

# **NEW COMPOSITE SOLUTIONS FOR AUTOMOTIVE UNDERBODY SYSTEMS**

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## **Abstract**

Although not a common feature on vehicles originating in the North American market, European automakers have been installing underbody closure systems on their passenger vehicles for some time. Starting with small plates intended to protect the engine and gear box, these shields have evolved into complete under-floor closure systems offering a number of benefits.

First, they reduce the vehicle's aerodynamic drag, which helps improve fuel economy – vital in a market segment where fuel prices average 0.98 – 1.56 €/ liter (\$5-8 USD / gal).

Second, they function much like the protective vinyl coating sprayed on the underside of most North American vehicles to reduce stone impingement, salt spray, and other damage to the undercarriage. Unlike the spray coatings, however, the shields also protect the undercarriage on bad roads and for off-road usage.

Third, they reduce noise – both inside the cockpit for occupants, as well as curb noise as vehicles pass through congested cities with narrow streets.

As underbody closure systems have proliferated, different materials and process development programs have been commercialized. Each participating OEM has sought to tailor these closure systems to achieve specific combinations of cost, performance, and mass for the various vehicle segments in which they compete. Although no single material / process option currently meets all OEM needs in all segments, 3 technologies – all thermoplastic – have emerged in Europe to dominate underbody closure systems. This paper discusses current material / process options and the kinds of application criteria where each are best suited.

## **A Short History of Underbody Closure Systems**

European automakers have installed various underbody shields on passenger cars nearly universally since the early 1980s. Functionally, these early shields were typically small protective parts meant to guard the engine and gearbox from stone impingement and corrosion while also sealing in oil drips and reducing road noise. It was not until the mid-to-late 1990s, however, that such systems were extended to close out the entire vehicle undercarriage.

Starting with the 1997 MY Mercedes-Benz® A Class and the 2000 MY Audi® A4 cars, the area behind the engine and gearbox was closed with large parts using compression-molded glass-mat thermoplastic (GMT) composites. As seen in Figure 1, the exhaust system for the A Class car runs down one side of the vehicle. Hence, the underbody shields were designed as 2 adjoining panels. Since the A Class vehicle was introduced as a “green” car, enclosing its undercarriage helped improve fuel economy.



Figure 1: Under-floor system for the 1997 MY Mercedes A Class, showing tunnel with aluminium heat shield (top, 2-color part), 2 large GMT shields (center), rocker panels (top and bottom most – also molded from GMT), and to the left, center, the GMT spare wheel well and 2 small GMT side panels

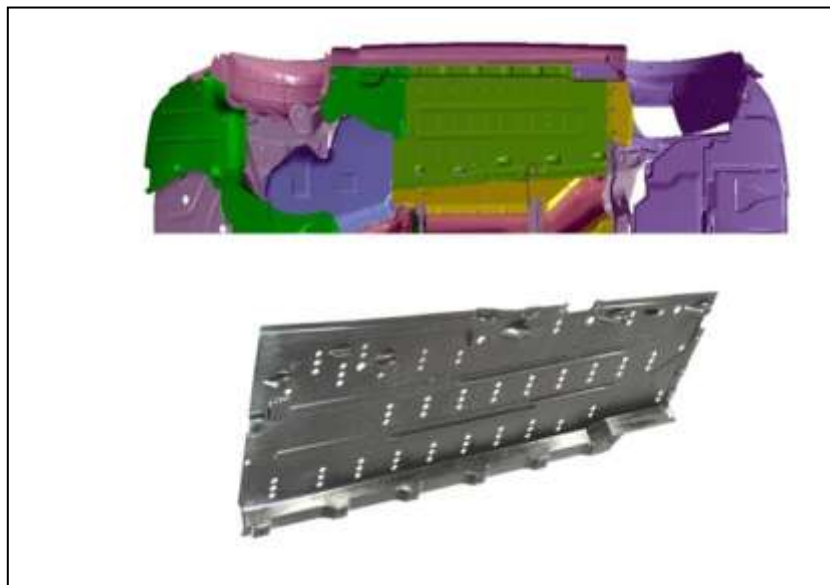


Figure 2: Under-floor system for the 2000 MY Audi A4 sedan – lower image is a photo of the underside of the large side panel; upper image is a CAD file for half of the vehicle showing the 2 front shields for motor and gearbox, a large side panel, and several small parts located at the rear of the vehicle's undercarriage – all molded from GMT

Since the undercarriage of the Audi A4 sedan featured a central exhaust system, the under-floor area was covered by 2 long panels on either side of the exhaust tunnel (Figure 2). Again, GMT composites were used. Installation of the under-floor closure system provided a number of benefits for this model, aside from the general ones previously listed. Because the A4 sedan can run at speeds of 250 km / h or higher, the shields helped reduce aerodynamic drag, improve driving stability – particularly during cross-(side)-wind conditions – and improve aero-acoustics due to a “clean” underbelly, Audi also wanted the parts to provide “lifetime design” durability – not only under normal operating conditions, but also under severe misuse conditions such as use on rough roads – without failure. GMT was the only material evaluated that met all these criteria.

Once installed, underbody systems began to evolve. Over the complete production run of the 2000 MY A4 car, wall thicknesses on the shields were reduced from 1.8 to 1.5 mm without compromising part performance due to the high inherent mechanical properties of GMT composites.

