

# Conceptual Development of a Multi-Material Composite Structure for an Urban Utility/Activity Vehicle

Christopher Flegel, Parth Bhivate, Liang Li, Yash Mathur, Sanket Phalgaonkar, Mark Benton, Prasanth Muralidharan, Johnell Brooks, Srikanth Pilla, and Paul Venhovens  
CU-ICAR

David Lewis  
Diversified Structural Composites

Garrett DeBry  
Art Center College of Design

Craig Payne  
Toyota Technical Center USA, Inc.

## ABSTRACT

The Deep Orange framework is an integral part of the graduate automotive engineering education at Clemson University International Center for Automotive Research (CU-ICAR). The initiative was developed to immerse students into the world of an OEM. For the 6th generation of Deep Orange, the goal was to develop an urban utility/activity vehicle for the year 2020.

The objective of this paper is to describe the development of a multimaterial lightweight Body-in-White (BiW) structure to support an all-electric powertrain combined with an interior package that maximizes volume to enable a variety of interior configurations and activities for Generation Z users. AutoPacific data were first examined to define personas on the basis of their demographics and psychographics. The resulting market research, benchmarking, and brand essence studies were then converted to consumer needs and wants, to establish vehicle target and subsystem requirement, which formed the foundation of the Unique Selling Points (USPs) of the concept. The various sub-systems within the vehicle were then developed; a systems integration approach was used to balance design, engineering, and project (cost, weight, and timing) compromises.

The paper discusses the BiW as an enabler of the vehicle USPs, including an very low, flat floor, a utility-oriented asymmetric door concept, and an integrated hatch and rear bumper which create a low lift-over height for loading and unloading. The development of the topology, geometry, and properties of the BiW structure in relation to the chassis, powertrain, and occupant packaging elements required balancing design space, functionality, cost, and weight. Novel manufacturing processes, materials, and joining techniques are described in addition to elaborations on the final realization of the BiW concept.

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## INTRODUCTION

Deep Orange was implemented in 2009 in the Automotive Engineering Department, which is housed at the industrial-academic collaborative campus of CU-ICAR [1, 2, 3, 4]. The Deep Orange framework is part of the Automotive Engineering graduate program and implements the "team in an engineering studio" approach through immersion of the students in the setting of a manufacturer of original equipment. Within, Deep Orange students, cross-disciplinary faculty, and participating industry partners produce a new vehicle/mobility concept each year incorporating product innovations and

new process approaches, giving the automotive engineering students experience in vehicle design, engineering, development, prototyping and production/implementation planning from their entry into the automotive engineering program until graduation. The overarching goal of Deep Orange is to use this platform to educate the future workforce while providing academia, entrepreneurs, and industry partners with an open-innovation platform to collaborate. The duration of each Deep Orange project is about 2 years, which is in alignment with the duration of obtaining the MS degree. The Art Center College of Design (ACCD) in Pasadena, California is a strategic partner to the Deep Orange initiative with the responsibility

for the interior and exterior design of the vehicle concepts. CU-ICAR and ACCD students jointly developed the value proposition that addresses a grand challenge related to future mobility needs.

Every Deep Orange project focuses on finding unique solutions related to a holistic aspect of personal mobility starting with understanding the brand, market, mega trends and associated challenges and opportunities. Each Deep Orange project regards these challenges as opportunities by utilizing technology as a stimulus for creative and innovative solutions. All Deep Orange projects focus around providing clean, safe, and affordable mobility incorporating aspects such as:

- Market analyses, benchmarking and heuristic evaluations of (competitor) vehicle concepts,
- Flexible, efficient and clean powertrains,
- Viable lightweight structural engineering,
- Sustainable manufacturing systems,
- Versatile reconfigurable vehicle architectures and production systems,
- Systems Integration and trade-off analyses (vehicle functions, design space, weight, cost, and manufacturing).

To date, eight Deep Orange vehicle concepts have been initiated with 5 concept vehicles completed as of 2015. For the 6th iteration of Deep Orange, the goal is to develop a blank-sheet, youth-oriented utility vehicle concept with a targeted U.S. market introduction of 2020, catering equally to both males and females. A focal point of the project was on the utility/activity vehicle aspects with the purpose of understanding what future active young people living in urban settings need in a utility/activity vehicle (such as pickup trucks, sport utility vehicles or crossovers).

