

Application of a Novel Metal Folding Technology for Automotive BiW Design

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ABSTRACT

The Deep Orange [1] initiative is an integral part of the automotive graduate program at Clemson University International Center for Automotive Research. The initiative was developed to provide the graduate students with hands-on experience of the knowledge attained in the various engineering disciplines and related disciplines (such as marketing and human factors psychology). For the 3rd edition of Deep Orange, the goal was to develop a blank sheet hybrid mainstream sports car concept targeted towards the Generation Y (Gen Y) market segment.

The objective of this paper is to explain the unique body-in-white (BiW) concept that offers space for 6-passengers and includes a dual-mode hybrid all-wheel drive powertrain. An additional objective of the project was to develop and showcase a body-in-white concept that will eliminate metal stamping and high capital investments associated with this technology (such as dies and stamping tools). It was chosen to explore Industrial Origami's patented technology that uses lighter gauge material folded into complex, innovative, high load-bearing structures, formed with simple, low cost fixtures, at the point of assembly.

Developing the topology, geometry and functionality of the BiW required an intensive collaboration between design students and chassis, powertrain, NVH and occupant packaging engineering students while carefully balancing functional properties, design space, cost and weight. Once the properties and design targets were met, the complete sheet Folded Metal Technology (FMT) design was realized using aluminum and structural adhesives. In addition to describing the conceptual analyses, the paper will also elaborate on the final realization of the BiW concept.

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INTRODUCTION

The ultimate goal of Deep Orange is to place automotive engineering knowledge into context to tackle complex problems through collaboration with colleagues whose perspectives are shaped by radically different experiences. During the 2-year MS program, students, faculty and participating industry partners develop and manufacture a vehicle prototype giving the students experience in marketing, design, engineering, systems integration, prototyping, production planning, verification and validation as well as product presentation from their entry into the program until graduation. For the third iteration of Deep

Orange, the goal was to develop a blank sheet fully functional hybrid mainstream sports car concept targeted towards Generation Y (Gen Y) with Mazda North American Operations as the primary sponsor and Art Center College of Design as the styling partner.

The size of the unique body-in-white concept developed is based on the requirements derived from a market analyses based on 70,000 surveys completed by owners of new cars and light trucks in the United States. The analyses revealed that Gen Y, as a social-savvy and environmental conscious generation, prefers to travel together in one single vehicle. The survey data clearly indicated that a large portion of Gen Y would prefer a sporty vehicle with 5 or more seating

positions. Additionally, the data revealed that Gen Y is willing to invest in sustainable powertrain technologies with a significant interest in all-wheel-drive (AWD) especially in the northern regions of the U.S. Based on these findings, a sports car concept was derived incorporating the Mazda design language (KODO Design), a 6-seater interior concept and a dual-mode hybrid AWD powertrain concept. An additional objective of the project was to develop and showcase a BiW concept that will eliminate metal stamping and high capital investments associated with this technology (such as dies and stamping tools). It was chosen to explore Industrial Origami's patented technology that uses lighter gauge material folded into complex, innovative, high load-bearing structures, formed with simple, low cost fixtures, at the point of assembly.

Developing the topology and geometry of the BiW required an intensive collaboration between design students and chassis, powertrain, NVH and occupant packaging engineers while carefully balancing functional properties, design space, cost and weight. The engineering of the BiW involved defining design relevant load cases (such as frontal/side/rear impact and static/dynamic stiffness properties), developing a topology to transfer the loads throughout the BiW, creating design space for occupants, chassis and powertrain components and conducting functional analyses of the BiW in terms of stiffness. Once the properties and design targets were met, the complete sheet metal folded design was realized using aluminum in combination with adhesives and rivets. The vehicle concept developed has been given the name NBT ("Next Big Thing") with a target start-of-production in 2015.

