30 Automotive Applications of Plastics: Past, Present, and Future

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30.1 Introduction

The modern automobile has seen a remarkable change in the types of materials employed in its manufacture. From being a metallic behemoth in the 1950s, the current automobile has moved toward extensive deployment of alternative lightweight materials. This dramatic shift over the years can be attributed to increasing demands for reducing vehicle weight in order to improve fuel economy and meet legislative and regulatory requirements. Such legislative and regulatory requirements include those on combating climate change by directing automobile manufacturers to increase fuel efficiency and thereby reduce CO_2 emissions. In particular, the Corporate Average Fuel Economy (CAFE) standards by the US Environmental Protection Agency (EPA) set a fleet-wide average of 54.5 miles per gallon by 2025 [1].

In order to meet the CAFE 2025 targets, automakers are currently investigating several approaches, including an aggressive pursuit of lightweighting cars, since a reduction of 10% in vehicle weight can result in the improvement of fuel economy by 6–8% [2]. Lightweighting can be achieved by parts consolidation, material substitution, and design optimization. Among these, material substitution, particularly by plastics, provides lightweight, easily processable, and corrosion-resistant parts for the automotive sector.

Use of plastics in the automotive sector can be traced back to the 1900s. However, its most prominent display was in 1941 when Henry Ford unveiled his plastic-bodied car made from hemp-, sisal-, and cellulose-based plastics [3]. Plastics incorporation in cars has steadily grown over the years from a mere 20 lbs. per car in the 1960s to 357 lbs. in 2010 [4]. Fig. 30.1 shows the comparison of plastic content in cars between the European and American automotive segments from 2003 to 2011 [4,5]. Traditionally, thermoplastics and elastomers [e.g., polypropylene (PP), polyethylene (PE), polyamide (PA), and thermoplastic polyolefin (TPO)] have been used in instrument panels (IP), seats, belts, gaskets, sealing adhesives, and tires. However, thermoset composites, such as carbon-fiber-reinforced plastic (CFRP) and glass-fiber-reinforced plastic (GFRP), have been

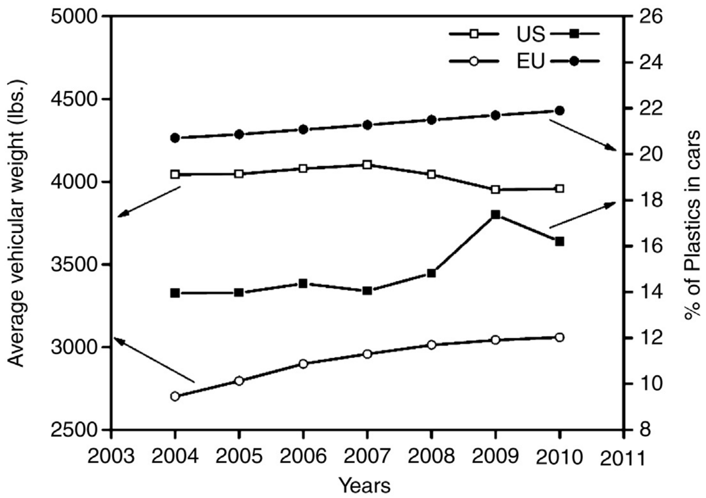

Figure 30.1 Trend of plastic content in European and American cars.

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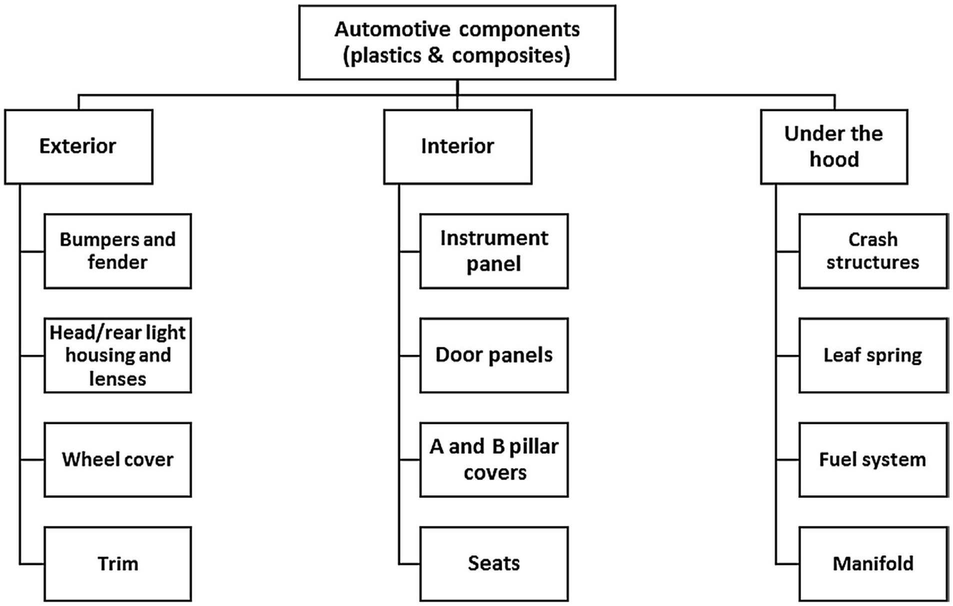

Figure 30.2 Categorization of automobile components made from plastics and composites.

increasingly used in structural components of a car, such as body-in-white (BiW), leaf spring, crash box, and A and B pillars.

This chapter describes the use of plastics and their derivatives (viz., composites) in several automotive components, which are categorized into three segments:

1. Exterior.
2. Interior.
3. Under the hood.

A list of different components in each section is given in Fig. 30.2.

30.2 Exterior Components

Exterior components of a car consist of parts like bumpers, wheels, mirror housings, and lenses as well as the external body structure (body-in-white). In general, exterior structures are expected to possess high strength, high crash resistance, and a smooth, aesthetic surface finish. In addition, given concerns with regard to improving fuel economy and lately about environmental sustainability, exterior components are also expected to be lightweight (to help reduce fuel consumption) and to be recyclable. All these concerns have helped in the flourishing use of plastics and composites in different exterior components; a brief description of such use for important exterior components is given next.

30.2.1 Bumpers

Mounted on both the front and rear sides of a car, bumpers act as shields by helping prevent and/or minimize damage to the car body caused by low-speed collisions. Bumpers are crucial, as they help protect car parts critical for safety reasons (e.g., headlights, taillights, etc.), as well as parts too costly to repair on being damaged (e.g., hoods, fenders, exhaust and cooling systems, etc.). Their importance can be gauged from the fact that in 2008 more than $6 billion was paid out in insurance to cover claims up to $4500—a figure indicating damage caused by low-speed collisions [6]. A bumper assembly consists of three parts: outer plastic fascia to control air flow and ensure aesthetics; energy-absorbing material, usually plastic, to bear a part of the shock impact; and a reinforcement bar/beam, typically made of steel, aluminum, or fiber-reinforced composite, in order to protect the car body by absorbing the crash energy [6,7]. Fig. 30.3 shows typical front-side bumpers for a car.

Typically in the United States, bumpers—front and rear—are expected to adhere to the standard 49 CFR Part 581 set by the National Highway Traffic Safety Administration [8]. As per this standard, passenger cars are subjected to barrier tests at vehicular speeds of 2.5 mph on full bumper width, followed by subsequent pendulum impact tests at vehicular speeds of 1.5 mph on full width and corners, with the pendulum impacting the vehicle at heights of 16–20 inches [8,9]. Bumpers are expected to withstand such

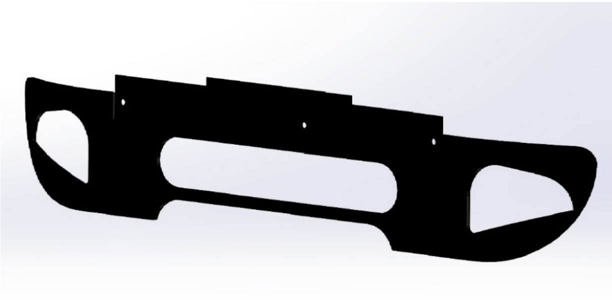

Figure 30.3 Front-side bumpers.

impact without any damage to the car body, though no such restriction is applied with regard to damage to the bumper itself. In Europe, vehicles are also expected to meet additional standards with regard to safety of pedestrians, which limit their protrusion [9].