## FROM TARGET MARKET TO VEHICLE ARCHITECTURE

To derive the vehicle architecture and unique selling points, information was synthesized related to the following aspects:

- Brand attributes
- Target market demographics and psychographics
- Market analyses of current vehicle owners
- Future trends
- Future legislation
- Benchmarking of concept vehicles

The Deep Orange 6 team evaluated various interior, exterior, and closure concepts through benchmarking, literature reviews and the use of decision matrices to come up with unique solutions to align with the requirements of the target customers considered. The process involved heuristic evaluations of options from a user perspective, achievement of functional properties, component cost, weight, and ease of manufacturability.

## Brand Attributes

AutoPacific data [5] were analyzed to develop an understanding of the brand attributes of the prototype vehicle and its market stature as perceived by consumers. Major criteria evaluated were: passive versus active, masculine versus feminine design, functionality, utility, driving attributes, comfort, safety, and cost of ownership. These characteristics were used to define the prototype vehicle's place in the competitive map against vehicle segments with which the prototype would share. These brand attributes derived as shown in Figure 1, were be used to relate the target consumer and unique selling points back to the prototype vehicle's design brief.

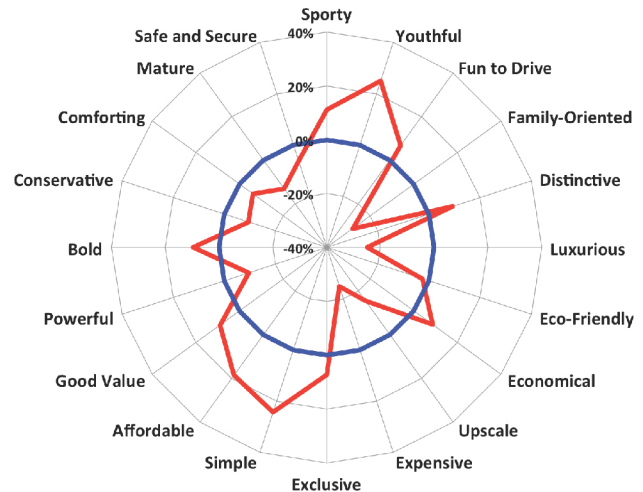


Figure 1. AutoPacific-derived attributes of the targeted brand (blue represents average; red represents Deep Orange 6 target)

## Target Consumers, Personas, and Vehicle Usage

The target consumer for Deep Orange 6 is Generation Z. In order to understand Gen Z's characteristics and future trends, a thorough literature review was conducted. Born 1995 and later, Gen Z is society's first true "digital natives," unaware of an existence prior to commoditized Internet access. Social networks are havens for this generation, allowing them to receive immediate feedback from friends, brands, and news outlets through multi-functional devices. The ability to have access at any time leads to a common theme with Gen Z: constant multitasking. They demand devices that can deliver multiple experiences and media that a tailored fit to their unique tastes while providing maximum value per dollar spent. OEMs desiring to sell vehicles to Gen Z should ensure vehicles supplement life's experiences and activities beyond transportation from A to B.

Gen Z is also highly pragmatic; they understand that the world will not change if humanity continues on the same path of pollution and natural resource consumption. According to the *Cassandra Report*, a study on Gen Z published by The Intelligence Group based on findings from 1,300 Gen Z participants, "Gen Z considers it a given and a necessity to recycle, conserve, and make green choices, and they are participating in some form of community service through their school, family, or church in disproportionate numbers," [6]. The status quo is viewed as outdated and able to be freely challenged in order to move towards a more balanced existence with humanity and the Earth.

Gen Z believes that current worldwide issues will require fresh solutions to provide a business opportunity to enact change on the status quo. New technology, and the knowledge of how to operate and create it, is the key enabler for their innovations. Constant connectedness blurs the lines of work and life, so they tend to desire the ability to work, study, play, and relax wherever and whenever. Pessimism towards the job market in recent years produces a desire to reduce reliance on others, so Gen Z is less apprehensive to try to create their own career. Living simply, for reduced environmental impact, coupled with an increased sense for financial security means Gen Z will tend to subsist on a more frugal lifestyle relative to previous generations [7].

Emily Anatole, a contributor to the *Cassandra Report*, says that Gen Z is excited to play a role in altering the future. According to the report, Gen Z—which has grown up amid major social change and innovation—is inquisitive and globally aware, demonstrating its preparedness for uncertainties with their problem solving skills [8]. Being an entrepreneur for Gen Z is a lifestyle choice as much as it is a financial choice. It allows freedom to mold a personalized lifestyle.

