Development & Engineering of Composite-Intensive Coach for
EN-V Demonstration Vehicle Fleet

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Abstract
This paper describes the design & development of the coaches (bodies) for the EN-V demonstration vehicle fleet. This fleet of 9 non-production vehicles (3 each of 3 models) featured extensive use of composite materials to successfully meet the integration challenges of a unique vehicle propulsion system as well as achieve compelling, innovative aesthetic design.

The architecture for the vehicles consisted of a common propulsion platform to which three unique, highly-differentiated bodies were interchangeably mounted. Significant focus was placed on engineering a common floor structure to achieve interchangeability and reduce sensitivity to upper structure design.

The coaches made extensive use of carbon fiber composites in interior, exterior and structural members. Carbon fiber composites were selected for their combination of high stiffness, low mass and ability to leverage low-cost, rapid-turnaround tooling. Finite element analysis was conducted to manage structural section sizes, thereby enabling styling flexibility and preserving occupant space. Polycarbonate glazing was used to enable weight reduction as well as achieve complex shapes. Additionally, sintered plastic parts were used for secondary reinforcements and were fabricated via additive manufacturing techniques to reduce tooling time & cost.

Background
As part of the 2010 World Expo held in Shanghai, General Motors and SAIC (Shanghai Automotive Industries Corporation) collaborated to develop and present a vision of personal urban transportation in the year 2030. A major element of this presentation was a fleet of demonstration vehicles, collectively known as EN-V (which is short for Electrical Networked-Vehicle). These demonstration vehicles were featured in daily usage in the Expo and have had continued usage since the conclusion of the Expo in late 2010.

The EN-V demonstration vehicle program consisted of nine vehicles, three each of three different body styles. (Figures 1-3) All three of the body styles mount interchangeably to a common propulsion platform. (Figure 4) Although the propulsion technology is not the focus of this paper, some background is useful to understand the associated integration and execution challenges to the coach.

The vehicle is propelled by electric motors in each of its two driving wheels. The motors not only provide power for acceleration, but also bring the vehicle to a stop. The propulsion platform utilizes dynamic stabilization technology, such that, while in motion, the vehicle balances on only its two driving wheels. As a result, the vehicle can literally “turn on a dime” within its own operating envelope.

The EN-V vehicles carry two passengers and light cargo in a footprint that is about a third of that of a traditional vehicle. In addition, the EN-V has drive-by-wire controls. By combining the
Global Positioning System (GPS) with vehicle-to-vehicle communications and distance-sensing technologies, the EN-V concept can be driven both manually and autonomously. In recognition that mobility is also a statement of personal choice, the EN-V vehicles demonstrate compelling aesthetic design with a high degree of embedded personal connectivity.

Composite materials played a key role in the execution of the EN-V program. The types of composite materials, key application/design factors and the underlying rationale are explained in the remainder of this paper.
Key Coach Requirements

In order to take full advantage of the propulsion system technology as well as achieve vehicle objectives, there were a number of key requirements for the coach, as outlined in Table I. These requirements are described further below.

Table I: Key Coach Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>lightweight</td>
<td>a) increased range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) increased acceleration/deceleration per kW of motor output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) maintain margin for ballast mass if needed to tune CG location</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d) maintain occupant payload</td>
</tr>
<tr>
<td>2</td>
<td>location of center-of-gravity (CG)</td>
<td>a) maintain balanced acceleration/deceleration capability</td>
</tr>
<tr>
<td>3</td>
<td>efficient packaging</td>
<td>a) maximize occupant space for given size of vehicle footprint</td>
</tr>
<tr>
<td>4</td>
<td>structural stiffness</td>
<td>a) ensure that elastic deformation of coach does not affect clearance to propulsion platform</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) ensure that elastic deformations (sag, twist) of closures &amp; body apertures do not affect closure operation</td>
</tr>
<tr>
<td>5</td>
<td>structural strength</td>
<td>a) ensure that coach withstands normal operating conditions without damage</td>
</tr>
<tr>
<td>6</td>
<td>styling flexibility</td>
<td>a) enable compelling, distinctive interior &amp; exterior appearance</td>
</tr>
</tbody>
</table>

Lightweight:

The benefits of reduced body mass in terms of increased vehicle performance (acceleration, range) are readily apparent. However, due to the nature of the dynamic-balancing propulsion technology, low body mass takes on even greater significance in the EN-V. The vehicle does not use friction brakes for stopping/slowing. Instead the wheel drive motors are used to apply a reversing torque to slow/stop the vehicle. The consequence is that the ability to stop/slow the EN-V is significantly affected by coach mass.

