

# INVESTIGATION OF OPPORTUNITIES FOR LIGHT-WEIGHTING A BODY-ON-FRAME VEHICLE USING ADVANCED PLASTICS AND COMPOSITES

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## ABSTRACT

This paper investigates the opportunities for light-weighting a current body-on-frame type vehicle using advanced plastics and composites. In addition, the safety benefits of structural plastics and composites applications in future lighter vehicles are identified and evaluated by frontal impact simulations as part of implementing the plastics and composites intensive vehicle (PCIV) safety roadmap of the National Highway Traffic Safety Administration (NHTSA). The methodology of the study includes two steps: (1) developing a light-weight vehicle based on a current finite element (FE) vehicle using advanced plastics and composites, and (2) evaluating the crashworthiness of the light-weighted vehicle by frontal New Car Assessment Program (NCAP) test simulations. An FE model of a 2007 Chevrolet Silverado, which is a body-on-frame pickup truck, was selected as the baseline vehicle for light-weighting.

By light-weighting components in the Silverado, the vehicle weight was reduced 19%. As a result, the content of plastics and composite in the light-weight vehicle becomes about 23.6% of the total weight of the light-weight vehicle. Frontal NCAP simulations of the light-weighted vehicle show that the light-weighted vehicles using advanced plastics and composites provide equivalent structural performance (intrusion and crash pulse) to the baseline vehicle in the full frontal impact condition. This study demonstrates that (1) using plastics and composites can reduce the vehicle weight efficiently; and (2) the Silverado, light-weighted using advanced plastics and composites, provides equivalent structural performance in the frontal impact condition as the baseline vehicle.

## INTRODUCTION

According to the U.S. Department of Energy (DOE), the United States consumed nearly 20 million barrels per day in 2010 [1,2]. The transportation sector

accounted for 28% of total U.S. energy use, two-thirds of the nation's petroleum consumption, and a third of the nation's carbon emissions. Nearly, 32% of U.S. greenhouse gas (GHG) emissions are generated from transportation, the second-largest source after electricity generation. It was estimated that 75% of fuel consumption directly relates to vehicle weight [3]. With everything else remaining the same and considering mass compounding, a 6 to 8 percent increase in fuel economy can be realized for every 10 percent reduction in vehicle weight [4,5]. However, there are several barriers to weight reduction in automobiles: (1) historically low prices of fuel in the United States, (2) higher costs of advanced light-weight materials, (3) lack of familiarity with light-weight materials, (4) extensive capital investment in metal-forming technologies, (5) lack of large automotive composites and magnesium industries, (6) preferences for large vehicles, (7) perceptions of safety, (8) recycling issues of plastics and composites, (9) increased emphasis on alternative fuels such as non-conventional petroleum, biofuels and electricity, (10) alternative propulsion systems such as hybrids and fuel cells, and (11) the automotive industry's lack of long-term pricing strategies and stable long-term partners [4,6].

The Corporate Average Fuel Economy (CAFE) standards in the United State had remained mostly unchanged for past three decades since 1975. The new CAFE standards issued in 2010 proposed that new passenger cars and light trucks, including minivans, sport utility vehicles (SUVs), and pickups, are now required to achieve at least 14.5 kilometers per liter (34.1 miles per gallon) automaker fleet wide average by model year (MY) 2016 [7]. Recent changes to the CAFE standards were driving automakers to seek more aggressive methods for fuel consumption deductions. Light-weighting of vehicles will be an important factor to meet these requirements due to the inherent relationship between vehicle mass and fuel consumption.

Vehicle weight reduction is a known method to improve fuel economy in vehicles. However, Cheah addressed that the opportunity to reduce vehicle weight is not simple on three different aspects [5]; (1) the average new U.S. vehicle weight has increased steadily over the past two decades [8]; (2) the topic of vehicle weight reduction should be studied with a life-cycle perspective, considering energy-intensive production and recycling of light-weight materials [9,10]; and (3) while the effectiveness of weight reduction at a vehicle-level is reasonably well understood, the effectiveness at a vehicle fleet-level is less so [11]. Reductions in vehicle weight can be achieved by a combination of (1) vehicle downsizing, (2) vehicle redesign and contents reduction, and (3) material substitution [5,11,12]. Actually, there are a number of major research projects that have sought to determine the mass-reduction technology and materials potential for future vehicles. Lutsey reviewed seventeen vehicle mass-reduction studies and summarized achieved mass-reductions and cost impacting findings [13]. In those studies, the new manufacturing technologies and the light-weight materials, such as high strength steel (HSS), aluminum, magnesium, plastics, and composites, are utilized to reduce the vehicle weight; and a range of mass reduction is 16 to 57% in body and 19 to 52% in vehicle with the average of these vehicle designs achieving about 30% mass reduction. More recently, a study by EDAG showed that mass reduction of up to 23% is likely feasible by MY 2020 while maintaining vehicle performance and safety functionality and staying within a 10% increase of the original baseline midsize sedan's MSRP (manufacturer's suggested retail price) [14].