Products are more important to Gen Z than the brands that produce them; they are brand conscious, but not brand loyal. Brands that invite Gen Z to participate in product creation and marketing by allowing them to define and share their personal experience will garner a more meaningful connection to the customer [6].

Based upon the AutoPacific data and Gen Z research, four personas (two couples: Sarah and Gregory who live in San Diego and Daniel and Madison who live in Dallas) were developed which included day-in-the-life scenarios with detailed lifestyles. These personas were used throughout the concept development phase to support and justify concepts. Key activities the personas would perform with and within the vehicle were further developed through brainstorming sessions. The role of the vehicle in these activities defined the vehicle use cases. These use cases defined system and then sub-system level requirements.

## EXTERIOR DESIGN IDEATION

In focusing to develop a design language that aligned with the Gen Z audience and appealed equally to a male and female target buyers, the exterior design concentrated heavily on emphasizing the utility aspects of the vehicle while representing a bold, youthful appearance in alignment with the brand essence. AutoPacific brand attributes were heavily relied upon, with primary consideration given to the “simple”, “bold”, and “distinctive” criteria. These criteria were balanced against lower or negatively viewed criteria such as “powerful” and “family-oriented”. In many regards, these criteria are in conflict; this posed a design challenge to emphasize one without implying the other.

In order to achieve this paradoxical design amalgam, the exterior concept selection was taken through an iterative process that considered the Gen Z traits, personas, future trends, and activities that take place in a stationary vehicle. Design decision matrices were used to evaluate the strengths and weaknesses of each concept. Initial design sketches such as those shown in Figure 2 placed heavy

emphasis on the simplistic aspects of a utility vehicle through use of simple shapes and continuous lines. This concept was approved to move forward, enduring more intensive refinement.

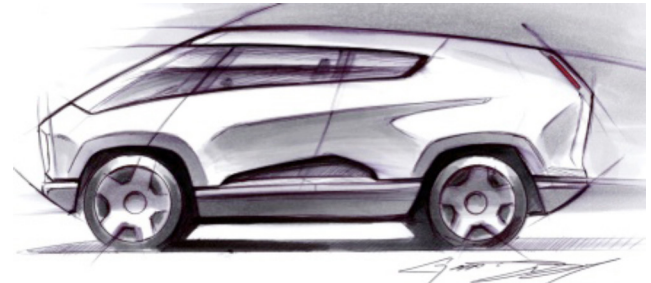


Figure 2. Chosen direction of the exterior design

Design detailing focused on emphasizing the brand attributes while relating to the customer personas. Key design factors were 1) a sprung-forward emphasis intimating motion when stationary while avoiding a family-oriented appearance, 2) a horizontal distribution of visual mass to capture the bold design statement, and 3) a muscular, poised stance through the integration of wheel arches drawing on natural design elements suggesting agility and athleticism. A visual depiction of these attributes is shown in Figure 3.

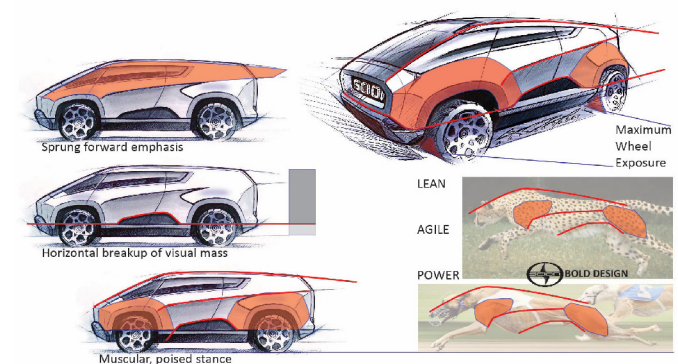


Figure 3. Explanation of the design language

A combination of sketches, computer renderings, and clay scale-models (Figure 4) were used to create a final exterior design. From this stage, the design and engineering convergence process began through digital model integration, with an additional iterative process of design and revision through compromise of design elements and engineering requirements that would evolve into a final concept.



Figure 4. Fifth-scale clay model

## HEURISTIC EVALUATION

A full-scale vehicle buck, shown in [Figure 5](#), was used to evaluate and emulate different aspects of the exterior, interior, and vehicle experiences. The persona activities derived from extensive Gen Z research and AutoPacific data were emulated in and around the vehicle. The confirmed activities and concepts were further developed. Loading and unloading of cargo and other utility activities related to the Gen Z personas were simulated on the vehicle buck before finalizing the concept.