In a good bumper system, the energy-absorbing medium withstands the impact and absorbs the crash energy to limit damage to the car. In addition, a good bumper system also possesses sufficient resilience and deformability, thereby restricting damage to the bumper itself. Bumpers are also expected to meet additional requirements currently, such as contributing to lightweighting of vehicles to improve fuel economy and reduce environmental pollution, as well as contributing to vehicle aesthetics and being recyclable [9–11].

The three bumper components thus require different materials to suit their necessary properties. About 40–50 years back, high-strength steels were used in making bumper beams due to their high tensile strength (~1500 MPa) and were coated with a chromium finish [9]. With issues like high costs and persistent problem of corrosion associated with steel, efforts were made to use aluminum as a replacement on account of its lower density; such efforts were, however, marred by aluminum's higher costs [12]. Focus has thus shifted to the use of plastics/polymer composites, which possess several advantageous properties: high corrosion resistance, pleasing aesthetics, light weight, ease of design, greater amount of shock energy absorption, and ease of manufacturing by use of injection molding – a process economical for large volumes of car production [11].

Various plastic materials have gained prominence with regard to use in different bumper components. For bumper fascias, polypropylene (PP), polyurethane (PUR), and polycarbonate (PC) remain the three major materials of use, as they have low density, good strength, and stiffness, characteristics that ensure they stick to the bumper body [7,9,11,13]. PP, PUR, and low-density polyethylene (LDPE) remain the major materials of use for mechanical energy absorbers, mainly as foams, though thermoplastic polyolefins (TPOs) have also gained prominence in recent times [7,11,13]. Often, these are reinforced with other materials to improve their strength and toughness, thereby improving their shock absorption ability. With regard to bumper beams and reinforcement bars, sheet molding compound (SMC) and glass-mat-reinforced thermoplastic (GMT) have proved to be effective replacements to steel and aluminum, and current research is focusing on replacing these with carbon-fiber-reinforced plastic (CFRP) on account of the latter possessing better mechanical properties and offering scope for as much as 66% reduction in weight [9,14]. Table 30.1 lists the mechanical properties of materials preferred for use in bumpers.

In addition to these materials, attempts have been made for using thermosets prepared through reaction injection molding in bumper fascias due to their crashworthiness at lower temperatures, though their use is impacted by issues with recyclability [10,11]. Higher-volume cars in Europe have made efforts in the past toward disuse of the reinforcing beam by using PP copolymers and TPO blends for the bumper cover without using any reinforcing beam [22]. Efforts are also under way toward recycling damaged or otherwise-replaced bumpers to make new bumpers, with Ford and Toyota having taken the lead in this direction [23]. Plastics have also been used as adhesives to ensure good bonding between the three parts of the bumper, as has been done by Volkswagen in its Golf, Jetta, and Bora models in Mexico [11].

30.2.2 Wheel Covers

In the 1920s, hubcaps were used to protect only the center hub containing the wheel bearing from dust, dirt, and moisture while ensuring that grease packed in the wheel bearing did not spill out. In the 1930s, hubcaps were replaced or supplemented by wheel covers, which were disk-like in shape (Fig. 30.4) and covered the entire wheel except for the rims, and are still in use [24]. Wheel covers perform additional functions of protecting wheel nuts and bolts from corrosion and from falling off in case they loosened, along with giving the wheel an aesthetically decorative appearance and featuring the logo of the car manufacturer [24–26]. In most cases, wheel covers (as shown in Fig. 30.4) are secured to the wheel using either retention clips or retention wire, usually made

Table 30.1 Mechanical and Other Important Properties of Bumper Materials

Material	Density (g/cm^3)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Impact Strength (J/m)	References
Steel	7.8	648	206		[15]
Aluminum	2.7	234	69		[15]
PP	0.9–0.95	33	1.4	27–100	[16,17]
LDPE	0.91–0.93	8–12	0.2–0.4	No break	[17]
PUR	1.12–1.24	3.4–24.6	0.4–31.6	58.7–800.7	[17,18]
PC	1.20–1.31	60	2.5	800	[16]
ABS—high impact	1.02–1.04	24–45	1.38–2.42	163–436	[17]
TPO	0.88–0.98	4–17	0.008–0.113	No break	[19]
SMC (UP-GF25)	1.7–2	65–80	8.5–12.5	6,000–9,000	[17]
SMC (UP-GF50)	1.85–2	124–204	12.2–19.1	12,000–20,000	[17]
GMT (30 wt.% PP)	1.1–1.6	40–70	5.2–8.0		[20]
CFRP (PC reinforced with 30% carbon fiber)	1.31	170	16	100–130	[21]
CFRP (PA 6 or 66 reinforced with 30% carbon fiber)	1.26	230	19	80–100	[21]

Figure 30.4 Wheel cover.

of steel, after ensuring that hubcaps inside them are fully seated to the wheel [25].

Hubcaps or wheel covers are exposed to all kinds of environmental and driving conditions, whether in extreme heat, cold or humid atmosphere, or on poor or good quality roads. Under these conditions, they are expected to remain undented, not come off easily, not rust off, and be easily paintable to ensure a smooth, aesthetically appealing surface [27,28]. They are also expected to be light, as lighter hubcaps are less likely to fall off in case of driving on bad roads [24]. To meet these requirements, hubcaps were initially made from nickel/chrome-plated brass until 1915, followed by aluminum hubcaps in the 1920s and subsequently chrome-plated stainless-steel hubcaps and wheel covers from the 1950s to the 1970s [26]. All these hubcaps faced a variety of issues, including their higher susceptibility to corrode on being scratched or driven on salty roads, or to come off easily from the wheel on account of their greater weight due to higher density [27].

Since the 1970s, plastics have become the prime material for making wheel covers on account of their advantageous properties: high resistance to corrosion and different kinds of extreme environments (salt, chemicals, heat, or cold), being lightweight, high dimensional stability, and being easily paintable [27–29]. The predominant plastic of usage is acrylonitrile butadiene styrene (ABS) in both pure and blended form; other plastics used include acrylonitrile styrene acrylate (ASA), thermoplastic polyolefin (TPO), and mineral-filled polyamide 6 (PA6) [11,24,28]. Preference for ABS in particular stems from its ruggedness, durability, and high strength, as well as its excellent resistance to breaking, scratching, or chipping [24,27]. In addition, all aforementioned plastics can be easily chrome- or silver-plated

Table 30.2 Materials Used for Wheel Covers by Various Companies/Car Models [28]

Company or Car Model	Material Used
Mercedes-Benz	30% Mineral-filled PA6, ASA (Vito)
SEAT	30% Mineral-filled PA6
Ford Mondeo, Fiesta, Nissan, Toyota, Renault	ABS or ABS/PC blends

or painted with a 2-step base coat/clear coat finish along with external addition of flex agents to improve their appearance and durability against a host of extreme environments [25].

Table 30.2 highlights the plastics materials used for wheel covers in various car models. Use of ASA in the Mercedes-Benz Vito is due to its better stability against ultraviolet (UV) radiation, which removes the need for chrome plating or painting [28].