THE VALUE PROPOSITION

The objective of this Deep Orange project was to develop a concept vehicle (from a blank sheet of paper) for Gen Y with Mazda as the core brand and a Manufacturer's Suggested Retail Price (MSRP) between \$20K and \$30K. In order to derive the value proposition, it became necessary to understand the brand essence of Mazda and conduct market research on the demographics and core values of the Gen Y cohort.

The target customers as defined by Mazda are, "Those individuals who stay young, have a good capability to express themselves, are always passionate and are self-confident in their choices". This statement clearly indicates that the Mazda brand does not target certain demographics. It was a deliberate choice in this Deep Orange project to deviate from the (generation independent) Mazda target customers in order to explore specific, unique aspects of the Gen Y target segment. The brand DNA as defined by Mazda is characterized by "Stylish," "Insightful" and "Spirited" with the product attributes outlined by "Distinctive Design," "Intuitive Function" and "Responsive Drive". These attributes have been followed throughout the entire concept definition phase to assure that the NBT concept vehicle can

be perceived as a true Mazda not only by its exterior/interior design but also in terms of functionality and an overall fun to own and drive experience.

The overall value proposition or unique selling points (USPs) of the NBT vehicle were predominantly based on extensive market analyses using the AutoPacific New Vehicle Satisfaction Surveys (NVSS) from the year 2010 [3]. The NVSS was used to understand and capture Gen Y in terms of vehicle purchase decisions, vehicle usage, vehicle satisfaction, future vehicle purchases/features and general demographics and psychographics. It enabled the team to draw conclusions based on quantitative data of real (Gen Y) customers that own new vehicles. In the literature various definitions for Gen Y [2] can be found. The age definition for this generational cohort was adopted from the AutoPacific definition and is defined as young adults born from 1977 to 1994 (age 16 to 33 in 2010).

The AutoPacific NVSS survey comprises of 53 questions and the database of responses for the year 2010 contained 3,330 samples for Gen Y (about 70,000 samples in total). The classification of the various vehicle segments (such as economy, midsize, sporty, full-size, etc.) has been adopted from the AutoPacific definitions and may deviate from other classification such as those used by the EPA. The first step in narrowing down the target vehicle segment was to study all 30 vehicle mini-segments as defined by AutoPacific. A first look at the results for Gen Y (independent of the Mazda brand and target costs) indicated that the "Mainstream Compact Car" (such as the Honda Civic, Volkswagen Jetta) was the most desirable vehicle segment for Gen Y followed by "Premium Mid-Size Cars" (such as the Nissan Altima, Toyota Camry) and "Mainstreams Mid-Size Crossover SUVs" (such as the Honda CR-V, Toyota RAV4). Various vehicle segments were eliminated based on criteria such as the vehicle's average MSPR per segment (target value between \$20K-30K) and segments where Mazda already had a strong presence (such as the "Mainstream Compact Car" with the Mazda3). In addition all luxury/premium segments were eliminated because vehicles in this market segment do not align with the Mazda brand essence. This elimination process resulted in a reduction from 30 to 5 segments with the "Sporty Car" segment (such as the Chevrolet Camaro, Scion tC) and "Hybrid/EV" segment (such as the Toyota Prius, Honda Insight) at the top of this list in terms of vehicles sold for this target market. These two segments were followed by "Compact Crossover-SUV", "Off-Road SUV" and "Mainstream Sports Car".

Subsequently all 5 of these vehicle segments were examined in terms of vehicle characteristics that were most important while shopping for a new vehicle. At this phase the Mazda product attributed according to the brand DNA (distinctive design, responsive handling and performance, exceptional functionality) and Mazda's sustainability initiatives (improving fuel efficiency, powertrain electrification, vehicle light-weighting) were incorporated. Analyzing the 5 remaining segments showed that the Sporty

Car and Hybrid/EV segment matched exceptionally well with the brand essence/future sustainability strategy. The “fun-to-drive” aspects and “fuel economy” were both the highest ranked reasons to purchase these vehicles, respectively (Table 1).