Figure 5. Full-scale vehicle buck

All existing door concepts were considered, including doors with double-hinged four bar mechanisms, sliding doors, gullwing doors, and conventional doors. Ease of ingress/egress, production cost, engineering complexity, and customer perception were key factors for consideration-later evaluated using a decision matrix. A usability analysis conducted of cargo loading and unloading, ingress/egress, and tight parking situations ([Figure 6](#)) were the basis for scoring the various concepts.



Figure 6. Evaluation of side closure concept

Entrapment studies for rear passengers in dependent door situations were also simulated and evaluated. This situation occurs when the front door must be opened prior to opening the rear side door, often with restricted door opening angles. Key factors continually scrutinized were the step-in height and width's effect on occupant ease of entry, which was a key consideration in the door concept selection process. An example of this evaluation is shown in [Figure 7](#).

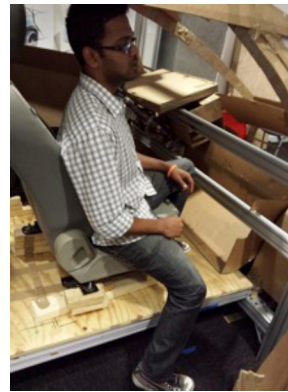


Figure 7. Evaluating ease of ingress/egress

Various rear closure concepts were considered and evaluated in the same manner, including vertically split hatches, conventional hatches, and split rear cargo doors. The heuristic evaluation showed that cargo loading from the side was vital to a utility/activity concept, which quickly eliminated split rear cargo doors from contention.

The final door concept was selected by forming a decision matrix to weigh different parameters related to engineering complexity and customer satisfaction. Factors considered were door opening effort, parking space side clearance, Gen Z perception, automated door opening time requirements if required, difficulty to close the doors in various vehicle-seating configurations, entrapment issues due to door dependency, and door opening in confined spaces. The concept with highest overall score - the suicide rear door concept with an integrated B-pillar - was chosen as the final concept for the vehicle, primarily because it was in keeping with the concept of maximizing useable interior space, allowed for easy loading/unloading of people and cargo, and would incur the lowest production cost while attaining the desired characteristics. Students conducted a statistical analysis of average parking space door opening clearance by measuring door-to-door distance of about 100 parked vehicles. This resulted in a mean door-to-door distance of 870 mm with a standard of deviation of 165 mm; maximum door opening angles of 50 degrees for the front and 90 degrees for the rear door were used to justify that entrapment due to insufficient door opening angle when both the front and rear doors were open was an unlikely situation during the heuristic analysis. Similarly, due to the very low and flat floor concept enabled by the electric powertrain architecture, a conventional rear hatch, with a low lift-in height below the rear bumper line, was selected using similar criteria ([Figure 8](#)).



Figure 8. Evaluation of low load floor cargo loading and closure concept

## UNIQUE SELLING POINTS

Based on the research and synthesis from the aforementioned AutoPacific data and competitive benchmarking studies, a number of key design elements were selected in order to represent the unique selling points (USPs) of the vehicle that would lead to the vehicle body architecture. The key concepts selected were: a very low and flat floor for increased cargo capacity, ease of ingress and egress, and simple re-configurability of the seating layout through continuous seat tracks from front to rear. An asymmetric wide opening closure concept with front and rear hinged doors, places emphasis on the driver while allowing unrestricted access to the occupant and cargo areas. The design development revolved around these concepts, and the resulting vehicle architecture is based around a modular composite/aluminum architecture to support the USPs by combining a low, flat floor with a utility-oriented asymmetric side closure concept and rear hatch design with a low lift-in height.

## BODY-IN-WHITE DEVELOPMENT PROCESS

### Strategy

With the fundamental vehicle concept selected, the BiW topology was developed to make greatest use of the electric powertrain architecture, occupant seating concept, and the resulting low/flat load floor. Other major considerations were the fabrication processes available to the project. Stamping dies were outside the scope of the project in terms of both lead-time and cost considerations, so an alternative architecture that was both structurally efficient and easily prototyped was sought. Additionally, exterior panels - while integrated with the structure - would not add significantly to the structural performance (stiffness, crashworthiness) for similar reasons.