Also, as a dynamically-balanced machine, the location of the center-of-gravity (CG) has great significance to resultant vehicle dynamics. Consequently, the location of the coach CG needed to be tracked & controlled during the design process. As a last resort, a lightweight coach enabled the potential to use ballast mass as a counter-measure to tune the CG without violating the target gross vehicle mass.
Location of Center of Gravity:

Forward & reverse motion of the EN-V is commanded by sliding the coach forward & rearward relative to the drive wheels. (Figure 5) For the vehicle to move forward, the coach (and occupants) is shifted forward (via an actuator) relative to the drive wheels. In this condition, the center-of-gravity of the vehicle is now forward of the drive wheels, which causes the vehicle to want to pitch/rotate forward. Left unchecked, the vehicle would pivot (as an inverted pendulum) until it contacted the ground. Instead, accelerometers in the propulsion platform sense this angular acceleration and the propulsion controller commands the drive wheels to move forward until the drive wheels are vertically under the center-of-gravity. Reverse motion/deceleration of the vehicle occurs in the opposite way.

Due to practical & packaging limitations, the amount of fore-aft slide travel of the coach was limited to ± 255 mm. In order to maintain balanced acceleration & deceleration capability, the center-of-gravity of the coach needed to be centered in this zone. This required the definition of a target zone for the fore-aft location of the CG of the coach. (Figure 6) Additionally, since the vehicle essentially operates as an inverted pendulum, the height of the CG above the tire contact patch also is an important consideration in overall vehicle dynamics. Consequently, the target zone for the coach CG not only included fore-aft position, but also vertical position.

On a practical basis, this required periodic assessment of interim Studio surfaces via numerical approximations to estimate the location of the center-of-gravity, for which centroid of the exterior shell was often used as a surrogate. These interim assessments were important to providing feedback to the Studio for adjustments to the shape of the exterior of the coach to position the CG more favorably to the target zone. It is important to note that these interim assessments had to be done as first-order approximations and without full definition of all component designs, inasmuch as by the time a full engineering design could be completed for a given exterior shape, the window of opportunity to adjust the exterior shape within program timing would have passed.
Efficient packaging:

One of the key goals for the EN-V vehicle is to minimize footprint, so as to enhance maneuverability & parking in congested urban areas. As a result, efficient packaging of the coach was key. In contrast to a typical vehicle, the EN-V coaches were explicitly designed for two passengers with limited cargo. To achieve an efficient package, focus was placed in three areas: a) selecting materials/designs that would enable small section sizes; b) establishing a more upright seated occupant position that permitted packaging of coach electrical components beneath the occupants (rather than in front of or behind occupants); and c) leveraging opportunities for effective functional integration (such as using closed sections of the body structure also for ventilation ductwork).

The importance of efficient vehicle packaging is shown in Figure 7, which illustrates that the ability to minimize vehicle width is heavily influenced by occupant seating height as well as the location/shape of coach structural members. In this regard, carbon fiber composites provided significant advantage in their ability to achieve highly contoured shapes and tailored reinforcement, so as to optimize section placement.

Maintain adequate structural stiffness:

Given the small size of the EN-V vehicles and the limited sources of on-board dynamic excitation, vehicle modal characteristics were not a significant consideration. However, static stiffness was an important consideration, especially for closures. To maintain reasonable ingress/egress into an otherwise small vehicle, the size of the single door was disproportionately large. As a result, high static stiffness of the closure and body aperture was important to ensuring that elastic deformation of the components did not cause misalignment, twist or sag during door operation.
Maintain adequate structural strength:

Given the high-profile nature of operation of the demonstration vehicles, it was important that the coaches be robust. However, since the vehicles were not going to be used on general-purpose or uncontrolled road surfaces, it was undesirable to incur the mass penalty associated with designing/engineering higher strength into parts than was reasonably necessary for intended operation. As a result, the coaches were generally designed to a fully-occupied inertial loading of:

- a) 1.8g vertical;
- b) 1.5g vertical / 0.3g fore-aft;
- c) 1.5g vertical / 0.3 g lateral.

On a practical basis, this relaxation in strength requirements from that of a typical passenger vehicle was not an active constraint in the design process, inasmuch as finite element analysis indicated that the coaches were stiffness-limited, not strength-limited.

Enable styling flexibility:

Although the EN-V coaches needed to satisfy a number of challenging engineering requirements, it was equally important that the aesthetic design of the coaches be compelling and highly-varied. Given the global nature of the World Expo, the coaches were styled by several different GM Design Studios across the world. Additionally, given the intent that the vehicles represent a concept of personal urban transportation in the year 2030, it was important that the coach materials & processes be innovative and differentiated from vehicles of today.

Program timing:

The overall timeline for the coach portion of the program is shown in Figure 8. Although the program had significant technical and styling reach, it nonetheless had firm deadlines for completion of the coaches. Of particular significance is that the timeline allowed only 12 months to completely style, engineer, and build the first coach of each body style.
Coach Architectural Definition

Early in the program, much focus was placed on establishing the coach architecture. Within this context, there were three key aspects: a) interface to the propulsion platform; b) occupant placement; c) structural configuration/materials. These are elaborated in the following sections.