In fact, to fully appreciate how far a technology has evolved and where it has evolved from, it is often helpful to compare extremes. For underbody closure systems, the extremes could be represented as follows: the classic Range Rover® Defender® series, which uses no under-floor system (Figure 3), and the Mercedes-Benz SLR McLaren supercar, which has an ideal, flat under-floor system made from a high-performance epoxy / carbon-fiber-reinforced composite (Figure 4). One vehicle has no under-floor protection at all; the other has a very lightweight, high-performance, high-cost system that completely covers the undercarriage.



Figure 3: Under-floor system for Range Rover Defender SUV uses no underbody closure system

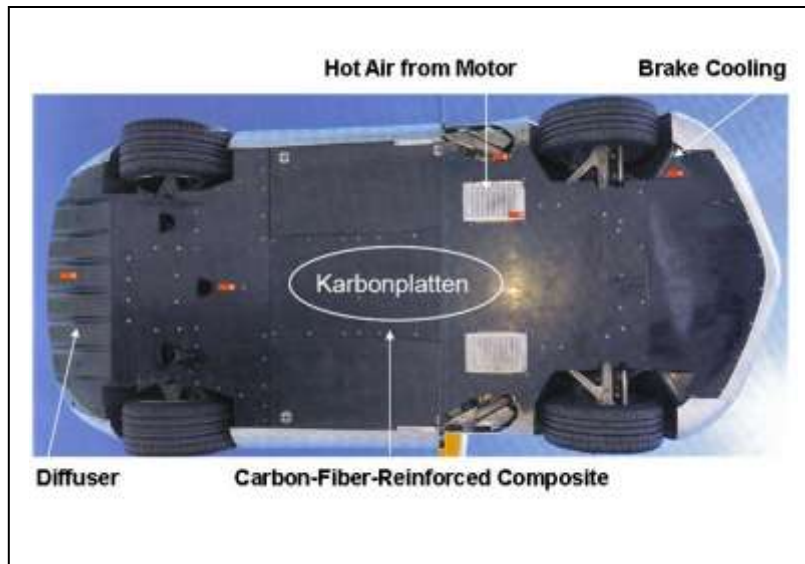


Figure 4: The Mercedes SLR supercar features a complete underbody closure system in an idealized, flat geometry using an epoxy / carbon-fiber-reinforced composite

## **Diverging Design Intent**

Thanks to the success of the initial systems, full-length underbody shields began to proliferate on European vehicles with the design emphasis splitting in a couple directions. Some OEMs focused on optimizing wall thickness to reduce part weight without sacrificing performance. A few OEMs on special programs studied ways to improve performance on both high-end vehicles and those destined for export to countries with rough roads. Still others focused on cost reduction, allowing for a concurrent reduction in certain performance requirements. For the latter, it was highly desirable to be able to use lower cost materials like direct-long-fiber thermoplastics (DLFT) and processes like injection molding that did not require post-mold trimming or hole punching as is necessary with compression-molded parts (e.g. GMT and DLFT). It was reasoned that a large component such as an underbody shield offered the potential for significant mass and cost reduction depending on the systems change made. The trade-off for using these lower cost materials with less post-mold handling was that performance requirements for the under-floor parts had to be reduced – in some cases, significantly. The main requirements that were changed included failure generation and failure increase up to total failure.

## **Balancing Performance Requirements for Different Types of Vehicles**

Part of the challenge of designing under-floor closure systems is balancing often conflicting requirements.

For instance, the street side of panels need to be designed as flat and smooth as possible both to reduce drag and also to improve acoustics. The other side of the panel requires complex design details necessary to fit around undercarriage geometry. Yet the entire panel needs to weigh as little as possible to meet performance criteria without compromising improvements in fuel economy.

With more upscale vehicles, acoustic performance becomes more of a focus. Besides conventional approaches to improving a vehicle's acoustics, underbody systems provide additional opportunities to tune the acoustical and aero-acoustical performance. In fact, some under-floor systems are so good at absorbing noise that other noise-management components can be eliminated, saving cost and mass.

For sportier cars with higher powered engines, which are always linked with higher heat generation, the service temperature range of the matrices used polymer composites has to be increased. In such cases, tough and economical polypropylene (PP)-based composites with long-term thermal capabilities to 115C are no longer sufficient, necessitating the switch to higher temperature resins or resin-blend systems, including thermosets. Use of these higher temperature matrices can add weight and / or cost to the system and may not provide the same level of durability over the life of the vehicle, particularly under rough-use conditions.

Export of vehicles into countries with a high proportion of bad (unpaved) roads is increasing steadily. In such cases, special measures for protecting the vehicle's undercarriage are needed, which tend to require higher performing composites that may add cost to the system. Requirements for these tougher underbody systems generally differ from those typically specified for vehicles intended for North America and Europe.

Finally the fast-growing SUV segment is extending to real off-road vehicles that require still greater undercarriage protection since these vehicles often experience rough contact with the ground, which can destroy the engine, gear box, or fuel tank if no protective shields are present.