30.2.3 Head/Rear Light Housing and Lenses

Headlights are lights installed in the front portion of a car, and are meant to enable the car's driver to see all kinds of moving vehicles, pedestrians, and traffic signals before her or him in darkness, as well as signal other drivers on the road of the car's presence and its actions—size, speed, and direction of movement. Taillights are installed in the rear portion of the car and are important for those behind the car to know about its presence and actions. Both sets of lights are extremely important at night and in poor weather conditions, and are housed in housings that also contain a reflector, a rim, a socket, and a lens [28,30]. Sockets hold the bulb and connect it to the battery, while reflectors magnify the brightness of the headlight beam and the lens focuses and diffuses the beam to ensure that the driver has a good view of the road while driving [30].

Head/rear light housings are expected to ensure a clear and visible light beam. They are expected to protect the lighting arrangement from dust, dirt, and moisture and to function in all kinds of extreme environments. In modern times, given the high amounts of heat generated by headlight systems, it is critical that headlight housings are also heat-resistant [10,28]. With regard to lenses, headlight lenses are expected to have high strength and fracture toughness; have high resistance to scratches, external impact, and heat/temperature as well as different kinds of environmental conditions; be easy to shape and design; possess good optical properties and be transparent; remain unaffected on facing UV radiation; and be inexpensive [10,11,13,28]. In addition to all these requirements, headlights and headlight assemblies are expected to adhere to the standards set under the Federal Motor Vehicle Safety Standard 108 (FMVSS 108) [31].

Until the 1980s, the predominant material of use for housings and optical parts—both headlight and taillight—was glass due to its optical transparency and being inexpensive [32]. However, glass also had major disadvantages. Its lower design freedom made it difficult to shape it to suitable design [10]. Its low resistance to scratches and impacts made it prone to damage in case of accidents; broken glass in turn could blow out tires or even fly toward the car, causing damage to it or its occupants [11,32]. In addition, like for other parts, efforts were being made towards lightweighting of housings, lenses, and reflectors to improve fuel economy. All these factors led to a major shift toward plastics for both components, with the United States and Japan making a shift in the 1980s, and Europe doing the same in the early 1990s [28]. Such a shift brought a number of advantages: ease of design and shaping, high impact resistance, significant potential for lightweighting, better resistance to heat generated by lamps (applicable in the case of headlights), and reduction in production cost due to use of injection molding at high volumes [10,11,13,28,33].

With regard to their use in lenses or reflectors, plastics or blends are expected to conform to the SAE J576 standard with regard to their physical and optical properties; details are given in Table 30.3. These also have to conform to standards set for lighting in FMVSS 108, for which details are listed in Table 30.4. Based on these standards, the Automotive Manufacturers Equipment Compliance Agency (AMECA) publishes the list of acceptable materials for making optical parts (lenses, reflectors) in cars on a regular basis [34,35].

To meet the aforementioned standards, plastics used in lenses and reflectors have to meet some critical requirements. First, they should be free of bubbles and foreign particles greater than 0.002 in. in size; at maximum, only one embedded particle larger than 0.008 in. is allowed for every 20 cm^3 of material [38]. Second, since the surface is required to have a smooth finish, surface imperfections of only 0.004–0.010 in. are permitted for every square foot [38].

Table 30.3 SAE J576 Testing Details [36,37]

Test	Requirement
Material thickness	Plastic is tested at three different thickness levels: 1.6 mm (0.063 in.), 3.2 mm (0.125 in.), and 6.4 mm (0.250 in.). In addition, a fourth thickness level of 2.3 mm (0.090 in.) is also suggested for testing.
Heat test	Samples will be placed for 2 h in a circulating air oven at a temperature of 175 ± 5°F, or roughly 79 ± 3°C. Samples should not show any significant change in either shape or general appearance when compared with the unexposed control samples. Additionally, trichromatic coefficients of the samples in the stated thickness ranges should also conform to SAE J578 standards.
Outdoor weathering	A sample of each thickness is tested at Florida (warm, moist climate) and Arizona (warm, dry climate), such that the exposed upper sample surface is at 45° to horizontal facing south, with a minimum area of 32 cm^2 (5 in^2) for a period of 3 years, and the protected surface for a period of 6 consecutive months starting in May. During exposure to outdoor weathering, samples are cleaned once every 3 months by washing with mild soap or detergent and water, and then rinsed with distilled water, without any rubbing.
Haze	After exposure of each sample to outdoor weathering, haze measurements are to be conducted as per ASTM D1003-61 standard. For plastics used in lamp lenses, haze should not be greater than 30%, while for reflex reflectors or lenses used in front of reflectors, it should not be greater than 7%. In addition, plastics used for headlights (excluding cornering lamps) should also not show any deterioration.
Luminous transmittance	After exposure of the sample to outdoor weathering, luminous transmittance of each sample is measured using CIE Illuminant A (2856 K) as per ASTM E308 standard. Compared to the unexposed control sample, luminous transmittance of exposed sample should not change by more than 25%.
Color	Chromaticity coordinates for each sample should conform to the requirements described in SAE J578 standard, both before and after outdoor exposure.
Visual inspections	After exposure to outdoor weathering, exposed sample must not show any physical changes (e.g., color bleeding, delamination, crazing, cracking, etc.) when compared with the control sample.
Minimum number of specimens per material, coating, and color type	For each material, three samples are required for each thickness level, with one of them being the control sample. In addition, two samples are required to perform heat tests for each thickness. In sum, this means five samples per each thickness level for each material.

Table 30.4 Lighting Standards for Car Lamps as per FMVSS 108 [31]

Lighting Device	Minimum Luminous Intensity Required in Any Direction (Referred to as “Required Visibility”) in Candela
Turn signal lamp	0.3
Stop lamp	0.3
Tail lamp	0.05
Parking lamp	0.05

Given the aforementioned standards, two plastics were considered for use in headlights: poly(methyl methacrylate) (PMMA), and polycarbonate (PC), given their transparent nature. PMMA is cheap and highly resistant to UV radiation and to scratches, but lacks impact resistance. In contrast, PC has high resistance to impacts and temperature, combined with its excellent dimensional stability, rigidity, and creep resistance, but has low resistance to UV radiation and abrasions [11,28]. Since it was easier to improve UV and scratch resistance through coatings, PC with coatings (such as on a silicone base) became the preferred material for use in headlight lenses, though issues such as yellowing of the lenses due to

UV radiation persist [11,28,39]. With increasing use of high-intensity halogen lamps in headlights and smaller housings, other materials like polyetherimide (PEI) and poly(*p*-phenylene sulfide) (PPS) are also being used to make headlight reflectors [10,28].

Rear-lamp lenses and reflectors have demanding needs of a different kind: to reflect light in different colors. This has led to the use of multiple-color injection-molding machines for making PMMA lenses, with a strict control on colors used [10,28]. Reflectors for rear lamps are generally made of ABS (pure or blend), or PP in cases where they must be made more cheaply [28]. However, other materials like ASA, PEI, and glass-reinforced plastics can also be used [10,28]. A list of plastics used to make lenses or reflectors in different car models is given in Table 30.5.

With regard to housings, differences exist between those meant for headlights and for taillights. For headlights, it is necessary to have a plastic with high resistance to heat, so plastics reinforced with glass fibers are often used on account of the latter's high temperature resistance and low coefficient of thermal expansion [28]. For rear lighting systems, housings are not required to possess a high resistance to heat, so even ABS (pure or blend) can be used; additional materials used include ASA and PP [10,28]. Table 30.6 lists the optical properties of various plastic materials.