Interface to propulsion platform:

The propulsion platform for the EN-V vehicles was a completely new, ground-up design that was being engineered simultaneously and remotely from the coach. To permit the development of the coaches and propulsion platform to be de-coupled as much as possible, a common set of mounting locations & clearance zones between the coach and propulsion platform were defined up-front. This common approach to mounting the coaches was particularly important because the coaches were being styled in a variety of GM facilities around the world, while the propulsion platform was developed in North America.

In addition to reducing program complexity, the strategy of interchangeable coaches also provided a mechanism for enhancing field reliability by permitting coaches & propulsion platforms to be quickly swapped in the event of damage. The only mechanical interface between the coach and propulsion platform were four elastomeric mounts. (Figure 9) The only other interface between the coach and propulsion platform were two small electrical cables that carried the drive-by-wire commands from the coach.

In practice, careful attention to the design & engineering of the coach interface to the propulsion platform enabled the coach to be removed from one platform and installed on another platform within three hours.

Figure 9: Interface of coach to propulsion platform (common)
Occupant placement:

As noted in “Key Coach Requirements”, the use of dynamic-balancing propulsion technology required careful attention to the location of the center-of-gravity (CG). Since the vehicle needed to be capable of operation both with and without occupants (for autonomous parking maneuvers), this required the occupants to be positioned to achieve a neutral location of their CG relative to the drive wheels. (Figure 6) This is particularly significant since the target mass of the coach was approximately the same as its two occupants.

Furthermore, since the occupants were going to be of a variety of sizes, their seated posture needed to be one that produced relatively small variation in CG fore-aft location. Consequently, the occupants were positioned in a more upright posture than in a traditional car. By keeping the legs & back nearer the occupant H-point, this reduced the amount that the CG moved among occupants of different sizes, as confirmed by analytical anthropomorphic studies. (Figure 10)

Structural configuration/materials:

Broadly, the structural configuration and materials needed to satisfy vehicle performance requirements (mass, stiffness, strength, styling flexibility) as well as program timing requirements. Several potential structural configurations and materials were considered early in the program. Among the structural configurations considered were: a) distributed sheet; b) space frame; and c) monocoque.

The distributed sheet configuration is typical of the construction of most passenger cars. It is characterized by formed inner & outer members that are joined together to create an integral structure. The space frame configuration is characterized by beam members (in this case, likely aluminum tubes) to which panels (likely composite) are applied. The monocoque configuration can be broadly characterized by the absence of explicit beam elements and the use of interior & exterior surfaces as actively-stressed members.

These concepts were evaluated and assessed against vehicle requirements and program risk
factors. These factors included program timing, budget, interior and exterior development phasing, styling flexibility, and engineering complexity. The distributed sheet configuration was selected and the question then became one of material selection.

A number of different materials were subsequently considered:

- a) aluminum
- b) steel
- c) glass-reinforced composites
- d) carbon fiber composites

To permit a rapid decision in the absence of detailed finite element models, an assessment was made based on the assumption that the overall body was going to be stiffness-constrained (which tends to be true for conventional passenger vehicles). Within the context, the stiffness (k) of a structural member can be idealized according to the following relationship:

\[ k \sim Et^\alpha \]  \hspace{1cm} (Equation 1)

in which:

- "E" is the elastic modulus
- "t" is the effective thickness
- "\alpha" is a thickness sensitivity coefficient.

For a pure thin-walled beam or axial member, \( \alpha = 1 \). For a plate in bending or torsion, \( \alpha = 3 \). Past studies have shown that in typical automotive structures, \( \alpha \approx 2 \).

From this relationship, the relative thickness of equivalent stiffness panels made from two materials (material “A” & material “B”) can be calculated as:

\[ \left( \frac{t_A}{t_B} \right) = \left( \frac{E_B}{E_A} \right)^{1/\alpha} \]  \hspace{1cm} (Equation 2)

For a structural member of a given geometry, the mass (m) is proportional to the product of material density (\( \rho \)) and effective thickness (t):

\[ m \sim \rho t \]  \hspace{1cm} (Equation 3)

Substituting Equation 2 into Equation 3, we can then establish that the relative mass of equivalent stiffness structures of comparable geometry can be idealized as:

\[ \left( \frac{m_A}{m_B} \right) = \left( \frac{\rho_A}{\rho_B} \right) \times \left( \frac{E_B}{E_A} \right)^{1/\alpha} \]  \hspace{1cm} (Equation 4)

Using this, the relative mass of alternate material structures of similar geometry designed to achieve the same stiffness can be quickly assessed.