## Materials & Processing Options Evolve to Meet Changing Design Goals

As underbody systems have expanded to a broader range of vehicle segments, numerous composite materials / process options have been explored and commercialized to meet specific OEM and tier requirements. These systems (and their benefits and weaknesses) include:

### Thermoplastic Systems

#### Glass-mat thermoplastic (GMT) composite types

- **Classic GMT** – *sheet-form composite with chopped glass mat in a PP matrix for compression molding* – earliest underbody closure system; offers good balance of cost, mechanicals, and durability; performance can be increased through selective addition of textile-reinforced GMT or higher performing resin matrices; has been displaced on programs seeking lower cost solutions (LFT or DLFT), elimination of post-mold trimming (injection molded glass-filled composites or LFT), lower mass (LWRT), or higher acoustics (LWRT).
- **Lightweight reinforced thermoplastic (LWRT)** – *a more recent variation on GMT technology, these sheet-form composites are produced either by needling a high-lofting long-glass fiber fleece with very-good 3D fiber entanglement or via a modified papermaking process with far shorter fibers and little 3D entanglement of fibers encapsulated in a PP matrix (although other matrices are beginning to be introduced)* – originally developed for headliners, low-pressure stampable LWRT composites are the lightest underbody closure option with high stiffness to weight ratios and excellent acoustic properties owing to their “open” structures; for applications where severe-use or water uptake is an issue, special surface layers can be added for greater protection; the fleece-based form of LWRT tends to be far more successful in under-floor closure systems owing to its superior drawability and mechanical strength, particularly important at attachment points (the most highly loaded areas of the undercarriage system) where they must withstand high pull-out forces.
- **Textile-reinforced GMT** – *these highly tailorable GMT-type composites feature high-performance woven and non-woven/stitched textiles in a PP matrix and provide significantly higher mechanical performance under all loading conditions (impact, creep, fatigue) , even at low temperatures and high strain rates* – one unique feature of GMT-type composites is that different mat types (of the same resin matrix) can be layered in the tool to optimize final part properties and cost, allowing high-performing textile-reinforced GMTs to be used just where they are needed; high-end under-floor systems with requirements for lifetime service and performance without failure under the most severe use conditions generally use a combination of classic and textile-reinforced GMTs.

#### Long-fiber-reinforced thermoplastic (LFRT) types

- **Long-fiber thermoplastics (LFT)** – *offered in pre-compounded pellet form for injection molding*, – LFT systems have replaced classic GMT in programs where cost reduction is a high priority and long-term durability is not key; LFT products offer greater glass length than conventional glass-reinforced thermoplastics, but suffer from the same orientation effects (with significant property loss in the cross-flow direction); typically used on programs that allow for the replacement of underbody shields several times over the lifetime of the vehicle; lower mechanicals are usually compensated for by increasing wall thickness and hence weight.
- **Direct long-fiber thermoplastics (DLFT)** – *compression or injection-compression moldable* DLFT is compounded and molded on the fly at the press – like LFT, DLFT systems have replaced classic GMT in programs where cost reduction is a high priority and long-term durability is less of a concern; while DLFT preserves fiber length better than LFT, it falls short of GMT, also necessitating the use of thicker cross-sections (at higher mass) to attain comparable mechanical properties, or a reduction of certain performance specifications (e.g. service life and survivability after misuse).

### Other thermoplastic processes for low-volume / low-end applications

- **Injection-moldable (IM) glass-filled thermoplastic** – typically conventional PP or nylon (polyamide (PA)) matrices with short glass fibers are used for underbody shields; advantages are that highly intricate designs can be produced with no post-mold trimming; disadvantages are that costly tooling requires high-volume to amortize, there is little 3D entanglement of short-glass fibers, which tend to orient strongly in the direction of flow and yield much lower mechanicals vs. GMT and LFRT types.
- **Vacuum forming or blow molding / twin-sheet thermoforming** – these processes produce single- or twin-wall structures for low-volume applications where a flat panel or a panel with very simple geometry is appropriate -- these unfilled extruded or sheet-form thermoplastics can offer significant cost savings, but at the expense of mass and performance; the 2-layer twin-sheet or blow-molded versions offer integration of sound absorbers, but at higher mass and lower performance.

### Thermosetting Systems

**Sheet-molding compound (SMC)** – sheet-form SMC is processed by compression molding and features a chopped glass and mineral filler combination impregnated with either a polyester or vinyl ester resin – SMC's thermoset matrix and high level of glass and mineral loading provides this composite with high stiffness, chemical resistance, and higher thermal performance than thermoplastic offsets for underbody systems, which makes SMC especially attractive under hot areas like the gearbox; however, higher density leads to heavier parts, which also have a tendency toward brittleness due to very-low elongation at failure; SMC is typically not specified for underbody components requiring lifetime service even under misuse conditions.

**Exotic thermoset technology** – super-high-end epoxy-carbon-fiber systems offer the highest mechanical performance in thin cross-sections at premium cost – for programs where exceptional performance is required and cost is little issue (e.g. supercars), exotic thermoset technologies from the aerospace and race car industries make an entrée into passenger vehicles; high cost and slow processing make them unsuited for all but the lowest volume, high-end vehicles.

A final but important note about reinforcement structures for composites is in order here. As most in the industry know, when evaluating stiffness, the reinforcing structure dominates the resin matrix properties at all but the lowest loading levels because the reinforcement's modulus is usually orders of magnitude higher than that of the polymer in which it is encased. Of course, higher reinforcement loadings in the same resin matrix yield a stiffer part, albeit one that can become increasingly brittle. That said, when comparing performance for various types of industrial composites, the discussion too often centers exclusively on fiber length. However, fiber length is only half the story when it comes to composites.