An underbody mounted, removable electric energy storage system was selected along with continuous seat tracks from front to rear on the inside. These considerations defined the primary occupant packaging, suitable for four 95<sup>th</sup> percentile male manikins. Driver sightlines, occupant elbow room and driver position defined the occupant packaging relative to benchmarked vehicles, which set the baseline for the development of structural topology. Major load paths were considered for crash load energy absorption for both full frontal and rear-end collisions. Based on predicted vehicle weight, this

defined the front and rear crash rail sizes necessary to meet crash pulls requirements, while Federal Motor Vehicle Safety Standards (FMVSS) and vehicle-to-vehicle compatibility requirements dictated their height above the ground surface. Wheel envelopes were defined based on suspension kinematics, wheel travel targets, bushing deflection, and steering kinematics; this located the crash rails laterally. In response to tightening expectations for crash performance by consumer groups, the Insurance Institute for Highway Safety (IIHS) small frontal overlap crash was also considered which led to the inclusion of an upper (3<sup>rd</sup>) load.

With primary load paths considered and energy absorbing structures placed, the remaining structure was designed to maximize the lightweight potential of the composite/aluminum structures composing separate vehicle modules to simplify assembly and manufacture in a prototyping environment while also maintaining mass-production feasibility. With these limitations and constraints in mind, the development process proceeded to unify the design aspects and engineering criteria.

### Virtual Development Process

Over a 12-month window, the virtual prototype was developed to encompass an increasingly detailed level of design maturity and to converge towards a unified design/engineering concept. Engineering and designer students collaborated in an iterative process to produce an integrated, cohesive design that met structural requirements and maintained the integrity of the original design intent.

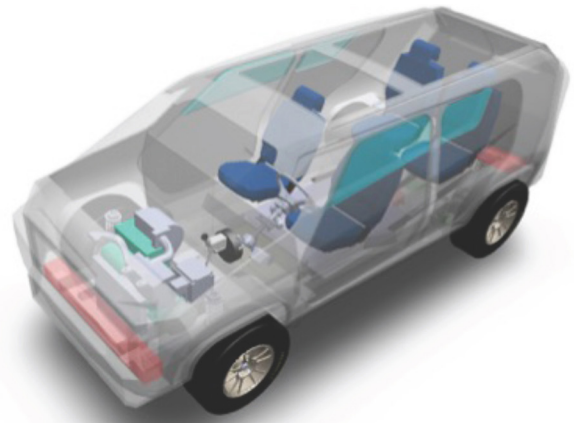


Figure 9. Initial vehicle cad model derived from clay model and interior, powertrain packaging

The initial packaging concept, shown in Figure 9, shows major packaging items located within the design envelope for the first time. Through the staged Virtual Design Review (VDR) process, the engineering and design overlays converged to form an integrated vehicle, seen chronologically in Figure 10. At each VDR, an exhaustive list of geometric collisions, functional requirements, assembly considerations and manufacturing tolerances was created to identify and resolve problems, drive decisions and initiate new design solutions that would be required during the next virtual built phase.

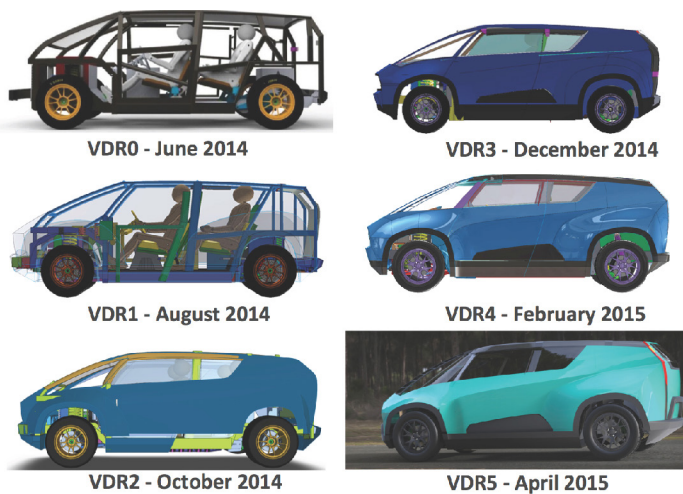


Figure 10. Maturation of vehicle structure at each VDR

The final virtual built model that was used to kick-off tooling is shown in Figure 11 both with and without exterior panels.