From a literature search of typical material properties for substitution into Equation 4, the relative resulting mass of alternate materials is summarized in Table II. From this assessment, carbon fiber composites were selected as the target material for the construction of the EN-V coaches. In addition to lightweight, carbon fiber composites also permitted the use of single-sided tools. This tooling strategy permitted significant reductions in lead time compared to that required for double-sided matched tools and this was important to achieving program timing.
### Table II: Comparative properties & masses of idealized panels of alternate materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Density (kg/m³)</th>
<th>Normalized Thickness</th>
<th>Normalized Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fiber composites (pre-preg)</td>
<td>35</td>
<td>1300</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SMC</td>
<td>14</td>
<td>1800</td>
<td>1.58</td>
<td>2.19</td>
</tr>
<tr>
<td>Fiberglass (manual wet lay)</td>
<td>7</td>
<td>1500</td>
<td>2.24</td>
<td>2.58</td>
</tr>
<tr>
<td>Aluminum</td>
<td>69</td>
<td>2800</td>
<td>0.71</td>
<td>1.53</td>
</tr>
<tr>
<td>Steel</td>
<td>207</td>
<td>7830</td>
<td>0.41</td>
<td>2.48</td>
</tr>
</tbody>
</table>

### Material utilization

As noted above, carbon fiber composites were selected as the primary coach material for a combination of light weight and ability to be fabricated from single-sided tools. However, carbon fiber composites were not the only material used in the coach, as outlined in Table III. The guiding principle in the design and engineering of the EN-V coaches was to use a variety of materials, but to apply those materials where they provided specific benefit to the needs of the program: lightweight; ability to enable rapid part fabrication; ability to enhance flexibility in developing shapes for exterior/interior surfaces. The primary materials and their application are outlined below.

### Table III: Primary Coach Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Material</th>
<th>Where used</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>carbon fiber</td>
<td>a) exterior panels</td>
<td>60 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) coach structure (inner &amp; outer panels)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) closure structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>d) interior trim panels</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>polycarbonate</td>
<td>a) glazing</td>
<td>20 kg</td>
</tr>
<tr>
<td>3</td>
<td>sintered thermoplastic</td>
<td>a) hinges for secondary closures</td>
<td>5 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) non-structural supports for interior trim panels</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>aluminum</td>
<td>a) structural reinforcements</td>
<td>9 kg</td>
</tr>
<tr>
<td>5</td>
<td>steel</td>
<td>a) hinge mechanism for doors</td>
<td>14 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) tapping plates</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>other</td>
<td>a) soft trim (foam, fabric)</td>
<td>10 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) structural adhesive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) paint/surfacing materials</td>
<td></td>
</tr>
</tbody>
</table>
Carbon fiber composites:

Carbon fiber composites were the primary material used in the coach. On average, each coach contained about 65 carbon fiber parts, with a cumulative mass of about 60 kg.

The specific carbon fiber was an epoxy pre-preg with 50% fiber volume fraction (40% resin by weight). The carbon fiber was a 2X2 twill weave with 3k yarn, with a fabric weight of 199 grams/m² and a nominal thickness of approximately 0.25 mm per ply. The epoxy was a low-viscosity formulation, specifically targeted for low-temperature cure. A pre-preg was used to achieve better control over part thickness and resin wet-out than what would generally be the case with a wet-lay process. The particular carbon fiber was also selected for its capability to be molded at room-temperatures, so as to reduce timing & construction requirements for the lay-up tools.

Carbon fiber composites were used for all of the primary exterior, structure and interior panels in the EN-V coaches. To illustrate, Figures 11 & 12 show exploded diagrams of the carbon fiber panels for the Jiao coach structure and interior.

![Figure 11: EN-V carbon fiber coach structure (Jiao variant)](image1)

![Figure 12: EN-V carbon fiber interior trim (Jiao variant)](image2)
Although there are a wide variety of commercially-available carbon fiber materials, a strategic decision was made up-front to utilize only a single type throughout the coach, so as to simplify inventory management and process control. The selected material provided approximately balanced properties in the longitudinal and transverse direction, so as to simplify lay-up schedules. Although greater mass reduction could have potentially been achieved with use of uni-directional materials, this would have required greater levels of finite element analysis and manufacturing process instruction/control and would have exceeded the project timeline.

As is well known, carbon fiber composites provide the opportunity to tailor the lay-up schedule to specific part requirements in order to fully optimize mass. However, this flexibility to tailor lay-up schedule also introduces manufacturing complexity, especially when lay-ups are being done manually (as opposed to via automated placement). Since parts for all three EN-V coach variants were going to be fabricated simultaneously in the same shop, a decision was made early in the program to restrict lay-up schedules to a few combinations. After early finite element analysis, three primary lay-up schedules were established as shown in Table IV.