Equally important to a discussion of mechanical properties – especially where impact strength, crack initiation, and crack propagation are at issue – is the nature of the reinforcement system and how the reinforcements interact with each other. One of the reasons that GMT-type composites offer significantly higher mechanical properties even at the same loading level in the same resin matrix vs. other glass / PP systems is that most GMT products have an interlocking 3-dimensional mat structure<sup>1</sup>. The more entangled the fibers after molding, the better the path for managing loads – particularly at high strain rates or severe loading conditions. This is why GMT – especially textile-reinforced grades – has among the highest stiffness, strength, impact, and fracture mechanics of any industrial composite system. It is also why GMT composites do not suffer the same tendency toward low-temperature brittle failure or flow-induced anisotropy

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<sup>1</sup> Not all GMT suppliers use the same technology to produce or handle their mats or their composites, so not all GMT products of the type have the same level of entanglement among fibers and the same level of performance.

that their short-glass PP analogs do. Despite the fact the DLFT systems have achieved significant gains in fiber length vs. earlier IM and LFT systems, they still offer poorer mechanical performance than GMT. Their glass fibers not only have far less entanglement (acting as individual fibers not an effective network to dissipate loads), but also tend to orient strongly in the flow direction, leading to significant property loss in the cross-flow direction. What this all means in the “real world” is that many GMT underbody shields that were converted to LFT and DLFT for cost reasons have come back to GMT because their long-term and severe-condition performance was simply not acceptable. Additionally, GMT parts with interlocking reinforcements tend to stay together even when they crack due to mistreatment. This is in marked contrast to injection-molded parts, for example, which tend to fall apart and drop off the vehicle as cracks initiate and propagate. German highways bear frequent witness to this fact.

## **Meeting Performance Requirements**

Each OEM and tier supplier has its own unique set of requirements for underbody closure systems. Ranking of the criteria may vary from one platform to another even at the same automaker. However, key performance criteria that tend to be common among producers (no matter what order they rank them) and most material / process options are evaluated against include:

Systems cost;

Mass per unit area (expressed as minimum area weight);

Mechanicals such as stiffness, strength, and toughness / impact;

Acoustics;

Ability to survive misuse (at its most extreme, involves the underbody system supporting the entire vehicle’s weight while balanced on rocks); and

Failure mode (brittle vs. ductile at room- and low-temperature conditions).

## **The Importance of Minimum Area Weight**

Often, when comparing the projected weight of parts to be produced in various materials and process combinations, the minimum wall thickness across the entire part is used. While that assumption may simplify calculations and may be necessary in preliminary evaluations where no physical parts yet exist, it can be misleading in complex geometries like underbody systems. This is because wall thicknesses are increased locally at attachment points and in areas most prone to stone chipping, where failure is otherwise more likely. Such localized thickness increases can significantly boost part mass. Hence, use of minimum wall thickness may result in an unfair comparison of materials / process combinations. To increase accuracy of the comparison, it is best to weigh actual molded parts and divide by the projected surface area of the part, a value which is readily available from the part’s CAD data. This gives a weight per square area (e.g. g/m<sup>2</sup> or gsm) of a given material / process combination, making it a useful process for comparing very different systems. The smaller the area weight value, the lighter the part will be in that material / process combination vs. other competitive systems. Once minimum area weight values are known, actual part mass can be calculated for each materials system in a given geometry by multiplying by the actual area of the part.

Table I provides an overview of the most common materials and processes in current commercial use for under-floor closure systems. The area weight values were not estimated but rather measured from actual molded parts.

Table I: Minimum area weight values for commercial composite material / process combinations used in underbody closure systems

| Type of Composite     | Method of Processing Composite                    | Minimum Area Weight (g/m <sup>2</sup> ) |
|-----------------------|---|---|
| SMC                   | Compression / Flow Molding                        | 3,200                                   |
| GMT                   | Compression / Flow Molding                        | 1,800                                   |
| LFT / DLFT            | Compression / Flow Molding                        | 2,300                                   |
| LWRT                  | Compression Molding / Stamping                    | 1,200                                   |
| Glass-Filled PP or PA | Injection Molding                                 | 2,600                                   |
| PP                    | Vacuum Forming, Blow Molding / Twin-Sheet Forming | 2,500                                   |

When comparing materials / process options in terms of minimum area weights, SMC and short-glass-filled IM PP or PA combinations had the highest values. In the case of the SMC, this was due to its higher density. In the case of the IM-PP and IM-PA options, this was due to the need to use thicker walls to meet comparable mechanical properties vs. composites with longer fibers and 3-d interlocking fibers. In contrast, long-fiber mat-based composites such as GMT (with chopped, continuous, unidirectional, woven glass reinforcement, or combinations thereof) and lower mass LWRT were at the lowest end of the spectrum. Standard GMT products have high mechanicals so can be used in thinner cross-sections, offering opportunities to take mass out without compromising performance. LWRT's higher glass loading and cellular resin matrix yields parts with high stiffness / weight ratios. With a non-entangled structure and intermediate glass fiber length, LFT and DLFT composites were found in the middle range, which would be expected since they offer mechanical values roughly intermediate between injection molded short-glass composites and the much longer entangled reinforcement structures of GMT / LWRT materials.

### Relative Toughness

There are many ways to measure impact strength and quantify toughness and failure – some more accurate than others. A small but growing number of automakers is beginning to look beyond conventional protocols to tests derived from fracture mechanics – such as instrumented drop-weight (“flex-plate”) impact and crack propagation. As the database of materials tested to these protocols expands, and their values are better understood, their role in helping evaluate performance of materials – particularly in demanding applications like underbody systems – will increase in importance. To begin to establish their usefulness, a comparison of drop-weight impact performance at room temperature and -30C was conducted on 6 materials commonly specified for underbody shields -- 30% chopped glass GMT at 2 area weights and 40% LWRT at a third area weight. Table II displays the data. Next, the same grades were evaluated for crack propagation, the results of which are shown in Table III.