Table 30.5 Plastic Lenses or Reflectors Used in Different Car Models

Car Manufacturer or Car Model	Component and Material Used	References
Ford Puma	Lens: PC	[28]
Ford Ka	Lens: PC Reflector: UP-MD60	[28]
Volkswagen New Beetle	Lens: PC Reflector: electroplated ABS/PC blend, PPS	[10,28]
Mercedes-Benz A-Class	Lens: PMMA/PC Reflector: electroplated ABS/PC blend	[28]
BMW	Reflectors: PEI, PPS	[10]

30.2.4 Body-in-White (BiW)

Body-in-white (BiW) is the name given to a car body's sheet when all its components—barring moving parts (e.g., hoods, fenders, etc.), trims (e.g., glass, seats, etc.), or chassis subassemblies—have been welded together. Usually, BiW constitutes about 27% of a car's curb weight [42], and remains the key determinant of how the car will perform. BiW can be made into two structures: the more common monocoque structure where all body members are carrying load with chassis in-built with BiW and are integrated with each other, and the body-on-frame structure where the frame is the main load-carrying member [43].

BiW is expected to possess a number of significant properties. It must have high tensile strength as well as high stiffness—bending, torsional, static, and dynamic. It must also provide good quality safety both to the car body and to its occupants against crashes of all

Table 30.6 Optical Properties of Selected Plastics

Plastic/ Polymer	Refractive Index	Luminous Transmittance (%)	Relative Haze (%)	Scratch Resistance (Rockwell Hardness M Scale)	Reference
PMMA	1.491	92	2	90	[38,40]
PC	1.586	89	3	50	[38,40]
Polystyrene	1.59	88	3	90	[38,40]
Styrene acrylonitrile	1.57	88	3	75	[38,40]
Cyclic olefin copolymer	1.525	92	2	75	[40]
ABS high heat	1.538	79–90.6	12	20–50	[38,41]

Table 30.7 Properties of BiW Materials

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Reference
Steel	210–1250	340–1520	[46]
Aluminum	90	195	[47]
CFRP		250–585	[48]

kinds—front, rear, side, or even rollover, meeting the Federal Motor Vehicle Safety Standard No. 208 [44]. It should also be able to protect occupants from noise, vibration, and/or harshness (NVH) by absorbing or reducing these conditions. Also, it should be easy to weld and form, as well as be highly paintable and easy to design. It should provide a good surface finish that is smooth, and should also be corrosion resistant. Improvement of fuel economy also necessitates the use of lightweight materials in BiW, as it constitutes a significant share of car's weight; in addition, given environmental concerns in recent times, it is also expected to be recyclable. Given such extensive requirements, only steel and aluminum have been used for making BiW; the former is preferred for its high strength and low cost, while the latter is preferred for its lower density that helps reduce car weight [42,45]. Table 30.7 details the materials generally used for making BiW, along with their properties.

Amid the raging debate on the suitability of aluminum as a replacement for steel in BiW, a major transformation has occurred in the form of the entire BiW being made up of carbon-fiber-reinforced plastics (CFRPs) in BMW's i3 model, a fully electric car [49,50]. To study the suitability of CFRP as a material in manufacturing various car parts as well as its potential in lightweighting automobiles, BMW decided to produce a car with main body completely made from CFRP, resulting in the production of BMW i3 at almost one-third of the market cost [49]. CFRP was chosen for its lower density and higher specific strength when compared to both steel and aluminum, as seen in Table 30.1 [51].

The main body of BMW i3 consists of two modules—life module and drive module—with the former made entirely from CFRP and the latter made entirely from aluminum [52]. Since batteries account for a significant share of an electric car's weight and have to be recharged on a frequent basis, CFRP's lower density helps lower the mass of BMW i3, thereby reducing the load on batteries and the requirement for their recharging [49,50]. Moreover, low density and high specific strength of CFRP vis-à-vis steel mean that only 130 CFRP parts have to be joined together to constitute the car's main body compared to an average of 400 steel parts per car [49]. All these features have together meant that as per measurements conducted in Clemson University—International Center for Automotive Research (CU-ICAR), use of CFRP in BiW brought about a reduction of nearly 52% in BiW weight of BMW i3 compared to that of the MINI F56 model, a similar counterpart, highlighting the high potential for lightweighting cars through the use of CFRP.

30.3 Interior Components

Interior components of a vehicle consist mainly of IPs, door panels, and seats; together, these account for the largest share of plastics in a car at 38% [53]. These components are primarily expected to cater to comfort, odor, aesthetic appeal, ergonomic layout, and durability requirements. For example, most interior panels must sport a Class A finish. From a safety perspective, all materials used to make interior components must prescribe to the Federal Motor Vehicle Safety Standard (FMVSS) No. 302, titled "Flammability of Interior Materials." As per this standard, the material shall neither burn nor transmit a flame front across its surface at a rate greater 4 in/min [54]. In addition, interior components are also required to possess fogging [55,56] and acoustic properties [57]. A detailed description of the plastics used for important interior components is given next.

30.3.1 Instrument Panel (IP) or Dashboard

The IP or dashboard embodies many roles in the modern automobile, from contributing to the structural integrity of the vehicle to providing sales appeal. The dashboard is vital as it houses a number of components such as speedometer, fuel gauge, tachometer, odometer, climate control system, and safety features such as airbag housings. IPs can be categorized as hard-touch or soft-touch panels. Hard-touch panels are used in high-volume cars as a base for manufacturing integrated IPs and/or cockpit modules, such that they can support airbags and provide basic functionality. In contrast, soft-touch panels consist of a base-level structural component with an integrated crossbeam and impact-absorbing foams or crash pads [28].

Table 30.8 Requirements for Instrument Panel as per FMVSS No. 201 [60]

Test Details	Requirements as per Standard
Area of IP within head impact area is struck as per the procedure laid out in Standard No. 201 with a head form weighing 6.8 kg and having diameter of 165 mm	The area has a relative velocity of 24 km/h for all vehicles. OR The area has a relative velocity of 19 km/h for vehicles that met the requirements set in Section S5.1 (through airbags) and Section S4.1.5.1(a)(3) (through Type 2 seat belt assembly at right-front designated seating position) of FMVSS Standard No. 208. In this case, head form should not decelerate at a value greater than 80 g continuously for a duration of more than 3 ms.

Figure 30.5 Conventional hard-touch instrument panel.

IPs are expected to have high global and local stiffness, specific dynamic behavior, good strength at high temperatures, and ability to comply with passenger safety requirements during impact. The latter is ensured by integration of energy-absorbing foams at potential human impact points [58]. They are also expected to be resistant to ultraviolet (UV) radiation, given their regular exposure to such radiation [13]. In addition, modern IPs are expected to withstand higher interior temperatures and higher thermal stresses with windscreens growing larger and flatter [59]. In the United States, IPs are expected to adhere to the Federal Motor Vehicle Safety Standard (FMVSS) No. 201 (Section S5.1), which is explained in detail in Table 30.8 [60]. Fig. 30.5 shows a typical conventional hard-touch IP.

Traditionally, IPs were made from several separate components that were painted and held together by a steel supporting beam placed behind the panel [61]. However, the use of steel beams resulted in lack of design flexibility, higher cost, and increased weight leading to higher fuel consumption. Over time, efforts to replace the beam with plastics became successful, with most modern-day panels made from a whole host of different plastics described in Table 30.9. The use of these plastics has enabled manufacturers to fabricate complex designs for accommodating the various integral components in IPs, while leading to a dramatic reduction in both cost and weight.

Use of plastics in IPs faces major challenges as they undergo photo-degradation on exposure to ultraviolet (UV) radiation ($\lambda \sim 300$–360 nm) [13]. This can be prevented by applying coatings to protect the underlying polymer or other substrate from mechanical and chemical stress as well as any other environmental impact. Such coatings can be categorized as UV absorbers, free radical terminators, or quenchers [13]. UV absorbers work by absorbing UV radiation and preventing the formation of free radicals, while free radical terminators inhibit the propagation of photo-degradation reactions, and quenchers prevent the activation of free radicals.

