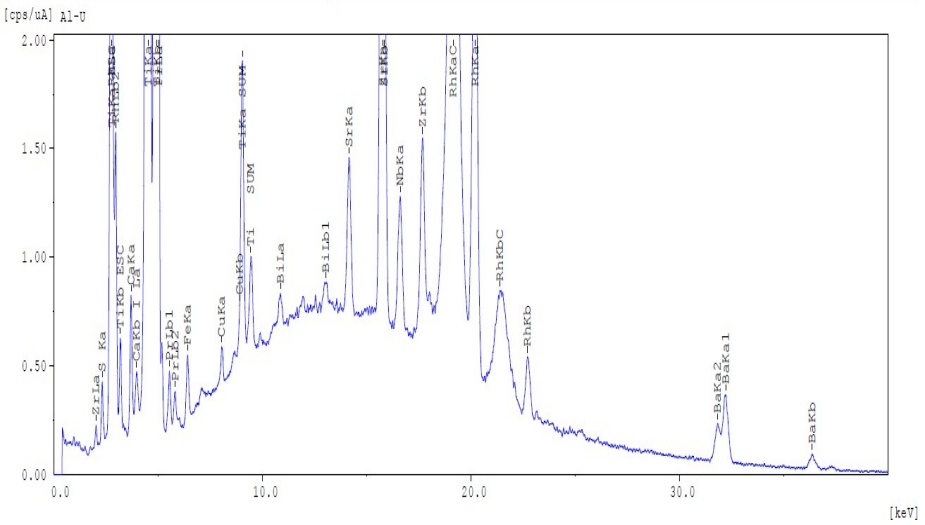


Fig 5: Elemental composition of outer car paint layer (Al-U channel) by EDX

Table 6: Elemental composition of outer car paint layer (Na-Sc channel) by EDX

Channel	Line	keV	Net Int.(cps/uA)
Na-Sc	PrMa	0.95	0.0085
	NdMa	0.95	0.0717
	SiKa	1.75	0.0855
	P Ka	2.02	0.2198
	S Ka	2.3	0.7339
	RhLa	2.71	6.8016
	TiKaESC	2.77	6.4466
	RhLb2	2.96	4.0565
	TiKbESC	3.17	0.7733
	CaKa	3.69	1.3902
	CaKb	3.96	0.2151

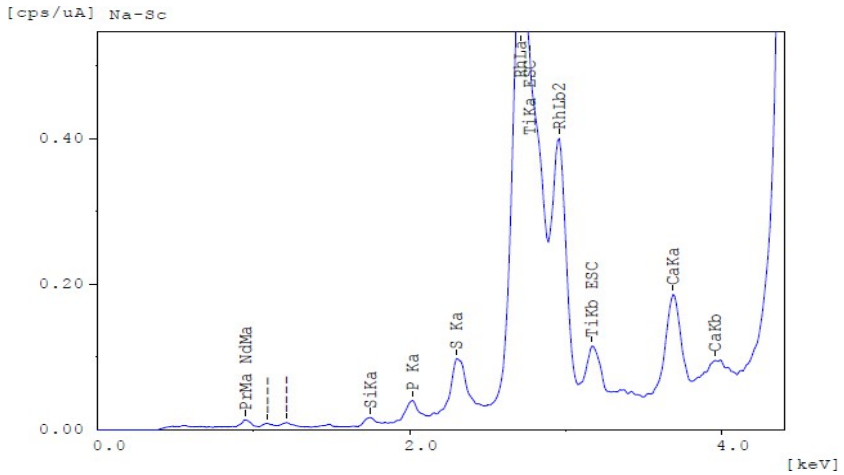


Fig 6: Elemental composition of outer car paint layer (Al-U channel) by EDX

Table 7: Elemental composition of inner car paint layer (Al-U channel) by EDX

Channel	Line	keV	Net Int.(cps/uA)
Al-U	PrMa	0.96	0.0019
	ZnLa	0.96	0.036
	CuLa	0.96	0.0138
	AlKa	1.48	0.1217
	SrLa	1.74	0.1121
	SiKa	1.74	0.7975
	ZrLa	2	0.0767
	P Ka	2	0.5336
	PbMa	2.32	0.6538
	S Ka	2.32	0.5032
	RhLa	2.72	10.7163
	TiKaESC	2.78	9.2888
	RhLb2	2.96	8.2439
	K Ka	3.32	4.3651
	K Kb	3.58	0.6111
	CaKa	3.7	21.6775
	CaKb	4.02	3.2367
	TiKa	4.52	623.7895
	TiKb	4.94	95.6438
	PrLa	5.04	1.768
PrLb1	5.54	0.9049	
PrLb2	5.88	1.0967	
FeKa	6.4	63.7198	
FeKb	7.06	9.6736	
CuKa	8.06	1.4447	
ZnKa	8.64	4.7658	
CuKb	8.9	0.2285	