Table 1. Top Vehicle Characteristics for Gen Y While Shopping for a Vehicle [based on AutoPacific 2010 NVSS]. A Score of 5 Means “Extremely Important”, 4 is “Very Important”, 3 is “Somewhat Important”, 2 is “Not Very Important” and 1 is “Not Important”

Ranking	Sporty Car	Hybrid/EV
1	Fun to Drive (4.7)	Fuel Economy (4.8)
2	Exterior Styling (4.7)	Overall Quality (4.6)
3	Exterior Color (4.7)	Durable/Long Lasting (4.5)
4	Overall Quality (4.6)	Driving Range (4.4)
5	Interior Styling (4.5)	Environmental Friendliness (4.4)

Three of the most important characteristics while shopping for a new sporty car were “Fun to Drive”, “Exterior Styling” and “Interior Styling”. These characteristics match very well with Gen Y's values on fashion, adventure, and entertainment. Three of the most important characteristics while shopping for a new hybrid/EV car were “Fuel Economy”, “Driving Range (miles to refuel)”, and “Environmental Friendliness”.

An additional query on “reasons not to buy” vehicles in these two segments resulted in almost opposite responses. Gen Y clearly steers away from currently available hybrid/EV vehicles because of (unattractive) exterior styling, (poor) vehicle handling and (slow) acceleration, while this generation also walked away from sporty vehicles because of (high) fuel consumption (Table 2).

Table 2. Top Reasons for Gen Y “not to buy” a Sporty Car or Hybrid/EV [based on AutoPacific 2010 NVSS]

Ranking	Sporty Car	Hybrid/EV
1	Fuel Economy (36%)	Exterior Styling (33%)
2	Exterior Styling (27%)	Vehicle Handling (27%)
3	Image (19%)	Acceleration & Power (26%)
4	Interior Styling (19%)	Exterior Size (25%)
5	Vehicle Handling (17%)	Interior Styling (21%)

The two segments retain characteristics that provide a natural inclination for combination in creating a positive symbiotic relationship between the typically opposite architectures when combined in a specific manner. Combining the strengths of both segments while eliminating the weakness of each segment can become a very attractive value proposition when executed correctly.

As part of the AutoPacific NVSS each respondent is allowed to configure their next vehicle using a feature list with purchase price associated with selecting that feature. This information was very helpful to understand and define

the powertrain and vehicle (interior) architectures relevant to the NBT concept. Important findings from this database query dealing with seating capacity are summarized in Table 3.

Table 3. Seating Capacity Preferences for Next Vehicle Purchase [source AutoPacific 2010 NVSS]

Seating Capacity	Sporty Car	Hybrid/EV
4	41%	38%
5	28%	37%
> 5	23%	25%

For the sporty and hybrid/EV segment cars 92% and 100% desired seating for 4 or more occupants respectively. This paired with the generation's high value on social interaction, dependency, and the environment, it is hypothesized that the NBT should have the capacity for more occupants, in addition to information and communication technology. Coupled with their needs for adventure and practicality in terms of storage, operating costs, fulfillment of experiences and increased vehicle usage are very important.

Additional queries in terms of powertrain type and powertrain configuration indicated that a significant amount of the Gen Y Sporty Car (41%) and Hybrid/EV (41%) buyers are willing to spend \$1,500 to include an all-wheel-drive (AWD) system in their next vehicle. This high demand for AWD can be explained by studying the geographic living location (on a State level) for all respondents that desired this option. Survey respondents that requested AWD systems predominantly live in northern States of the U.S. or in mountainous/hilly areas. The demand here is for more traction and driving safety and not so much for performance in these mountainous and winter weather condition stricken areas.

The overall value proposition for the NBT concept vehicle was derived from combining all of the aspects discussed above and is summarized in the Venn diagram in Figure 1.