The IP also houses the steering wheel, switches, bearings, and steering columns. These are typically made from molded or pigmented vinyl ester resins or from reaction injection-molded (RIM) pigmented urethane, which are used due to their high mechanical and thermal stability [63].

30.3.2 Door Panels

Door panels serve as an interface between the interior of the car and the inner workings of the door, and between vehicle occupants and the door. They are expected to meet a variety of design specifications regarding safety, aesthetics, and functionality. In addition, they are expected to continue the material theme of the dashboard and pillars while concealing intricate electrical and mechanical components for operating locks, windows, and other features. The door panel has evolved from a simple two-part system of latch and simple winding mechanism to a more sophisticated enclosure. Doors currently have an inner full-width panel consisting of electronic windows, central locking system, and speakers. These panels typically consist of a foamed core covered with either textiles or plastics. Fig. 30.6 shows a conventional car door panel.

Door panels are expected to meet one of the toughest sets of requirements among interior car components. These panels should be designed to withstand and channel loads into the body of the car while

Table 30.9 Plastics Used in Instrument Panels/Dashboards

Plastic	Reasons for Use	Advantages	References
Polypropylene (PP)	High heat resistance, superior to that of polyethylene (PE) Low cost	Helps maintain a cohesive material theme throughout the interior of the vehicle through use of the same base material in different parts like pillar covers, door panels, and IP. As these parts are in constant contact with each other, use of PP enables them to withstand temperature cycles.	[28]
Thermoplastic olefin (TPE-O or TPO)	Low gloss and density High stiffness and toughness Recyclability	Can be easily injection-molded to form various parts in IP—is used more as skin of PP foam in recent vehicles.	[28]
Acrylonitrile butadiene styrene (ABS)	High impact strength and toughness due to rubber from polybutadiene High resistance to chemical stress cracking due to acrylonitrile Easy processability	High degree of versatility as ratio of A, B, and S can be varied, enabling its use in pillars, IP, and door panels.	[28]
ABS/PC blend	Can be easily processed High heat deflection temperature Can produce many different surface types	Available in four different grades: general purpose, high flow, blow molding, and low gloss. Currently used in Jeep Cherokee and Audi A4 (B5) models.	[28]
Polyvinyl chloride (PVC) (often used with ABS)	High price/property ratio High flame retardancy	Can be blended with ABS to form sheets used for making skin of IP covers, though TPO can be an equally good alternative.	[62]
Styrene-maleic anhydride copolymers (SMA)	Excellent heat resistance compared to typical polystyrenes	Can be reinforced with glass fiber to enhance heat resistance, and with rubber to prevent plastic from becoming too brittle. Are used in IP in BMW 3 and 5 series and in Fiat Coupé, covered with polyurethane foam.	[63]
Polyurethanes	High impact strength under low temperatures High temperature stiffness, preventing heat sag	Polyether polyols have been used to form instrument and door panels via reaction injection molding (RIM). Energy-absorbing polyurethane foam, with semiclosed cell structure, has been added to pillars and door panels, enabling better protection of passengers in case of side impacts.	[28]

being thin (<2 mm). These loads could be horizontal and vertical in nature, like the force applied on opening or closing doors while leaning/resting on them or when stepping on the armrest to access the roof [64]. An additional consideration is their ability to protect occupants from injury during a side collision, where most injuries are inflicted on the chest and pelvis as a result of crushing force of the door [65]. Federal Motor Vehicle Safety Standard No. 214 therefore sets forth directives to manufacturers in order to limit this injury [66]. It states that the Thoracic Trauma Index (TTI) should not exceed 85 g for a four-door or 90 g for a two-door passenger car. This test is performed at impact velocity of 53 km/h, which accounts for 90% of side impacts in North America [67].

Materials used as door panels must have high dent resistance. The dent force of a material can be calculated using (Eq. 30.1) [68] as:

$$P_t \propto t(\sigma_p)^n \tag{30.1}$$

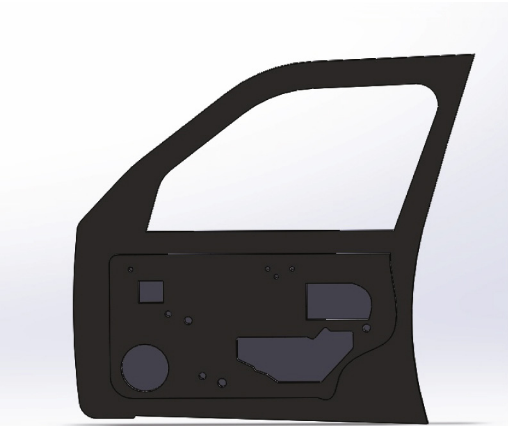

Figure 30.6 Conventional automotive door panel.

where P_t represents the dent force, t stands for material thickness, σ_p represents the flow stress under strain of some forming parts, and $n \sim 0.4$.

Conventionally, door panels as shown in Fig. 30.6 consisted of polyvinyl chloride (PVC) or polyurethane foamed core with appropriate textile fabric coverings. Subsequently, there was a shift toward thin-wall moldings of ABS or PP backed by textiles in order to manufacture a contour-backed panel with recesses. This is primarily because integrated injection-molded door panel assemblies reduce the need for other energy-absorbing materials, resulting in cost reduction for manufacturers due to simplification of door construction. Currently honeycomb-based plastics are attracting attention due to their tougher, lighter, and better acoustic properties. Table 30.10 gives a list of plastics used by various car manufacturers in making door panels.

30.3.3 A and B Pillar Covers

Structural pillars are vital, as they support the roof and provide a frame for holding the windows intact. These vertically angled supports are labeled in alphabetical order as A and B pillars as we move from the front to the rear of the vehicle. While the A pillar connects the hood to the roof and bounds the sides of the windshield, the B pillar forms a side of the window frame for the first door from the front of the car, though it can have several configurations depending on the vehicle type. Due to their significance in providing roll protection for the vehicle in the event of a crash, A and B pillars are typically made from high-strength steel [83].

Materials used in making these pillars are required to possess high collapse strength and ability to absorb the kinetic energy of a head impact. Collapse strength of a material can be calculated using (Eq. 30.2) [68] as:

$$P_s \propto t(\sigma_b)^n \quad (30.2)$$

where P_s represents the collapse strength, t stands for thickness, σ_b is the tension strength of the material, and $n \sim 0.5$.

To satisfy the twin requirements of high collapse strength and ability to absorb a high amount of kinetic energy, foams or structural ribs are added to the hard trim [84]. Structural ribs tend to be less expensive than foams, as they can be injection-molded as a single part; however, current technology requires approximately 25 mm of crush space [85]. A number of automobile manufacturers have included curtain airbags underneath the A and B pillar covers. As a result, additional design considerations are taken into account in order to ensure proper functioning of these airbags when the latter are required to be deployed [67].

Since head injury ranks among the major causes of death in car accidents, efforts have been undertaken by car manufacturers to design the hard trim

Table 30.10 Properties and Use of Plastics in Door Panels by Various Automakers

Polymer	Tensile Strength (MPa)	Flexural Modulus (GPa)	Automaker	References
Glass fiber–PUR	253.8	0.4–0.5	VW	[69–71]
Long glass fiber reinforced–PP	151	9.36	Ford	[72,73]
TPO	15–26	0.44–0.58	Dodge	[63,74,75]
Kenaf–PP	58	2529	Ford	[76–79]
Jute–epoxy	110	1.5	Mercedes-Benz	[77,80]
Flax/hemp/ coconut–PP	30–60	1–3	Daimler Chrysler	[77,80,81]
Flax/sisal–PUR	40–50	1.5–3.5	Audi	[80,82]

in a manner as to minimize the risk of such injuries [86]. This has been further reinforced by the Federal Motor Vehicle Safety Standard (FMVSS) No. 201, which provides safety criteria for interior parts of the vehicle. As per this standard, upper interior components of vehicles must have a head injury criteria (HIC) value of 1000 or less, the HIC value based on acceleration at the center of the head during a collision, and must hold for several different impact approach angles [60]. Considering the proximity of A and B pillars to the heads of passengers in a vehicle, attention has been given to the coverings used for these pillars. Typically, PP (pure or blended with wheat straw), PET, and PET-PA blends are used for such coverings [87–89].