Table II: Drop weight impact data for GMT and LWRT

| Material Type                   | PP-GM30 | PP-GM30 | PP-GM30 | PP-GM30 | LWRT 40% | LWRT 40% |
|---------------------------------|---------|---------|---------|---------|----------|----------|
| Temperature (°C)                | 23      | -30     | 23      | -30     | 23       | -30      |
| Thickness (mm)                  | 2       | 2       | 4       | 4       | 4        | 4        |
| Area Weight (g/m <sup>2</sup> ) | 2,260   | 2,260   | 4,520   | 4,520   | 1,575    | 1,575    |
| Max. Force (N)                  | 1,900   | 2,100   | 4,800   | 5,100   | 1,350    | 1,500    |
| Force at Failure (N)            | 950     | 1,050   | 2,600   | 2,800   | 800      | 950      |
| Energy at Max. Failure (J)      | 5.5     | 5.7     | 16.6    | 17.1    | 5.1      | 5.9      |
| Energy at Failure (J)           | 13.7    | 14.8    | 40.3    | 42.6    | 12.1     | 13.5     |

Table III: Crack propagation data of GMT and LWRT

| Material Type                   | PP-GM30 | PP-GM30 | PP-GM20 | PP-GM20 | LWRT 40% |
|---------------------------------|---------|---------|---------|---------|----------|
| Thickness (mm)                  | 2.0     | 1.4     | 2.0     | 1.4     | 1.1      |
| Area Weight (g/m <sup>2</sup> ) | 2,260   | 1,580   | 2,100   | 1,470   | 1,200    |
| Average Force (N)               | 590     | 450     | 390     | 280     | 440      |
| Maximum Force (N)               | 760     | 620     | 480     | 370     | 590      |

## Meeting Key Mechanical Performance Requirements

Table IV shows relative comparisons between the same material / process combinations discussed earlier and shown in Table I. This time, they are rated in terms of their ability to meet key performance requirements for underbody closure systems.

In this ranking, the SMC composites offered the highest stiffness, followed by the IM-PA grades. Note that these materials also have the highest area weights, which would lead to the heaviest parts at a comparable part size. Under normal service loads and at room temperature, there were no significant difference in part strength values for the various material / process combinations tested, since all were able to meet requirements such as withstanding high-speed air pressures without severe deformation or failure. However, when properties like toughness, ability to survive misuse, and mode of failure were compared, significant differences emerged. As mentioned previously, the 3D reinforcement structure of most GMT and LWRT composites tends to isolate and stop crack propagation, so parts stay together on vehicles; in materials with more individual fiber bundles, crack initiation can quickly lead to propagation and failure, with the shield coming apart and falling off the vehicle. The same relative performance seen in small-scale tests like flexural plate impact and crack-propagation studies are also seen in large-scale driving tests performed by automakers on full-size parts mounted to vehicles.

Table IV: Relative performance of various composite material / process combinations for key property requirements for underbody closure parts

| Type of Composite     | Minimum Area Weight (g/m <sup>2</sup> ) | Method of Processing Composite                    | Stiffness | Strength | Toughness | Ability to Survive Misuse | Failure Mode (Ductile vs. Brittle) |
|-----------------------|---|---|-----------|----------|-----------|---------------------------|------------------------------------|
| SMC                   | 3,200                                   | Compression / Flow Molding                        | ++        | 0        |           |                           |                                    |
| GMT                   | 1,800                                   | Compression / Flow Molding                        | +         | +        | ++        | ++                        | ++                                 |
| LFT / DLFT            | 2,300                                   | Compression / Flow Molding                        | +         | +        | -         | -                         | -                                  |
| LWRT                  | 1,200                                   | Compression Molding / Stamping                    | +         | +        | ++        | ++                        | ++                                 |
| Glass-Filled PP or PA | 2,600                                   | Injection Molding                                 | + / ++    | + / +    |           |                           |                                    |
| PP                    | 2,500                                   | Vacuum Forming, Blow Molding / Twin-Sheet Forming | -         | 0        | -         | -                         | -                                  |

### Increasing Fuel Efficiency via Drag and Mass Reduction

When the goal of a particular vehicle design is to achieve better fuel efficiency, this can be accomplished either by reducing aerodynamic drag or vehicle mass. A study performed on a Citroen<sup>®</sup> C5 passenger vehicle found that when a full-length under-floor closure system was used, a reduction in fuel consumption of 4.1% was achieved [1]. To reach a comparable improvement in fuel consumption by mass-reduction alone, the study reported that the weight of the C5 car would have to be lowered by 46 to 181 kg, depending on the conditions under which it was being driven (road conditions, driving speed, etc.).

Because drag is a function of speed squared, a small improvement in drag can often have a bigger impact on fuel economy than a more significant reduction in curb weight. This is why use of underbody closure systems can have such a positive impact on improving fuel economy despite a slight increase in vehicle weight.

Reducing drag is an important goal for all cars subject to a high amount of highway driving (e.g. fleet vehicles) because it can yield high potential operating cost savings over the life of the vehicle as seen in Figure 5 [2]. These data from Ford Motor Company in Germany show that a reduction in the coefficient of drag value – expressed as  $C_d$  in English and  $C_w$  in German – of 0.03 – accomplished by closing the undercarriage of a vehicle – can reduce fuel consumption by 20% at a constant highway speed of 180 km/h [2]. This has an even more significant impact in countries with high or no speed limits (e.g. Germany).