Schewel identified that light-weight vehicle could be a potent solution to triple safety (safety of climate, drivers and other road users) simultaneously, without compromise [15]. Clearly, light-weight automobiles enhance the global environment (climate) safety through their higher fuel efficiency. However, the safety (self- and partner-protections) of light-weight vehicles is not clearly evaluated yet. There have been many debates about the relationship about between safety and vehicle weight and size. The Rocky Mountain Institute (RMI) reviewed the light-weight automotive safety studies and summarized conclusions of these studies [16]. The conclusions of light-weight safety studies have not provided clearly the safety implications of light-weight vehicles to vehicle weight and size. These light-weight safety concerns are still actively studied by many researchers [17,18].

In 2006, the U. S. Congress directed the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (DOT) to begin development of a program to examine the possible safety benefits of light-weight Plastics and Composite Intensive Vehicles (PCIVs) and to develop a foundation for cooperation with the DOE, industry and other automotive safety stakeholders [19]. In the 2008 PCIV safety workshop sponsored by NHTSA in supporting of implementing this mandate, attendees indicated that a minimum of 30% to 40% (by weight) plastics and composite content in one or more subsystems beyond interior trim could qualify a vehicle as a PCIV [20]. There are two roadmaps for PCIVs [21]; (1) a government-led roadmap under the direction of the NHTSA focuses on a holistic safety-centered approach to PCIV innovation [17,20,22-24], and (2) an industry-led roadmap developed by the American Chemistry Council - Plastics Division (ACC-PD) outlines the industry's action priorities for achieving the technology and manufacturing innovations required to realize PCIVs [21,25-27].

NHTSA concentrated on the safety-related research issues affecting the deployment of PCIVs in 2020. In 2007, the Volpe Center developed a safety roadmap for future PCIVs and described the approach, activities, and results of an evaluation of potential safety benefits of PCIVs [22,23]. Barnes *et al.* identified outstanding safety issues and research needs for PCIVs to facilitate their safety deployment by 2020, and recommended three topics pertinent to crashworthiness of PCIVs: (1) material database, (2) crashworthiness test method development, and (3) crash modelling [24]. In the vehicle mass-size-safety workshop in 2011, NHTSA brought together experts to discuss about the effect of vehicle mass and size on safety, vehicle structural crashworthiness, occupant safety, and advanced vehicle design; and to understand what might be appropriate level of mass reduction for future CAFE rulemaking [17].

In 2001, the American Plastics Council (APC), now the ACC-PD, outlined a vision and technology roadmap for the automotive and plastics industries [25]. In the technology integration workshop in 2005, the ACC-PD provided an expansive safety road mapping effort examining PCIVs [26]. In 2009, the ACC-PD updated the vision and technology roadmap to outline the industry's action priorities for achieving the technology and manufacturing innovations required to realize PCIVs [27]. Also, the ACC-PD recommended three research activities: (1) improve the understanding of composite component response in vehicle crashes,

(2) development a database of relevant parameters for composite materials, and (3) enhance predictive models to avoid costly overdesign [21].

Since composites were introduced firstly to automotive industry in 1950's [28,29], the use of composites in vehicles has increased steadily. Today's average U.S. light vehicle contains about 174 kg (384 pounds) of plastics and composites in 2009 – about 10% of total vehicle weight but more than 50% of vehicle volume [1,21]. Advantages of composites compared to steels for automotive and transportation are: (1) weight reduction of 20-40%, (2) styling flexibility in terms of deep drawn panels, which is limited in metal stampings, (3) 40-60% savings in tooling cost, (4) reduced assembly costs and time in part consolidation, (5) resistance to corrosion, scratches and dents, and improvement in damping and NVH (noise, vibration and harshness), (6) materials and process innovations capable of adding value while providing cost saving, and (7) safer structure due to the composite material's higher specific energy absorption (SEA) [4,6]. Sehanobish reported that the use of 45.4 kg (100 pounds) of plastics could replace approximately 90.7 kg (200 pounds) to 136.0 kg (300 pounds) of mass from the use of traditional materials [30].

Although the benefit of composites are well recognized by the industry, composite use has been dampened by (1) high material costs [31,32], (2) slow production rates [31], and (3) the lack of design experience and knowledge caused by different material characteristics from conventional metal [6,33]. Thus, the application of plastics and composites is still limited mostly to non- or semi-structural components of vehicles [6,30,33]. However, many studies have shown the potential and future use of composites for light-weighting vehicle structural components [34-38]. Actually, numerous investigations of composite intensive automotive body have taken place over 30 years [28,39-43]. Bonnet [39] and Beardmore [40] designed the body-in-white (BIW) and front-end module of a passenger car using carbon fiber reinforced plastic (CFRP) composites and achieved about 65% reduction in weight. Boeman and Johnson [41] developed the composite intensive BIW of a passenger car with CFRP composites and achieved 60% mass reduction. Fuchs [42] studied about designing the composite intensive passenger vehicle while satisfying all safety requirements. Deb *et al.* [43] compared the frontal impact performances of the glass-FRP (GFRP) composite and steel rails of a passenger car. Those studies were dealing with unibody structures. There was a study to develop a light-weight optimized

frame in a body-on-frame type SUV by using high-strength steel, not composites [44].