<table>
<thead>
<tr>
<th>Item</th>
<th>Schedule</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°/45°/45°/0°</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>2</td>
<td>0°/45°/0°/0°/45°/0°</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>3</td>
<td>0°/45°/45°/0°/0°/45°/45°/0°</td>
<td>2.0 mm</td>
</tr>
</tbody>
</table>

In order to provide meaningful input to subsequent finite element analysis as well as assess consistency of part-to-part properties, a simplified qualification test program was conducted. In this test program, 300 mm x 300 mm test plaques were fabricated over a series of several months and then cut into specimens for measurement of flexural modulus (across a variety of orientations within the plaque) as well as density. From this testing, the following properties were established for subsequent finite element analysis:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (quasi-isotropic)</td>
<td>26.5 GPa (3.8 Msi)</td>
</tr>
<tr>
<td>Density</td>
<td>1450 kg/m³</td>
</tr>
</tbody>
</table>

Several comments are worthwhile. The first is that a literature search will undoubtedly reveal different properties for similar carbon fiber materials. However, the properties shown above represent what was reasonable to achieve within the build shop that was actually fabricating the parts. Within the context of EN-V program timing, it was more effective to focus efforts on establishing stable design properties than to pursue a parallel program to further enhance achievable material properties through additional manufacturing process control/optimization.

Secondly, the use of a quasi-isotropic elastic modulus is clearly an approximation, but was
viewed as a reasonable simplification, given the particular lay-up schedules and the fact that the pre-preg material had approximately balanced transverse & longitudinal properties. Additionally, since the detailed engineering design/analysis of the coach structures for all three variants needed to be completed within 6 months, there was insufficient time to do more rigorous orthotropic finite element analysis of the coaches.

**Polycarbonate:**

Polycarbonate was used for all glazing in the EN-V coaches. On average, each of the EN-V coaches contained about 20 kg of polycarbonate glazing, with a typical thickness of 5 mm.

Polycarbonate was used for two primary reasons: styling flexibility and weight. Since the EN-V coaches were all small in comparison to typical passenger cars, a significant portion of the exterior was intended as glazing in order to provide increased visibility and sense of occupant spaciousness as well as to provide a distinctive exterior appearance. For the EN-V coaches, approximately 45% of the exterior surface was glazing, in comparison to 25% for a small passenger car. A comparison of density for glazing materials is shown in Table VI. Even allowing for the fact that polycarbonate glazing needs to be thicker than glass, polycarbonate still provided a significant mass reduction.

<table>
<thead>
<tr>
<th>Item</th>
<th>Glazing Configuration</th>
<th>Areal Density (kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>laminated glass (6 mm thick)</td>
<td>14.8</td>
</tr>
<tr>
<td>2</td>
<td>tempered glass (4 mm thick)</td>
<td>10.8</td>
</tr>
<tr>
<td>3</td>
<td>polycarbonate (6 mm thick)</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td>polycarbonate (5 mm thick)</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Equally as significant, polycarbonate permits much greater complexity in the surface of the glazing in comparison to glass. This was particularly important inasmuch as the large glazed surface area of the EN-V coaches meant that surface features and forms needed to traverse into glazed areas. The canopy of the Jiao EN-V coach (Figure 13) was particularly challenging in the double-curvature feature running down from the upper “corners”.

*Figure 13: Complex polycarbonate canopy (Jiao EN-V variant)*
Sintered thermoplastic:

Sintered thermoplastic was used in a number of applications in the EN-V coaches. Although sintered thermoplastics do not offer material properties (Table VII) comparable to carbon fiber composites or other structural materials, they may be processed by additive manufacturing techniques which offer extremely quick turn-around (a few days) and eliminate the need for tooling. Within this context, sintered thermoplastics were used to great advantage for semi-structural and non-structural applications.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (kg/m^3)</td>
<td>1000</td>
</tr>
<tr>
<td>elastic modulus</td>
<td>1400</td>
</tr>
<tr>
<td>yield strength (MPa)</td>
<td>38</td>
</tr>
<tr>
<td>heat distortion temperature (°C)</td>
<td>188</td>
</tr>
</tbody>
</table>

A particularly good example of this application was for the hinging on the charge port doors and rear access panels. Using the Jiao variant as an example, the rear charge port door and rear access panel hinges are illustrated in Figure 14. By virtue of the exterior shape and packaging, the swing of these panels required hinge geometries of moderate complexity. If executed in aluminum, these hinges would have required 5-axis machining or multiple set-ups and would have taken much longer to manufacture.

In general, the lower material properties associated with sintered thermoplastics were offset by designing with increased material thickness. Even with the increased thickness, the sintered thermoplastic parts were still substantially lighter than what they would have been in aluminum.

The aggregate mass of sintered thermoplastic parts in each coach was about 5 kg. More importantly, this 5 kg consisted of over 30 individual parts per coach, for which the savings in aggregate fabrication time was significant.
**Structural adhesive:**

Bonding was the primary means of joining the carbon fiber panels together. A 2-part urethane adhesive was used throughout the coach structure. The specific adhesive was an extended pot-life version of a urethane adhesive already in use for composite panels on GM production vehicles. Where relevant, the properties of the adhesive were included in finite element analysis.