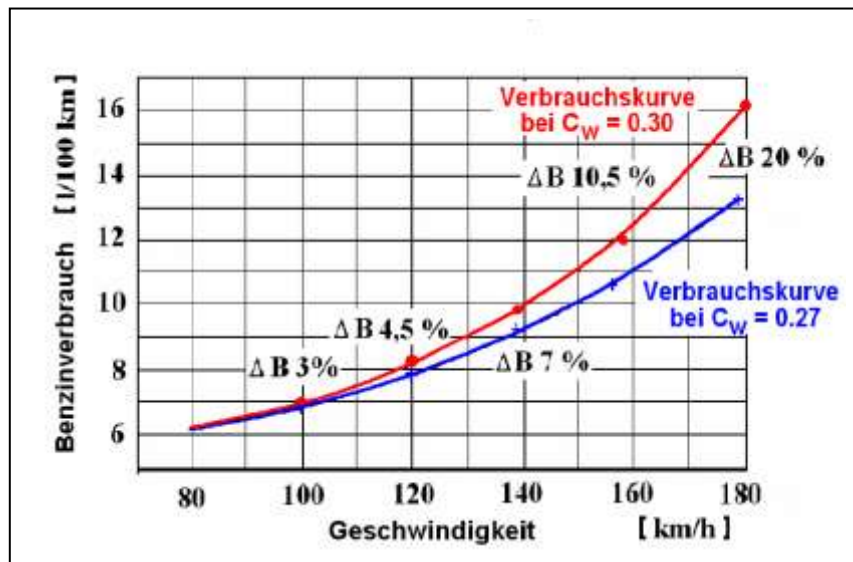


Figure 5: Fuel consumption (l/100 km) as a function of driving speed (km/h); red line  $C_w = 0.30$  and blue line  $C_w = 0.27$  (source Ford Motor Company)

Use of under-floor closure systems have clearly been shown to reduce vehicle drag and improve fuel economy; however, installing shields adds mass, which (if sufficiently high) can decrease fuel economy. The challenge is clearly in balancing these concerns. For vehicles where improved fuel economy is important, the goal is to produce the underbody closure system from a lightweight, stiff, and tough material. This has typically been met by using the LWRT composites previously mentioned. With these materials, mass reduction is not achieved by reducing wall thickness – which would compromise stiffness – but rather by reducing density, since these materials have a higher stiffness / weight ratio than conventional GMT composites and offer the ability to vary thickness across the final part while maintaining the same area weight and keeping a flat surface to the road. Where greater flexural stiffness is needed, the part is left thicker in the molding process; but where greater tensile strength is required (e.g. around fixation points), the part is pressed thinner and more fully consolidated.

The first automaker to use this material / process for under-floor closure systems was BMW®. Initially the 5 and 6 Series vehicles were outfitted with LWRT underbody shields in 2003, followed by the 3 and 1 Series vehicles in 2004. Figure 6 shows the under-floor closure system for a 6 Series vehicle using 4 parts. The components are molded in family tools capable of producing 4 parts / cavity fitted to low-pressure molding equipment. This level of productivity and the use of relatively low-cost tooling and presses helps make the technology cost competitive between GMT and DLFT. Because LWRT composites without a facing skin are open porous structures, initial versions of these underbody systems were faced with a PP skin on both sides of the part to avoid the potential for water uptake on wet roads.

LWRT underbody closure systems continue to evolve. Recent developments on new models at other OEMs have shown that the area weight of the parts can be reduced even further (down to 1,100 – 1,000 g/m<sup>2</sup>) while still meeting performance requirements, including extreme tests like the high- and low-speed water driving tests. At one German OEM, 2 existing under-floor parts – formed, respectively, using DLFT and injection molding – were consolidated into a single LWRT part that was 70% lighter than the 2 parts it replaced. Thanks to tooling savings on that program, the LWRT part was also cost competitive vs. the lower performing technologies it replaces. New models and parts will be seen in early 2007.



*Figure 6: CAD design showing underbody closure system for BMW 6 Series vehicles*

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### **Acoustical Performance**

The acoustical performance of passenger vehicles is becoming a greater focus not only for development engineers, but also customers. Use of an underbody closure system can contribute to the overall acoustical performance of a vehicle in 2 ways: first, it provides insulation and sound absorption for motor and gearbox noises, helping lower drive-by noise levels; and second, it absorbs noise generated by the wheels, as well as reducing the sound of water splash and stone impingement on the underside of the vehicle, helping reduce interior noise levels.

While this trend started with luxury models, interest in creating quieter vehicles is translating across other platforms as a way of differentiating products from their competition. More demanding acoustical performance requirements began with the new Mercedes-Benz S Class, but will subsequently be translated to other premium models.

The acoustical properties of 3 different materials with different porosity are shown in Figure 7. The values were measured by impedance tube according to EN ISO 10534. Not surprisingly, the material with the highest sound absorption was the 1,175 gsm (highly lofted) LWRT composite. Its porous structure makes this material excellent for absorbing sound. The next best product was the natural-fiber composite, since many of its plant-based reinforcements have hollow stems. And the poorest sound absorption properties were seen in the consolidated LWRT composite, which would have very similar acoustical properties to other fully consolidated (compressed) materials like LWRT, GMT, DLFT, and IM.