TiKaSUM	9.04	3.4716
PrLLSUM	9.04	0.4018
Ti SUM	9.48	1.304
ZnKb	9.58	0.7533
PbLa	10.56	3.6036
Ti SUM	10.92	0.8905
PbLb1	12.64	2.52
SrKa	14.16	4.5971
PbLg1	14.8	0.3844
SrKb	15.78	0.765
ZrKa	15.78	3.5782
NbKa	16.62	0.5379
ZrKb	17.66	0.5828
RhKaC	19.16	6.9771
RhKa	20.22	4.7809
RhKbC	21.56	1.0252
RhKb	22.74	0.6149
BaKa2	31.82	0.8256
BaKa1	32.2	1.4043
BaKb	36.34	0.2971

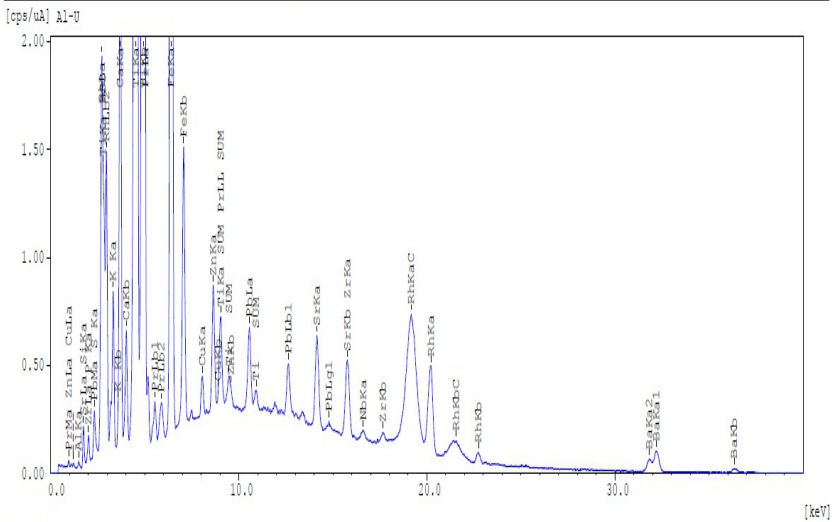


Fig 7: Elemental composition of inner car paint layer (Al-U channel) by EDX

Table 8: Elemental composition of inner car paint layer (Na-Sc channel) by EDX

Channel	Line	keV	Net Int.(cps/uA)
Na-Sc	PrMa	0.95	0.0055
	NdMa	0.95	0.0609
	EuMa	1.1	0.0272
	EuMb	1.2	0.0447
	AlKa	1.48	0.0426
	SiKa	1.74	0.4236
	P Ka	2.01	0.2422

CaKaESC	2.01	0.0786
S Ka	2.31	0.5715
RhLa	2.7	4.4147
TiKaESC	2.77	0.7161
RhLb1	2.83	2.3914
ArKa	2.96	3.6868
TiKbESC	3.17	0.2891
CdLa	3.17	0.1032
K Ka	3.31	1.3362
CdLb1	3.32	0.1316
K Kb	3.59	0.1871
CaKa	3.69	7.0852
CaKb	4.01	0.9981

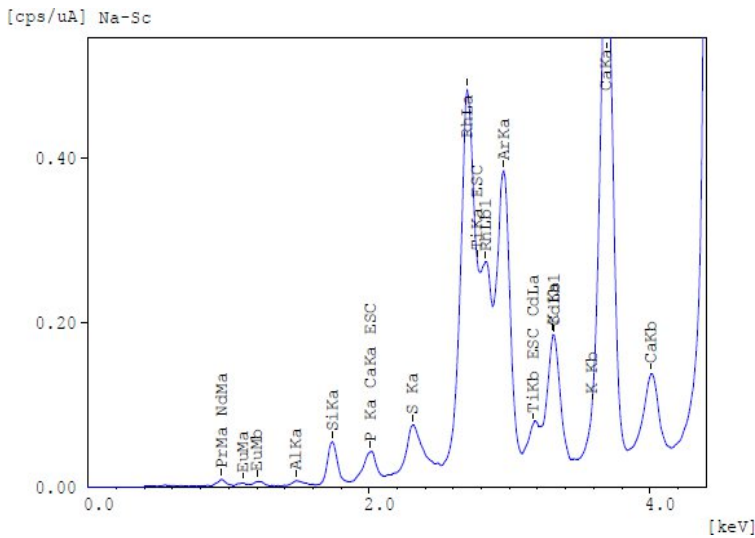


Fig 8: Elemental composition of inner car paint layer (Na-Sc channel) by EDX

4. Summary

The systematic examination of paint samples collected from the Maruti Suzuki Swift Dzire model car have been carried out using X-Ray Fluorescence Spectra as well as Energy-Dispersive X Ray Spectrometry to evaluate the physical appearance of the collected paint samples, investigate the relationship between colour characteristics and elemental composition, analyse the multilayer architecture of the coatings, and estimate the distribution of major inorganic constituents across different layers.

It is evident from the X-Ray Fluorescence Spectra as well as Energy-Dispersive X Ray Spectrometry data that the elemental composition of both the car paint samples (outer and inner layer) confirms the presence of the elements Titanium, Rhodium and Strontium and Zirconium to greater extent, whereas along with Rhodium and Titanium the presence of Calcium and Iron is also detected. The comprehensive elemental profiles of both paint layers, derived from the combined analytical techniques, are thoroughly presented and discussed in this study.

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