**Metals:**

Although the focus of this paper is the successful use of composites in the EN-V coaches, metals still played an important role in the execution of the vehicles, particularly in the execution of the door hinging and high-load structural reinforcements. A good example is the carrier for the door hinge system in the Miao body variant. In this case, the front door operates as a very large 4-bar link and its motion is controlled by three stainless steel shafts sliding in pillow blocks. (Figure 15)

![EN-V Miao door hinge bracket configuration](image)

For smooth operation of the door and good control of the kinematics during opening, the relative dimensional position of the pillow blocks must be closely controlled. For this reason, the pillow blocks were designed to be attached to a single structural bracket. The original design for this bracket was as an 8-ply (2 mm) carbon fiber lay-up with multiple metallic reinforcements. However, early testing of coaches revealed that this bracket demonstrated excessive twist as the door opened, due to the cantilever load that developed as the door approached the open position.

As a result, the bracket was re-designed as a single-piece milled aluminum component with a nominal thickness of 8 mm. This aluminum design provided sufficient stiffness to ensure
smooth door operation. Additionally, a 7-piece assembly was integrated into a single part. The key point is that there were instances in the EN-V coach in which metals permitted a more effective, robust engineering solution than composites by themselves. In aggregate, each coach used about 9 kg of aluminum and 14 kg of steel, representing about 11% of total fully-trimmed coach mass.

Coach Design Approach

As noted in “Coach Architectural Definition”, the overall configuration of the EN-V vehicle architecture could best be described as “body-on-frame”, in which the propulsion platform was designed to house all of the propulsion/chassis system components (propulsion, steering, braking). As a result of the need for the body variants to be interchangeable on the propulsion platform and the fact that the propulsion platform was being designed/engineering simultaneously with the coaches, the underlying design philosophy was that the coach was to be self-supporting and have sufficient stiffness/strength to manage occupant loads without reliance on structural contribution from the propulsion platform.

In designing the panels on each of the EN-V coaches, the strategy was to minimize part count as much as possible. This was done to reduce part tooling and subsequent assembly time as well as improve overall dimensional control. For example, the body structure of the Jiao EN-V coach (Figure 11) consisted of only 10 major panels. Similarly, the closure (canopy) structure of this vehicle consisted of only 7 major parts. (Figure 16) In all cases, the ability to create large complex parts via carbon fiber composites was a key enabler.

During the engineering design phase of the project, finite element analysis was conducted to provide appropriate guidance to sizing structural members. (Figure 17) By necessity, this finite element analysis had to strike the appropriate balance between detail/rigor and turn-around time.
Coach floor design:

An area of particular focus for both structural performance as well as part integration was the coach floor. As discussed in "Coach Architecture", a key element of the coach floor was attachment at common locations to the propulsion platform for each of the variants. Since the majority of the floor was packaged for consistency with the (common) upper surface of the propulsion platform, this permitted the coach floors to be common among the EN-V variants, except for the perimeter of each floor where the floor mated to the remainder of the exterior. With the awareness that the side & upper structure of the each of the variants would be highly specific, the engineering effort focused on designing the floor structure to provide a significant proportion of the overall coach structural stiffness. Correspondingly, a target was established that the floor structure should provide about 65% of the torsional & bending stiffness of the complete coach.

The resultant design of the coach floor is shown in Figure 18. Several points are noteworthy. First is the use of a honeycomb construction. The floor consists of 1.0 mm (4-ply) upper & lower surfaces of pre-preg carbon fiber, separated by 6.35 mm (¼") honeycomb. This was done to increase bending and torsional stiffness, especially since there was insufficient room for underbody rails below the floor. A second key feature is the use of co-molded aluminum inserts at the four body mounts to provide sufficient local strength. A final key feature is that the entire coach floor was molded as a single part, rather than as a bonded assembly of multiple parts.

Specifically, a single-sided female tool of the upper surface was used to first lay-up the 4 upper plies of carbon fiber pre-preg. Then a number of milled low-density (approximately 7 lb/ft³) foam reinforcements were installed, followed by the aluminum inserts and honeycomb reinforcement. Lastly, four plies (1.0 mm) of carbon fiber pre-preg were applied to encapsulate the assembly. The resultant cross-section is shown in Figure 19. This approach offered several important advantages: a) only a single tool was required to fabricate the coach floor, instead of separate tools for the upper & lower faces; b) a high-level of dimensional control was achieved; c) high structural integrity was achieved because there was no need for subsequent bonding.
As noted above, the design target was for the coach floor to provide about 65% of the overall coach static stiffness. In order to do so, substantial finite element analysis was performed to assess torsional & bending stiffness at a component level. (Figure 20) Additionally, local finite element analysis was performed at the coach mounts to ensure adequate strength. (Figure 21)
**Unique closures:**

As part of differentiated styling, each coach featured its own unique & unusual closure configuration. (Figure 22) Composite materials played an important role in the successful execution of these closures.