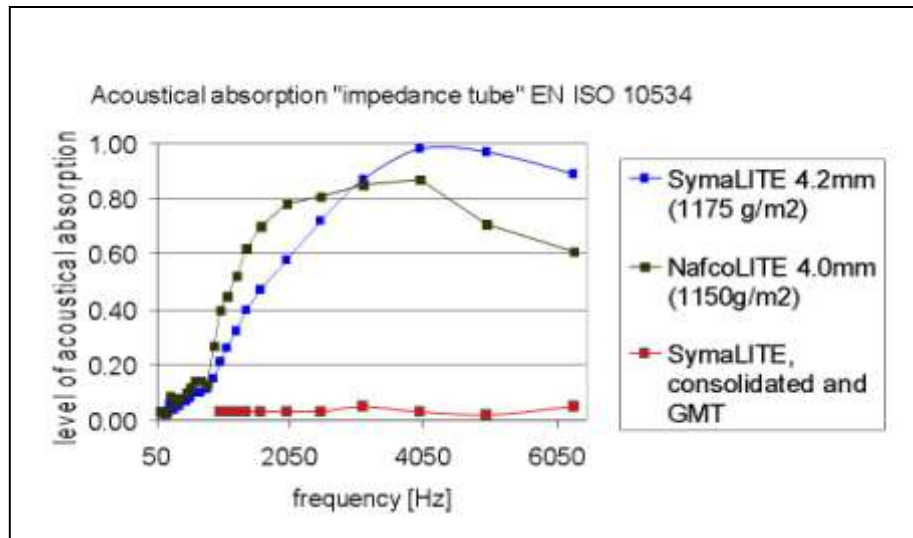


Figure 7: Sound absorption of porous LWRT composite (blue line), natural-fiber GMT composite (black line), and non-porous materials: consolidated LWRT, GMT (red line)

Use of surface films such as PP, which were employed on first-generation LWRT underbody systems to seal the porous composite from water uptake, were found to reduce the material's acoustical absorption significantly. Once again, engineers were faced with a trade-off between reducing the potential for moisture absorption and decreasing the sound-damping properties of the shield.

In the meantime, tri-laminate composites containing thermoplastic polyester fleeces on both sides with a core PP-film were being used for wheel-arch liners. These laminates also possess a porous outer structure yet performed without problems in a wet environment. This led to the acceptance of some water uptake for parts on the underside of the vehicle. It is perceived that improving the acoustical performance of the vehicle has higher priority and value than the potential that water may drip from parts after driving on wet roads. A water uptake of roughly 20% of the part's weight is now considered acceptable among European OEMs as long as the part fulfills all other performance requirements regardless of whether it is wet or dry. Testing has shown that even when the parts are allowed to take up water, then frozen, the moisture has no negative effect on the material or molded-part performance.

For locations where acoustical insulation is needed to improve sound absorption, such as under the motor and gearbox, a compromise has been reached by closing the street side of the composite with a PP film, but leaving the car side of the composite acoustically open. This is accomplished by adding special fleeces of thermoplastic fibers. If maximum sound absorption is required, both sides of the composite are designed to be acoustically open. Figure 8 shows how sound absorption of an LWRT composite is affected when different skins are used on one or both sides.