30.3.4 Seats and Associated Parts

Car seats consist of many parts: armrest, backrest or seat back, headrest, seat base, and seat track. In addition, the seating assembly also contains the seat belt and airbags for safety purposes. In the United States, standards for the different parts of a car seat along with seat belt and airbags are provided for under three different statutes/entities:

1. National Traffic and Motor Vehicle Safety Act, 1966 [90].
2. Chapter 301 under Title 49 of U.S. code on motor vehicle and driver programs [91].
3. Federal Motor Vehicle Safety Standards (FMVSS) 207, 209, and 210—provided for by the National Highway Traffic Safety Administration under Chapter 301, Title 49, of the U.S. code [92–94].

We describe plastics used in each of these parts in detail.

Seating in cars is subjected to stringent standards as mentioned in the Federal Motor Vehicle Safety Standard (FMVSS) No. 207 [92], as detailed in Table 30.11. Based on these standards, until the 2000s seat back frames for frontal seats were made only from steel, and plastics had no scope for use as they offered less safety and were more expensive than steel [11,22]. However, experimental approaches have been made toward using various plastics in front seat back frames, such as the use of impact-modified glass-fiber-reinforced PA6 in the Keiper Recaro A8 sports car (1991), and structural reaction injection-molded (SRIM) seat back frames in the Chevrolet Corvette (1997) [22]. Plastics have gained greater prominence for use in rear seat backs since the early 2000s with the introduction of the PC/ABS blend [11]. A number of plastics have been tried for rear seat backs in various car models, some of which are mentioned in Table 30.12.

Seat covers are required to be resistant to a number of aspects—abrasion, light and UV radiation, variable temperatures, and humidity—and also to be able to withstand frequent usage while remaining

Table 30.11 Standards for Seating Systems [92]

Feature	Standard
Each occupant seat	Ability to withstand forces in both forward and rearward direction, the magnitude of the force being equal to 20 times the mass of seat (in kg) multiplied by 9.8. In its rearmost position, ability to withstand force producing a moment with magnitude of 373 Nm (Newton meters) moment about the seating reference point.
Seat adjustment	Remaining in its adjusted position during testing.
Restraining device for hinged, folding seats and seat backs	Must be equipped with self-locking device for restraining; designated seating positions and auxiliary seating accommodations behind the seat must be equipped with control to release the restraining device, and the control must be readily accessible.
Performance of restraining device	*Static force:* Restraining device should not fail on being subjected to force applied on that portion of the seat through its center of gravity, the magnitude of the force being equal to 20 times the mass of hinged or folding portion of seat multiplied by 9.8. Force will be in forward longitudinal direction for forward-facing seat and in rearward longitudinal direction for rearward-facing seat, respectively. *Acceleration:* Restraining device should not fail when subjected to an acceleration of magnitude 20 g (g = 9.8 m/s^2), the direction of acceleration being longitudinally opposite to the direction of the folding of the seat.

Table 30.12 Plastics for Rear Seat Backs in Various Car Models

Car Model(s)/Company	Plastics Used	References
Mercedes-Benz S-Class	PU mat molding Injection-molded glass-fiber-reinforced PA	[22]
Mercedes-Benz V-Class minivan	Glass-fiber-reinforced PA6	[22]
Fiat—Tipo and Fiera models	BMC	[22]
Ford Taurus/Mercury Sable GM Buick Park Avenue Mercedes-Benz C-Class GM Buick Roadmaster GM Chevrolet Caprice	PP	[22]
Mercedes T-series estate car (Europe)	GMT/PP	[53]

soft and without any creases to enhance user comfort [22,95]. While leather and subsequently polyvinyl chloride (PVC) were used as materials of choice in the 1940s, these were largely replaced by woven nylon and polyester fabrics by the 1960s [96]. Polyester fabrics today constitute about 90% of all car seat fabric, and are typically used as trilaminates, with the face and lining fabric having a thick layer of foam, usually of polyurethane (PUR), in between [53,95]. PUR is used for its flexibility and energy-absorbing properties [53].

With regard to seat cushioning for reducing the impact of shock, noise, and sudden braking, polyurethane dominates the scene for several reasons. It has low density (only 0.03–0.05 g/cm^3), high specific strength, good shock and sound absorbing and vibration dampening properties, and high corrosion resistance; offers ease of design; and has high recyclability [97]. Given these advantages, polyurethane offers tremendous scope in lightweighting of cars, thereby considerably reducing the cost of providing the cushions [22]. It can also be coated with tuftane thermoplastic polyurethane (TPU) films to protect it by improving its sound absorbing properties [22].

Seat belts are safety devices installed in a car to protect its occupants (including the driver) from harm by restricting their movement during any collision or a sudden stop. They are considered the most effective way of protecting a car passenger. FMVSS 209 details the standards to be met by a seat-belt assembly, while FMVSS 210 details the standards to be met by the assembly anchorage [93,94]. Table 30.13 lists the standards to be met by seat belts with regard to car occupants; other standards are not described here for lack of space. Based on these standards, it can be said that seat belts are required to possess a combination of properties. Along with high strength

Table 30.13 Occupant Standards to Be Met by Seat Belts [93]

Parameters	Standards to Be Met (Minimum and Maximum)
Weight (kg)	46.3–97.5
Erect sitting height (mm)	785–965
Hip breadth (sitting, mm)	325–419
Hip circumference (sitting, mm)	925–1199
Waist circumference (sitting, mm)	599–1080
Chest depth (mm)	190–267
Chest circumference (mm)	775–1130 (nipple) 757–1130 (upper) 676–1130 (lower)

and rigidity to prevent inertial movement, they should have high impact strength so as not to break at high force, and low friction and wear given their frequent usage [28,53]. To meet these requirements, typically belts are made of polyester fiber, though nylon is also sometimes used, while the belt mechanism is made from polyamide 6 (PA 6), polyamide 66 (PA 66), and polyethylene terephthalate (PET) [28,53].

30.4 Under-the-Hood Components

Structural and mechanical parts located under the hood of a car, such as the engine and related parts, fuel system, cooling system, and crash members, are the focus of this section. Replacement of metals with composites has gained ground over the years due to increasing concerns regarding reduction of fuel consumption and ensuring a cleaner, healthier environment. In the initial years of car manufacture and use, application of composites in under-the-hood parts was not very common, unlike in interior and exterior parts, due to concerns about their resistance to corrosion, wear, and high temperature, and about their performance under conditions of noise, vibration, and harshness (NVH). However, the situation has changed considerably, and today it is possible to see a number of composite-made parts under the hood. We describe a few selected major components in the sections that follow.

30.4.1 Intake Manifold

Intake manifolds carry the desired amount of air for combustion into the cylinders. They connect the air filter (with pipe) on one side to the engine block, and are expected to be capable of carrying the same amount of air or air/fuel mixture to each cylinder at the same time and at the same temperature. Given the conditions they experience, materials used for making intake manifolds are expected to possess high strength and stiffness in order to endure the weight of the throttle body, as well as high chemical resistance due to fuel flow through the runners [10,28]. Fig. 30.7 shows a typical intake manifold of a passenger car.