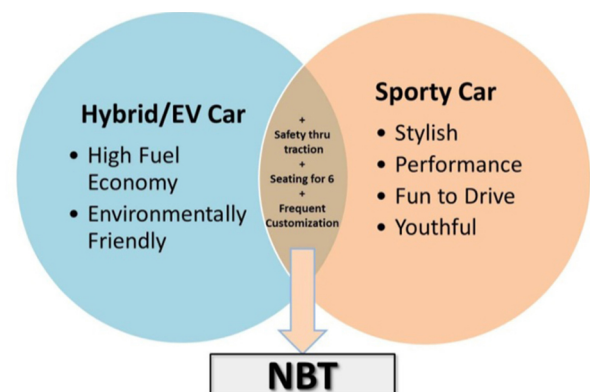


Figure 1. Relationship Combination for NBT Architecture

The value proposition of the NBT is based on the hypothesis that the combination of the market research outcome as described above will formulate the Next Big Thing for Gen Y. The NBT should be a sporty hybrid AWD 6-seater vehicle concept that combines the positive qualities of the sporty and the hybrid/EV vehicle segments while eliminating the negative ones. This combination also offers a balance of male-to-female Gen Y buyers as the majority of sporty car owners are male (52%) and the majority of hybrid/EV owners are female (62%), helping the vehicle remain gender neutral.

VEHICLE ARCHITECTURE

For every challenge there are always multiple solutions. In order to create the NBT, a sporty hybrid AWD 6-seater architecture the Deep Orange team settled on a systems integration solution that resulted in a synergy between all of the major selling propositions where relationships are complementary instead of unfavorable. From a marketing perspective, three primary unique selling propositions were created in which to organize the major features of the vehicle. These features have been summarized in [Figure 2](#).

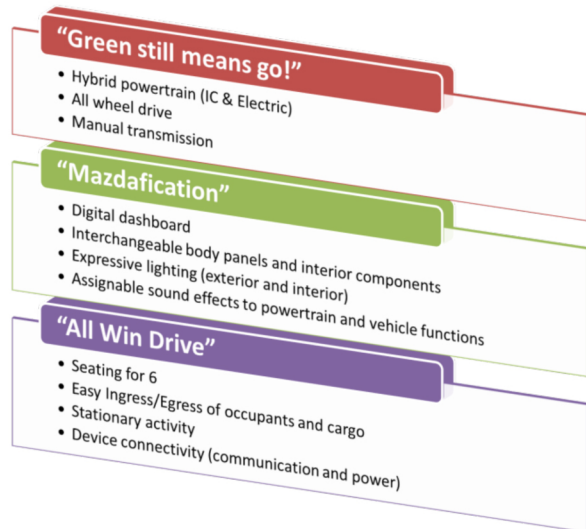


Figure 2. NBT Unique Selling Proposition Summary

While determining the final architecture of the vehicle in terms of technology and packaging solutions all relevant engineering perspectives were considered including function, geometry and production as derived from the completed marketing analysis. Everything from vehicle performance and overall customer usability as well as production cost and manufacturability while including Mazda's brand essence and all relevant regulatory requirements for the U.S, European, and Japanese markets.

As shown in [Figure 3](#), the vehicle packaging places a traditional ICE powertrain including a manual transaxle in the front of the vehicle. The rear of the vehicle contains an electric machine with a single gear reduction differential. This powertrain configuration enables the NBT to achieve

torque delivery to each wheel as well as decreased fuel consumption through regenerative braking and optimized engine operation. The energy storage system for the NBT has been placed underneath the rear seat pan for passive safety as well as packaging reasons. The driver's side contains a fuel tank, while the passenger side houses the lithium polymer based battery pack.

The powertrain concept chosen eliminates the need for a tunnel in the center of the vehicle that would typically house the transmission and driveshaft. This concept only required a small tunnel large enough for the exhaust system to exit from the rear of the vehicle. This provides increased packaging space for the interior cabin providing ample space for the 6 occupants.