![Image](image.png)

*Figure 22: EN-V door configuration (left: Xiao; center: Miao; right: Jiao)*

The strategic decision was made early in the program that each coach would have only a single “door”, in order to reduce the weight associated with hinging/latching hardware. Throughout the coach, mass reduction was important, but particularly so in the closures, in order to maintain reasonable opening & closing efforts. As noted in the “Materials” section above, a significant portion of each “door” consisted of glazing. Additionally, given the desire to minimize the footprint and frontal area of the vehicle, the section size for the closures was highly constrained. Within this context, carbon fiber composites were used to achieve an appropriate balance between section size and overall stiffness. In general, the section depth for the closure structures was 35-40 mm.

The design of the canopy for the Jiao body style provides a good case study in the effective application of composites. As was noted earlier, independent of weight, the intended shape of the glazing was not feasible in glass, so the use of polycarbonate was a key enabler to allow the styling studio to achieve the desired shape. The hinge mechanism for the coach is shown in Figure 23. The basic concept is that the hinge pivot was located behind the occupants and that the weight of the door system was to be counterbalanced by damped springs acting on lever arms behind the occupants.

However, due to tight vehicle packaging, the length of the lever arms was highly limited. Since the length of the door was determined largely by the length of the vehicle, the ratio between the center-of-gravity of the door and the length of the spring levers was approximately 25:1 and could not be appreciably changed. The implication is that for each pound of weight in the canopy the resultant force required in the assist spring was 25 pounds. Additionally, as the required force in the spring increased, this necessitated more structure (and weight) into reinforcing the hinge mechanism and coach structure, with the net effect being that of a mass-compounding spiral.

Consequently, minimizing the weight of the canopy had great significance to overall coach weight and opening/closing efforts. Significant finite element analysis was conducted to achieve...
an appropriate, but not excessive level of structural stiffness. Ultimately, between the combination of polycarbonate glazing and effective design of the carbon fiber composite canopy structure, the resultant total weight of the canopy was able to be effectively managed and overall field performance was highly robust.

![Figure 23: Jiao coach canopy hinge configuration](image)

**Functional Integration:**

A final key element of the coach design approach was to achieve a high-level of functional integration. Even though composite materials can provide inherent benefits to mass reduction, the reality is that functional integration provides a lower-mass design for any material. Within this framework, the engineering team placed a high value on: a) getting parts to perform multiple functions; or b) eliminating the need for multiple parts. Several examples may be used to illustrate this approach.

A first example is the seat ventilation duct on the Jiao coach. For purposes of maintaining interior ventilation for occupant comfort, the front of the canopy features an inlet grille. Ventilation fans are located in the rear of the vehicle and pull this air across the occupants and into ducts located on the “package shelf” behind the occupants. (Figure 24) Rather than create a separate duct for purposes of managing this air flow, the structural beam section in the upper half of the seat (Figure 25) is used as the duct, thereby eliminating the need (and weight) of a separate part.
A second example of functional integration is the elimination of the seat motion system and subsequent ability to design the seat structure as a lateral load path to increase overall coach stiffness. As noted in “Architectural Definition”, the location of the center-of-gravity of the occupants has a significant impact on the overall operating dynamics of the EN-V. Consequently, the starting point for occupant packaging was to establish a seating position in which the CG of the occupants was centered over the drive wheels. In practice, there was actually a dis-incentive to permit occupants to shift their position relative to the coach, given the potential to affect vehicle dynamics.

Since the EN-V vehicles were drive-by-wire with all controls being hand-operated, there was no reason for the seats to move for purposes of permitting occupants of different sizes to reach foot pedals. Also, as a consequence of a more upright seating position, an acceptable “fixed” position was found for the steering control that eliminated the need for the driver to move fore-aft. The net consequence was that the direct mass associated with moving seat mechanisms was eliminated from the EN-V coach.

Furthermore, with the seats fixed, this created the opportunity to use the seats as a structural element. This is illustrated in the configuration of the seat structure for the Xiao body style. This body style is somewhat tall and narrow, with an extremely large door. (Figures 2 & 22) Given the size of the door, the body aperture was particularly sensitive to “matchbox” distortion of the coach, with the potential for subsequent misalignment and difficult door operation. Consequently, the need was identified to enhance torsional stiffness of this body style.

Rather than adding separate structural elements, the strategy was to functionally integrate the seat structure (Figure 26) into the coach structure and to use the seat structure as a shear element to enhance coach stiffness.