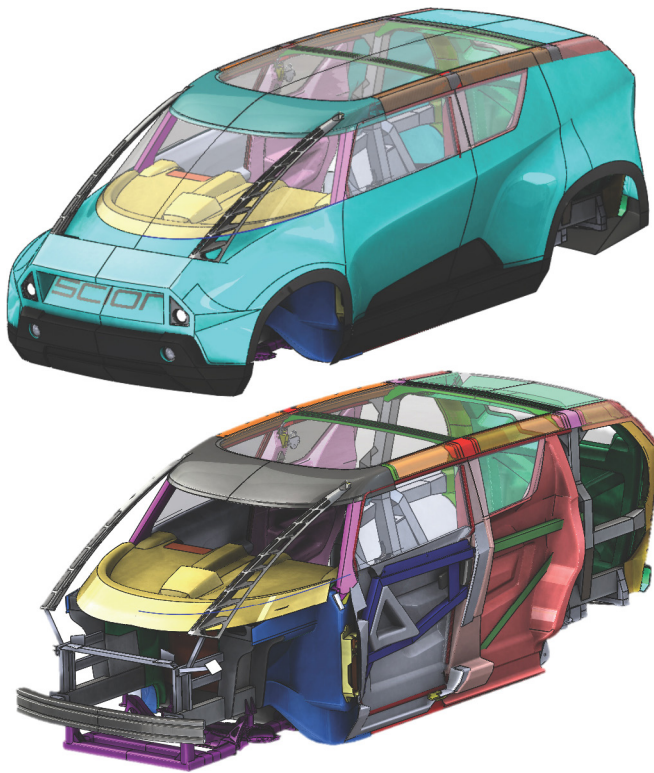


Figure 11. Final multi-material BiW structure

### Development Targets and Requirements

One of the largest industry-wide forces governing new vehicle development has been the implementation of Corporate Average Fuel Economy (CAFE) regulations. The 2025 CAFE fleet average target of 54.5 MPG has compelled every OEM to increase the fuel efficiency of their fleet. Many solutions were proposed and implemented to increase efficiency, with light-weighting of the BiW

structure being one of the main areas of focus. A lightweight BiW and its resultant mass de-compounding effect will aid in producing an efficient vehicle. The combined effect of a lightweight vehicle with an electric powertrain in the Light Duty Truck - 1 (LDT-1) category will also help to offset other vehicles in the OEM's fleet that have higher MPG values.

Apart from future fuel economy legislation, a steady increase in vehicle safety requirements has been initiated by the National Highway Traffic Safety Administration (NHTSA) and IIHS. Additionally, consumers have become more aware of vehicle crashworthiness ratings and are looking for vehicles, which perform well in various crash tests. As a result - and falling in line with customer persona expectations of a brand with a high level of safety as an expected property - a BiW topology that would meet or exceed regulatory and consumer requirements in the vehicle's respective category was required. Static stiffness targets were based upon benchmarked vehicles in the segment, and to ensure structural natural frequencies more than 10 orders of magnitude higher than primary ride natural frequencies.

### TOPOLOGY DEVELOPMENT

Basic crashworthiness test and vehicle compatibility requirements were used to define the initial BiW topology. Several safety standards - FMVSS 208 frontal impact test, IIHS 25% offset test, FMVSS 214 side impact crash test, FMVSS 216 roof crush test, and Part 581 standards - were considered to derive the necessary load paths in the BiW topology. Preliminary analyses were carried out to study the deformation in case of a full frontal non-deformable barrier test where load flow, deceleration, and deformation length were determined.

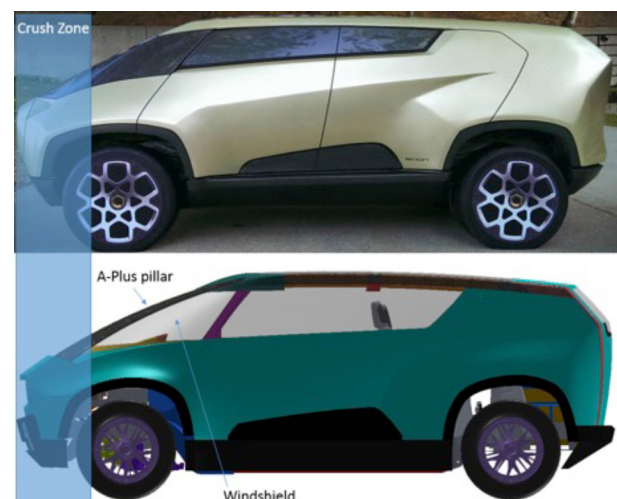


Figure 12. Windshield versus crush zone design (design intent- top-versus realized concept-bottom)

One particular concern of the cab-forward design was to limit the deformation zone to avoid windshield intrusion. The styling required the windshield to extend into deformation zone (474 mm), which