To provide the required number of occupants and storage capacity without compromising ingress and egress of passengers or objects, a three-seat two-row configuration was chosen. The closures for the side of the vehicle include approximate equal length suicide doors and a tailgate-hatch combination in the rear. This also supports increased usage of the vehicle while stationary (i.e. tailgating and similar). Seats with the ability to fold flat have been utilized to reach luggage capacity targets and offer convenience features such as wireless charging for portable devices embedded in the seat backs of the center seats. The dashboard of the vehicle includes both a digital center stack and instrument cluster to support the customization aspect of the vehicle in conjunction with the audio and exterior variability.

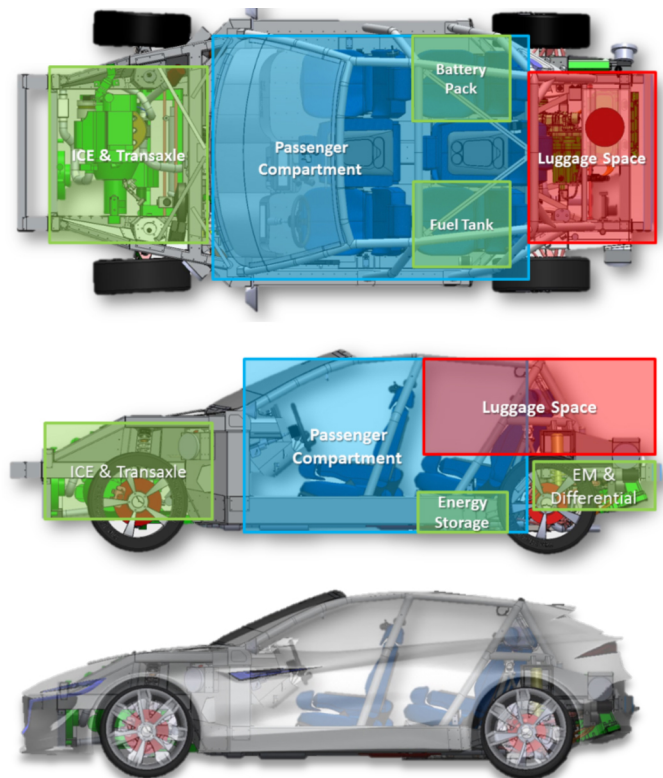


Figure 3. The NBT Vehicle Architecture

In order to provide a sporty driving experience, a suspension system with a double wishbone setup in the front and a multilink configuration in the rear were selected. The vehicle also contains a low seating position and a dash-mounted manual gear lever with clutch to further support this sporty experience while providing legroom for the middle passenger.

The structure of the vehicle utilizes folded metal technology implemented using Industrial Origami's patented fold feature geometry wherein the body is constructed nearly entirely of sheet metal joined using a bond/rivet process adapted from the aerospace industry.

In summary, the usage of the described technology and packaging of this vehicle creates an architecture well suited to meet the seeming disparity in the overall vehicle concept without the negatives associated with either sporty or hybrid/EV automobiles.

VEHICLE DEVELOPMENT TARGETS

The overall vehicle interior/exterior packaging was developed from the inside out and initial targets were derived based on benchmarking existing vehicles in the sporty car, hybrid/EV car and sporty hybrid car market segments (Table 4).

Table 4. Basic Vehicle Properties

Length [L103]	4,450 mm
Width [W103]	1,905 mm
Height [H101]	1,350 mm
Ground Clearance [H156-GVM]	110 mm
Wheelbase [L101]	2,730 mm
Acceleration 0-60 MPH	7.5s
EPA Combined Fuel Economy MPG	45 MPG
Curb Weight	1,400 kg
Target MSRP for 2015 MY	\$27,995

Vehicle Occupant Packaging

Based on the marketing analysis discussed above, a "4+2" seating layout has been developed to meet Gen Y's expectations. The four outer seats accommodate 95th percentile American males and the two middle seats accommodate 50th percentile American males. RAMSIS® ergonomics design and analyses tools were used in combination with CATIA® to develop the vehicle interior concept (Figure 4).