Initially, intake manifolds were produced using the lost-core method of injection molding, in which a low-melting metal alloy is inserted in a mold, plastic is injected, and then the metal is melted either in a hot oil bath or by heating. Although this method is still in use, it has been overshadowed by vibration welding, which lowers the cycle time and cost of injection molding. In this method, pressure at a certain frequency and amplitude is applied on the two halves of the injection-molded part that are in frictional contact with each other [98]. Traditionally, intake manifolds have been made from aluminum, cast iron/steel, and magnesium alloy. However, these have given way to plastics and composites since the 1990s on account of a host of reasons: reduction in weight and cost of a car, low thermal conductivity, higher performance due to better surface finish, and noise reduction [99–101].

Figure 30.7 Intake manifold.

Mass production of intake manifolds using composites started with the production and use of BMW six-cylinder engines in 1990 [10]. High-volume commercial intake manifolds were introduced in the US market in the 1990s by General Motors, AC Rochester, and DuPont Automotive. PA6 and PA66 plastics reinforced with 30–35 wt.% glass fibers are currently the first material of preference in the manufacture of intake manifolds. DuPont has integrated an exhaust gas recirculation (EGR) adapter into its design with PA66 resins as it helps reduce EGR temperatures to levels tolerable for plastic intake manifolds. PA66 intake manifolds have been observed to achieve savings of 2.9 lbs over the aluminum intake manifold for the Dodge Neon 2L engine [101]. In addition to weight reduction, use of nylon intake manifolds has been observed to reduce CO_2 and NO_x emissions due to lower energy consumption during manufacturing and life-cycle use of the product, in addition to providing better corrosion resistance and higher chemical conductivity compared to intake manifolds made from cast iron and aluminum alloys [101,102]. Volkswagen later shifted from 35 wt.% glass-fiber-reinforced PA to 35 wt.% glass-fiber-reinforced polypropylene (PP) as the latter brought additional advantages of high resistance to heat and chemicals, vibration, and fatigue, while bringing further weight reduction by as much as 15% when compared to polyamide [99]. Concerns regarding the negative impact of plastic intake manifolds on noise, vibration, and harshness (NVH) have been addressed in recent times by the addition of additional ribs, which help plastic intake manifolds pass the NVH test by providing them with appropriate thickness [101,103].

30.4.2 Fuel Tanks

Fuel tanks are meant for storing the required amount of fuel needed to run the vehicle. Although different vehicles have fuel tanks of different volumes, the average volume of the tank is usually around 50 L. In general, for light-duty trucks and passenger cars, they are assembled on the rear part of the chassis, while for heavy-duty trucks and buses, they are located either on the right or the left side of the chassis. A desired fuel tank design is one that can be easily filled, has good quality sealing to prevent leakage, and has enough ventilation to prevent

Table 30.14 FMVSS 301 Standards for Fuel Spillage [104]

Parameter	Standard or Allowed Value and Condition
Fuel spill	Until vehicle stops: Should not be more than 28 g for barrier and frontal impacts Until 5 min after the vehicle stops: Should not be more than 142 g for barrier and frontal impacts

Table 30.15 European Standards for Plastic Fuel Tanks [106]

Tests	Method
Evaporative emission testing	Weight loss of fuel tank is recorded at +40°C at 8 weeks to measure average permeation of fuel evaporated.
Mechanical strength	30 kPa internal pressure is applied to the tank, which is filled with water at 53°C given conditions for 5 h.
Impact testing	30 Nm impact energy is applied on the fuel tank, which is filled with the glycol/water mixture.
Thermal testing	First, tank is filled with water at 20°C, then moved into a test chamber at 95°C for 1 h.
Fire resistance	Half of the tank is filled with fuel and subjected to flame for 2 min.

evaporation. The National Highway Traffic Safety Administration (NHTSA) standard of FMVSS 301 aims to decrease the number of deaths and injuries caused by fuel leakage after vehicle crashes, so it sets standards as given in Table 30.14 [104,105]. On the other hand, European standards for fuel tanks made from plastics are given in Table 30.15 [106].

Conventionally, sheet steels have been used to manufacture fuel tanks. Such use, however, was discontinued due to steel fuel tanks being prone to corrosion on account of the sulfur content in fuel, which damages the fuel system [107]. A comparison of steel and plastic fuel tanks undertaken by the US Environmental Protection Agency (EPA) shows that for the 1996 GMT 600 passenger vans, steel fuel tanks on average weigh 48.32 lbs., while plastic fuel tanks weigh 31.02 lb., amounting to around 35% reduction in weight [108]. In addition, the study also shows lower fuel consumption in the case of usage of plastic fuel tanks compared to the steel ones, with the former offering better safety, greater design flexibility, lower cost, and higher corrosion resistance when compared to steel-made fuel tanks [108].

Plastic-based fuel tanks were first used in Volkswagen Passat in 1972, and since then the interest in using these tanks in vehicles has been on the rise [10]. When high-density polyethylene (HDPE) fuel tanks were initially used, fluorination was observed to reduce fuel permeation; permeation resistance was then increased over the years by the invention of a coextrusion blow-molding process [109]. HDPE with high molecular weight, which also increases its toughness, is produced by companies like BASF, Fina, and Solvey to meet European and US regulations for fuel tanks [28]. Studies have also shown HDPE to be more environmentally friendly than steel over the car's life cycle [110].

30.4.3 Crash Applications

Attention on passenger safety has been increasing over the years. Although the number of registered vehicles in the United States has increased from 193 million (1990) to 250 million (2013), the total number of annual deaths in accidents has reduced from 44,000 to 30,000 in the same period [111]. Vehicle design is the most important factor in determining and reducing the effect of accidents and improving road safety. Crashworthiness is described as the ability of the vehicular structure to absorb dynamic energy and minimize injury to passengers during a collision, and is considered among the important criteria in determining vehicle design with regard to passenger safety [112]. The crash box is an important component in determining crashworthiness of a vehicle, and is placed between the bumper and side rails [113]. Automotive manufacturers aim to reduce vehicle weight in order to meet economic and environmental concerns without sacrificing on safety standards for car crashes set under the Federal Motor Vehicle Safety Standards (Standard No. 208) [44].

Traditionally, aluminum and steel have been used for making crash boxes in cars [114]. However, insistence on lightweighting combined with high specific stiffness and strength has led to composites gaining preference for use in cars, as all these properties are crucial in achieving better crashworthiness. Energy absorption (E) and specific energy absorption (E_s) are two important parameters that define the crashworthiness of a material [115]. Parameters that determine the energy absorption of composites crash boxes include fiber type and architecture, matrix type, geometry of the structure, and fiber volume fraction [115]. Geometrical and dimensional aspects have a vital role in helping improve the absorption capacity for crashworthiness, as well as improving materials deformation and progressive failure characteristics [116].

Many studies have been done to examine the structure of composite materials and their ability to absorb energy during a collision, compared with traditionally used materials. Comparison of crashworthiness of aluminum and woven fiber-glass/polyamide composite crash boxes was undertaken experimentally as well as through numerical simulation, with results showing that composites crash boxes absorbed 17% more energy with a reduction of 26% in specific energy absorption compared to aluminum crash boxes [115]. Table 30.16 summarizes the specific energy absorption (E_s) for these materials, showing that the highest specific energy absorption value is shown by carbon fiber/polyetheretherketone (PEEK) due to its high interlaminar fracture toughness and high strength of carbon fiber.

Recently, attention has gained ground on replacing currently used plastics with natural plastics in cars in order to reduce their negative impact on our environment. Examples of such composites include silk epoxy composite tube, kenaf fiber, and bombyx mori silk fiber, whose crashworthiness has been studied [123–125]. The Lamborghini Sesto Elemento is the first high-performance sports car to use carbon-fiber-reinforced plastic (CFRP) in making crash boxes [114]. Other cars like Formula cars, LeMans cars, Mercedes SLR, Porsche Carrera GT, Porsche 911, and Ferrari have made efforts toward use of composites in crash structures [126].