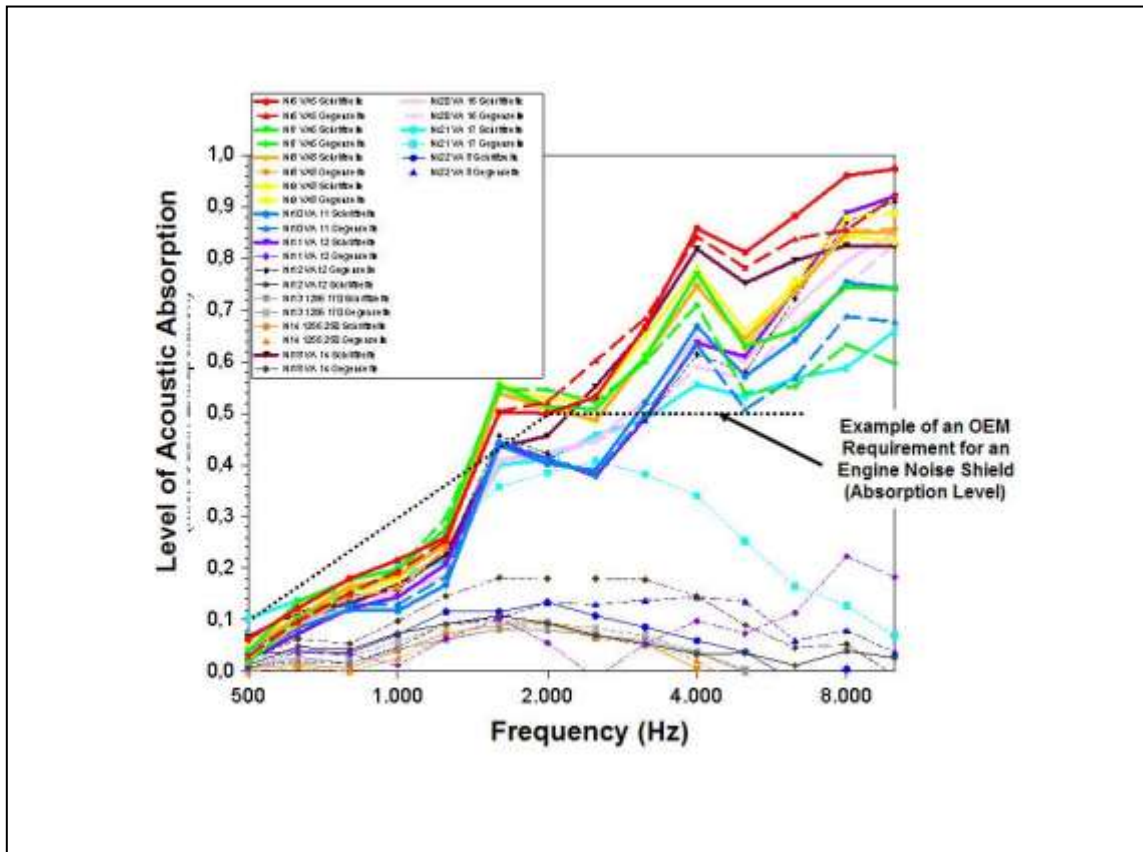


Figure 8: Acoustical absorption capabilities of LWRT materials with various surface layers

## Service Temperature

A consequence of using larger, more powerful engines and packing more components into the underhood compartment (with less airflow) is that engine temperatures are on the rise. This thermal gain is seen not just under the hood, but also below the motor compartment.

The standard lifetime service temperature rating for PP-based composites is typically in the 110 – 115C range, with a slight degradation on the surface of parts toward end of life. To achieve an intermediate level of thermal performance at an intermediate price range, a blend of PP and nylon has been shown to yield good results. When this blend is used as the matrix for GMT-based composites, the same processing equipment (hot-air ovens) can be used, since low-viscosity PA grades are used in the blend. However, oven settings should be increased from the typical 210C setting for PP-based composites to 240C to properly soften blanks prior to molding. In addition to raising the service temperature rating of the composite roughly 20-25C, use of the PP/PA matrix also provides slightly higher mechanical properties, particularly at elevated temperature. This, in turn, provides interesting opportunities to reduce weight further. For example, at 140C, the tensile strength and modulus of PP/PA-based GMT composite with 35% glass reinforcement has 25% higher strength and 33% greater stiffness than that for PP-matrix GMT with the same glass loading. Hence, wall thickness on the PP/PA composite could be reduced from 2.8 to 2.2 mm and still provide comparable performance as the PP composite, saving weight and offsetting the higher material price.

## Bad-Road / Off-Road Performance

As noted previously, the number of cars being exported to countries with a high amount of unpaved roads is increasing steadily. Vehicles designed to be driven under such conditions

require higher performance from the under-floor closure system, since there may be frequent contact with the road and the shield must prevent damage to the vehicle's undercarriage. Solutions for rough-road usage have already been developed and commercialized on models produced by Audi, DaimlerChrysler, and BMW.

In some cases, sandwich composites of classic GMT with chopped glass mats are used in conjunction with textile-reinforced GMT composites selectively added to those areas requiring higher performance. The high inherent elongation of these engineering fabrics creates high resistance to crack generation and propagation.

Another solution has been to use LWRT composites with pre-impregnated glass fabrics as surface layers to provide a highly resistant surface for the PP / glass core. The porous nature of the LWRT core helps to absorb mechanical energy, and the tough textile skins provide scuff resistance and improved impact protection. Applications are under development.

A significant growth of models in the SUV segment and their derivatives was seen during the last decade. Increasingly, SUVs are also being exported to countries with poor roads where they are used as off-road vehicles to reach remote locations. In some cases, performance requirements for such heavy-use models are the same as other vehicles for bad-road conditions. However, sometimes these requirements can be even higher. For example, the recently launched Mercedes-Benz M-Class model has the auto industry's most demanding performance requirements for under-floor parts.

Figure 9 shows 2 under-floor panels (positioned behind the motor-shield panel) after aggressive driving tests. During these tests, the car is driven up and onto rocks and the complete vehicle's weight must be borne by the under-floor panels. To meet these harsh requirements, new grades of textile-reinforced GMT composite have been developed with more layers of glass fabrics and a higher overall glass content. Of interest to many, it is only a small step to move from these highly loaded underbody parts to a full structural composite floor system for a vehicle. Not surprisingly, the idea of combining automotive floors and under-floor systems has become a hot topic of discussion.

## **Summary and Outlook**

A full-length underbody closure system has been shown to contribute significantly to improved fuel economy for a vehicle. While many commercially proven composite materials / processing combinations are now available for such parts, it is important to define the level of performance, mass, and cost a platform can support. Different types of vehicles necessarily have different requirements. For vehicles where the highest level of part performance in combination with greater mass savings are required, highly consolidated classic GMT or low-density LWRT composites offer clear benefits. As interest in reducing the curb- and interior-noise levels of a vehicle grow, the ability of LWRT composites to absorb noise while also reducing mass on a vehicle are becoming more attractive. For special requirements such as higher service temperatures or greater mechanical loads, existing GMT-based composites have been modified to provide tailored solutions developed in partnership with OEMs and tier suppliers. Future under-floor closure systems are likely to require even higher levels of mechanical performance, fuel efficiency, and light weight – potentially evolving into integrated floor / underbody systems. The successful use of textile-reinforced GMT grades for very demanding applications has proven the capability of these new products for more structural applications.



*Figure 9: Under-floor panels for the new Mercedes M Class vehicle after driving tests that forced the panels to bear the weight of the entire vehicle*

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