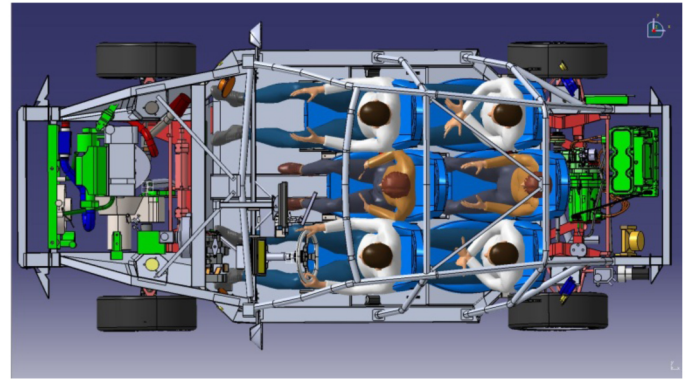


Figure 4. Vehicle Occupant Packaging.

During the development process the BiW topology was built around the occupant packaging giving high priority on realizing the desired interior space while still achieving a very sporty exterior style.

BiW Development Targets

The functional development targets for the BiW structure of the NBT concept were derived based on competitive benchmarking of existing unibody vehicles as well as market regulations for safety. Figure 5 displays a large sample of modern unibody vehicles (steel, aluminum and mixed material concepts) manufactured between 2000 and 2012.

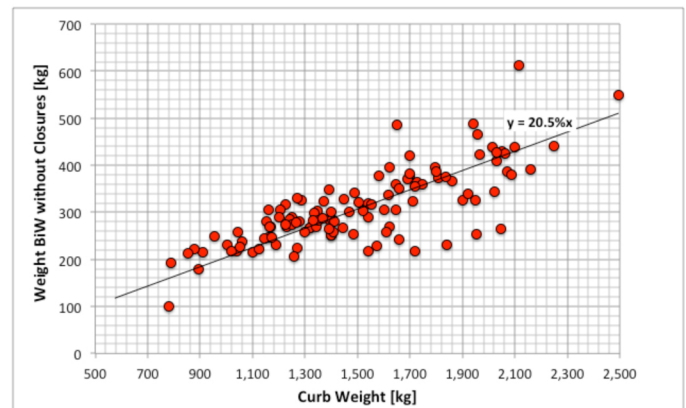


Figure 5. Weight of BiW as a Function of Vehicle Curb Weight.

The trend line clearly indicates a linear relationship between the weight of the BiW (M_{BiW}) and the vehicle's curb weight (M_{curb}). The weight factor for BiW structures made from steel equals 20.5%. In case of the BiW fully constructed from aluminum the weight portion of the total vehicle reduces to 15.0%. The target weight for an Aluminum BiW structure of the NBT concept vehicle was thus determined by:

$$M_{BiW} = 15.0\% \times M_{curb} = 210 \text{ kg}$$

This became the target for the BiW without closures, the target with closures was 266 kg (19% of curb weight). The torsional and bending stiffness values were derived from competitive benchmarking results comparing the vehicle's curb weight and BiW static stiffness values. Figure 6 shows that a linear trend exists between these two variables with the 3-box vehicle designs being the stiffest and open-box design being the weakest. Since the NBT concept vehicle was a 2-box design, the target for the static torsional stiffness C_T was set at:

$$C_T = 13.2 \times M_{curb} = 18,480 \text{ Nm/deg}$$

The suspension design was also considered for setting the torsional stiffness target for the BiW structure. The stiffness of BiW structure should typically be 10 times the roll stiffness of suspension [4]. The roll stiffness of suspension was 1952.8 Nm/deg. Therefore the target for the global torsional stiffness was assigned a value of 19,528 Nm/deg.