Table 30.16 Specific Energy Absorption of Different Composites

Material	E_s (KJ/kg)	References
Glass fiber/vinyl ester	68	[117]
Glass fiber/polyester	50	[118]
Glass fiber/epoxy	47	[119]
Carbon fiber/epoxy	110	[120]
Carbon fiber/PEEK	226	[121]
Kevlar/epoxy	32	[119]
Graphite/epoxy	63	[122]

30.4.4 Leaf Springs

Leaf springs are a crucial part of the suspension system of a car. They consist of a number of layers of leaves with a gradation in their size, the bigger layer being on the top with each layer joined to the other. Leaf springs are directly attached to the frame, either at both ends or at one end. For the latter, the front end is attached to the frame while the other end is attached to a short swinging arm through a shackle. The main function of leaf springs is to provide comfort to the passengers by minimizing the vertical vibration caused by the nonuniformity of road geometry. Studies show that the desired leaf spring material should have high strength and low modulus of elasticity in the longitudinal direction [127]. In addition, high fatigue resistance is one of the most desired properties for leaf springs, since they carry the entire load of the vehicle and experience dynamic load under driving conditions [128]. Leaf springs are guided by the SAE J1123 standard titled *Leaf Springs for Motor Vehicle Suspension—Made to Metric Units*, and can be full, semi-, or quarter-elliptic with one or more leaves. Fig. 30.8 represents the mono-leaf spring [129].

Conventionally, high-strength steel containing 0.9–1 wt.% carbon has been used for leaf spring applications due to its high tensile strength and stiffness [128]. However, interest has grown in use of leaf springs made from composites meeting the desired standards while ensuring the desired properties. Many studies have been done to analyze the suitability of composite materials for leaf springs. One such study

Figure 30.8 Mono leaf spring.

Table 30.17 Stress and Displacement in Leaf Springs Made from Various Materials [134]

Materials	Stress (MPa)	Displacement (mm)
Steel	453.92	10.16
Graphite epoxy	653.68	15.75
Carbon epoxy	300.3	16.21
E-glass epoxy	163.22	15.89

involving analysis of four materials—steel, carbon fiber/epoxy, E-glass/epoxy, and S-glass/epoxy—for use in leaf springs shows weight reduction of 80% on use of composite leaf springs over the steel one [130]. Although the carbon-fiber/epoxy composite showed the highest specific strain energy among spring materials, it lacked impact strength and is costly, and so may not be the best candidate. The glass fiber/epoxy composite, while lacking in stiffness and strength, has high impact strength and density compared to carbon fiber while also being cheaper. Although S-glass fiber has better mechanical properties than E-glass fiber, the latter is usually the preferred option due to its lower price [130]. Other studies have compared the stress and weight reduction achieved by the use of composite leaf springs over steel ones, and the results from one such study are given in Table 30.17, with E-glass epoxy showing the lowest stress while displacement values are close to one another. Overall, composites offer several advantages over steel in applications to leaf springs: reduction in weight and noise, high specific strength, high resistance to corrosion and fatigue, and enhanced cost-effectiveness [127,128,131–133].

A composite leaf spring has been produced for the Volvo XC90 by using resin transfer molding (RTM), with a reduction of 4.5 kg in weight compared to a similar steel leaf spring, thus helping achieve weight savings of nearly 65% [135]. Given the need for leaf spring materials to be flexible and possess tolerance to high fatigue, polyurethane (PUR) matrix resin has been used, as its high toughness factor helps improve the fatigue resistance of leaf springs. PUR matrix resin that cures faster than epoxy resin for the resin transfer molding process was used for RTM of glass-fiber-reinforced leaf springs by Henkel AG [135]. The low viscosity of PUR helps it to penetrate easily with less delamination, thereby reducing the total cycle time. However, greater use of plastics in leaf springs is expected to take time, given the recent initiation of this trend.

30.4.5 Other Components

In addition to the components mentioned previously, there are many other under-the-hood components that are made from composite materials. Examples of some of these components and the plastics or composites used to make them are given in Table 30.18.

30.5 Future Outlook

The future of the automotive industry is fundamentally tied toward the design and manufacture of multiple-material or sandwich structures, which are vital for a lightweight and fuel-efficient automobile. The shift to composite or sandwich structures

Table 30.18 Use of Plastics/Composites in Under-the-Hood Components

Component	Plastic/Composite Used
Transmission sensors	Polyetherimide [136]
Stationary transmission parts	Phenolic resins with glass fiber [136]
Brake pads	Tough aramid fiber [136]
Fuel lines (Fiat)	Castor oil–derived nylon [137]
Radiator support	Nylon, polypropylene [10,136]
Battery boxes	Polystyrene and polypropylene [6]
Air filters	Polypropylene and polyurethane foams [10]
Engine covers	Polyamide and polypropylene [10]
Air ducts	ABS and polypropylene [136]
Housing brakes	ABS, PA, polybutylene terephthalate (PBT) [10,136]

presents new challenges in joining components. Adhesive bonding is set to play a pivotal role in the manufacture of future cars due to shorter cycle times, better crash properties, and uniform force distribution [138]. Plastic or composite usage in cars will also gain thrust from the impetus toward autonomous cars, with a transformation in their functionality from mere instruments of mobility to machines accommodating a variety of features, ranging from high-tech gadgets to increasing passenger comfort and safety. While not constituting the entire car, plastics and composites are expected to increase their share in car manufacturing and significantly reduce vehicle weight.

A massive transformation is also expected in the nature of plastics used in the automotive sector given the current environmental concerns with regard to the use of synthetic plastics. We envision this transformation to occur in three stages. In the first stage, we are likely to see attempts towards developing bio-based precursors for synthesizing conventional polymers such as bio-nylon, bio-polyethylene, bio-epoxy, and bio-polyurethane. Such plastics, while structurally and chemically similar to those derived from petroleum resources, will also help in conserving crude oil for other significant applications while promoting sustainability.

The second stage of transformation will likely result in synthesis of new bio-based plastics such as polyhydroxy alkanoates and polylactic acid. Such plastics are chemically and structurally different from conventional plastics, but will be similar to the latter in terms of their properties, making them potential alternatives to both petroleum and bio-derived conventional plastics. Both the first- and second-generation transformations are, however, likely to generate concerns about the use of food-based precursors for synthesizing plastics, given that they will divert crucial food resources meant for human and animal consumption.

In our view, this will inevitably lead us to the third stage of transformation, wherein we anticipate all precursors, including those leading to obtainment of conventional polymers and bioplastics, to be derived from nonfood-based resources. A significant step in this direction will be the development of bioplastics from wood (e.g., epoxidized pine oil) and carbon dioxide (e.g., polyalkyl carbonates). Among the three, the third stage is what we can term *true transformation* since it advocates sustainability by not taking away the food resources of the current generation. Overall, these transformations will not only help to conserve the environment via a lowered carbon footprint, but also provide an expedited closed-loop system for producing plastics.

30.6 Conclusions

Over the past 50 years, plastics have gained a major foothold in automobile manufacturing. Their ability to reduce vehicle weight combined with advantageous properties ranging from better mechanical and optical properties to improved surface finish and corrosion resistance have made them a necessity in today's automotive sector. This chapter has presented an overview on the use of plastics in different parts of a car. Reasons and incentives for use of plastics, as well as specific plastic materials used in different parts of a car, were also discussed. Finally, this chapter presented a brief outlook on the future of plastic usage in the automobile industry, opening new directions for research in this regard. It is hoped that such enhanced usage can help improve fuel economy, reduce carbon emissions, and help contribute to mankind's fight against global warming and climate change.

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