A final example of functional integration was the deployable driver control arm in the Xiao body style. (Figure 27) In this coach, the driver control arm is a closed oval section that is shaped into a circular arc. In the stowed position, the arm is stored beneath the seat to permit convenient occupant ingress/egress. After entering the vehicle, the driver pulls this arm out along a circular path and then rotates the driver control head into the driving position. The specific shape of the driver control arm is shown in Figure 28. Several elements are key: a) a closed section for high stiffness; b) a hollow section for routing cables from the driver control head down to the propulsion platform; c) a perpendicular pivot at the upper end of the arm for
attachment/rotation of the driver control head; d) creation of high-stiffness geometry at the lower end of the driver control arm to interface to a roller guide.

The original concept for the driver control arm was that of bent aluminum extrusion, to which separate parts would be welded to create the necessary interfaces at the top & bottom. However, as the design evolved, it became apparent that this would require the fabrication & assembly of multiple parts and that the radius of curvature of the bend would be difficult to achieve without section collapse. Instead, the design was revised to that of a single-piece carbon fiber infusion, which provided a quicker, lower-mass, lower-cost execution.

Figure 26: Fixed seat structure integration into coach structure (Xiao EN-V)

Figure 27: Deployable driver control arm – deployed position (Xiao EN-V)
Manufacturing strategy

The key requirement for the manufacturing strategy was to enable the timely, simultaneous execution of multiple high-quality copies of each of the coach styles. The scope of the original program was to produce a total of nine (9) coaches (3 each of 3 styles) within 9 months. By the time that the build actually ended, a total of 15 coaches were manufactured within 13 months. Equally important, the first of each of the three coach variants needed to be completed within 7 months of release of surface data from the Studio. This timeline required both very quick turn-around as well as good process repeatability.

Carbon fiber composite parts:

As noted earlier, the carbon fiber composite parts were made from an epoxy pre-preg, using three (3) different lay-up schedules. The parts were made as manual lay-ups from single-sided tools and were subsequently vac-bagged and post-cured. Vac-bagging was done instead of autoclaving to reduce the loads that the fabrication tools would experience, so as to permit quicker fabrication. Parts were post-cured for 6 hours at 150°F. In both cases, higher pressures and curing temperatures would have further increased mechanical properties, but this did not offer sufficient structural benefit to offset the timing impact.

The tools themselves were constructed in one of two ways. For high-visibility exterior panels, a male master model was constructed and then a steel-reinforced high-temperature epoxy tool was created as a splash from the male master model. For structural inners and interior parts, the tool was constructed directly by CNC-milling high-temperature tooling foam as a female mold.

In total, almost 200 tools were created for the project, from which approximately 1000 parts were produced.
Coach assembly:

The coaches were assembled using typical prototype methods. Assembly fixtures consisted of aluminum positioning “flags” mounted to roll-around bases. (Figures 29 & 30) Assembly was done manually within the GM Prototype Shop. Structural adhesive was applied manually with an electrically-driven dispensing gun.

Additive manufacturing:

Additive manufacturing techniques (primarily, selective laser sintering) were used extensively for hinges for secondary closure panels as well as supports for interior trim panels. These parts were manufactured internally within GM using commercially-available equipment.
Thermo-forming:

Glazing was fabricated via drape forming over a male tool with a combination of vacuum-assist and multi-element heating tables. The key goal of the forming process was to achieve the desired geometric shape while minimizing optical distortion. In some cases, secondary forming tools were required to achieve surfaces with reverse curvature.

Several specific suppliers were leveraged in plastic glazing development, due to their experience and expertise in thermo-forming. These suppliers provided not only technical guidance as well as completed parts for use on the coaches.

Conclusion

Ultimately, the EN-V demonstration vehicle program was highly successful. Composites played an important role in meeting coach performance requirements, providing mass reduction as well as enabling a high level of functional integration & part consolidation. Equally important, the use of composites permitted a high degree of freedom on the part of the styling studios to achieve surface shapes that would have been very difficult to achieve with other materials. Also, the use of composites allowed use of fabrication processes with short lead times and significantly enhanced the achievement of program timing.

The carbon fiber composites were highly-effective at achieving an appropriate balance between section size, occupant packaging and structural stiffness. Standardizing on a limited number of materials & lay-up schedules proved very useful in optimizing part fabrication throughput and manufacturing complexity. The use of simplified finite element analysis (quasi-isotropic assumption) was effective in achieving appropriate confidence in the structural design with short turn-around time.

In the broader sense, the EN-V coach program provided GM with on-going learning and experience with lightweight materials for future consideration.

Acknowledgements

The successful execution of the EN-V demonstration vehicle program required collaboration across many GM groups and suppliers. The same is true of the successful execution of the EN-V coach program. The authors wish to thank their numerous engineering counterparts within General Motors for their efforts and dedication in carrying out the detailed design & engineering of the individual coaches. The authors also wish to acknowledge the teamwork and contributions of the GM Design Center Fabrication Shops, who had primary responsibility for the tooling, fabrication and assembly of the coaches. Additionally, the authors wish to thank their colleagues from GM Design Center for their creative, collaborative approach to the aesthetic design of these highly-unusual vehicles.