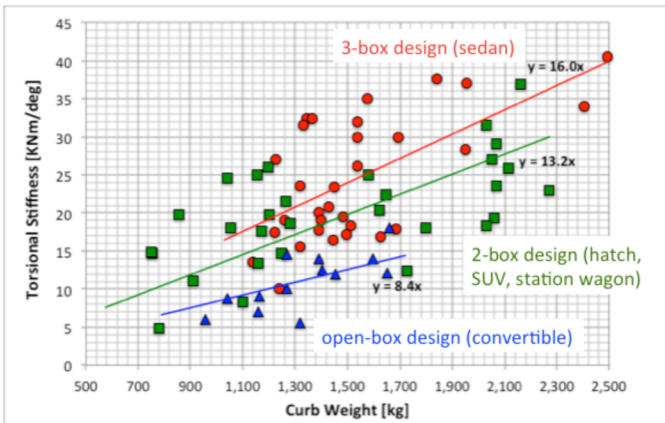


Figure 6. Torsional Stiffness as a Function of Curb Weight.

Similar relationships exist between the static bending stiffness C_B and the vehicle's curb weight. The target for the static bending stiffness was set at:

$$C_B = 7.0 \times M_{curb} = 9,800 \text{ N/m}$$

With the mass, torsional stiffness and vehicle dimensions determined it is now possible to calculate the lightweight index L defined by:

$$L = 1,000 \times \frac{M_{BiW}}{C_T \times A}$$

where A [m²] is the vehicle's footprint area defined by the wheelbase (L101) times the average track width (W101). Figure 7 shows the evolution of the lightweight index over the past 4 decades for a variety of unibody vehicle types (open, 2-box and 3-box design) and materials (steel, aluminum, and mixed material concepts).

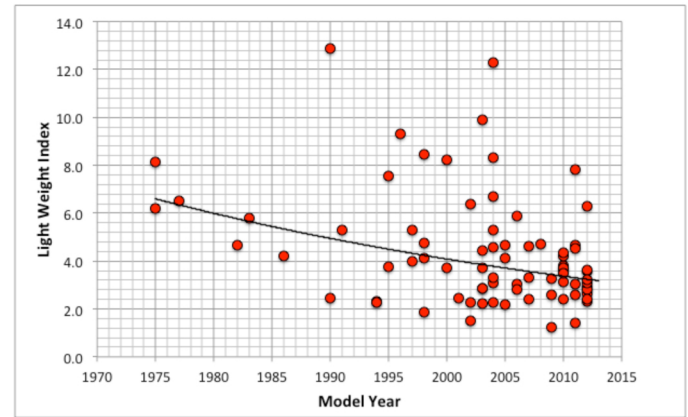


Figure 7. Evolution of Lightweight Index of Unibody Vehicle Structures.

The trend line clearly indicates the massive improvement in structural design despite vehicles becoming overall heavier over time. Modern mass production unibody concepts have an index between 2 and 4. Recent more exotic vehicle concepts constructed from carbon fiber monocoques or aluminum space frames have an index close to 1.3. With the mass of the BiW, the torsional stiffness of the BiW and the vehicle's footprint available, the lightweight index of the NBT can be determined by:

$$L = 1,000 \times \frac{210}{18,480 \times 2.733 \times 1.670} = 2.5$$

This is a good value for modern production vehicles.

As a side note, the exterior of the vehicle was to be constructed from other methods and is out of scope for this project. This BiW was designed to fit underneath an exterior structure designed in collaboration with ACCD.

BIW TOPOLOGY

The BiW topology was based on the study of production cars like the Artega GT, Mazda 2 and BMW 1 series. The figures below show the load paths for different major loading conditions. Figure 8 shows front crash load paths. Figure 9 shows rear crash load paths. Figure 10 shows side crash load paths. Figure 11 shows loads during cornering while taking right turn. Figure 12 shows loads during braking. Loads during acceleration will be similar, but opposite in direction in this figure. The load flow studies for front and rear crash as well as side crash determined the overall shape of the structure while balancing design, interior, and chassis packaging requirements. The acceleration, braking and cornering load flow studies were used to strengthen the structure locally around the chassis mounting points.

The crash rail heights were determined by the bumper height. The crash rails were placed such that there is no offset between the bumper and crash rails. The bumper height was