In this paper, the opportunities for light-weighting a current body-on-frame type vehicle using advanced plastics and composites are investigated as part of implementing the PCIV safety roadmap of the NHTSA. In addition, the safety benefits of structural plastics and composites applications in future lighter vehicles are identified and evaluated by frontal impact simulations.

## METHODS

The methodology of the research includes two steps: (1) developing a light-weight vehicle based on a current finite element (FE) vehicle model using advanced plastics and composites, and (2) evaluating the crashworthiness of the light-weighted vehicle by frontal impact simulations. At first, a light-weight vehicle is developed to investigate the light-weighting opportunities in a current vehicle. An FE model of a 2007 Chevrolet Silverado, which is a body-on-frame pickup truck, was selected as the baseline vehicle for light-weighting. Plastics and composites were considered as the primary substitute materials in this study. Based on the literature review and with help from the ACC-PD's member companies, candidate steel vehicle components in the Silverado were identified and light-weighted by substituting advanced plastics and composites for the heavier steel components. After that, the frontal New Car Assessment Program (NCAP) tests of the light-weighted vehicle were simulated to investigate the weight reduction effect on vehicle crashworthiness, to evaluate the crash performance of the composite structural component, and to look into the opportunities of using plastics and composites for weight reduction in a current vehicle. In this study, only the frontal impact configuration is considered.

In addition, costs were not considered in this study. In particular, a cost increase as compared to the used of other advanced materials (e.g., ultra high strength steel) is one of the critical barriers to using plastics and composites in automobiles. However, in order to investigate opportunities for light-weighting vehicles using plastics and composites and indentifying the potential safety benefits of plastics and composites applications in future lighter, this study mainly focused on identifying currently available plastics and composite materials and their applicability to current vehicle components, and did not consider cost variations. Also, the manufacturability for vehicle components using plastics and composites is another critical issue. Instead, the existing vehicle design,

which has optimal structures for steel material and steel manufacturing technologies, was utilized to develop the light-weight vehicle using plastics and composite as material substitutes in this study. So, the design changes of original vehicle structures and components were limited to replacing components, and therefore are considered to be a minimal approach that could be taken for reducing the weight in the light-weighting process. A more optimal approach would have been a comprehensive, clean sheet design from the ground up to achieve a maximized weight reduction for the Silverado. However, such an approach was beyond the scope of this study.

### Baseline FE Vehicle Model

According to NHTSA's aggressivity metric based on the Fatal Analysis Reporting System (FARS) reported fatalities and the General Estimates System (GES) reported crash involvements, the light trucks and vans (LTVs) are over three times more aggressive than passenger cars in all vehicle-to-vehicle crash configurations [45,46]. Blum *et al.* did a study that looked at the aggressivity of the striking vehicle to the driver in the struck vehicle and found that the most important determinant of the risk of injury to a driver in the target vehicle is the weight of the striking vehicle [47]. Since 1990 the average LTV's weight has increased from 1868 kg to 2046 kg in 2000 [46]. So, in the aspects of improving fuel efficiency as well as alleviating aggressivity, an active effort to reduce the weight of LTVs is required.

A 2007 Chevrolet Silverado pickup truck was selected as the baseline vehicle in this study. Figure 1a shows the 2007 Chevrolet Silverado and Figure 1b shows the FE model of this vehicle, which was created by National Crash Analysis Center (NCAC) at the George Washington University (GWU) and is available to the public from the FE model database of NCAC/GWU [48]. The vehicle is a 4-door crew pickup truck (4.8L V8 SFI engine), which is a body-on-frame type vehicle. The vehicle weight is 2307 kg and its size is 5,846 mm (L) × 2,029 mm (W) × 1,917 mm (H). The FE vehicle model consists of about a million elements and 680 parts. The FE vehicle model was validated with test results from front and side crash tests [49] and from suspension tests [50,51]; that is, the FE model is a validated representation of the real vehicle.

The FE vehicle model is divided into assemblies as shown in Figure 2. Since it is a body-on-frame type vehicle, all assemblies are connected to the ladder frame structure. The vehicle mass breakdown is

summarized in Figure 3. It shows that the weight of the power-train related and suspension related components accounts for almost 50% of the vehicle weight. The weight of the ladder frame structure is about 13% of the vehicle weight.



(a)



(b)

Figure 1. 2007 Chevrolet Silverado (crew pickup body style); (a) actual vehicle, (b) FE model.

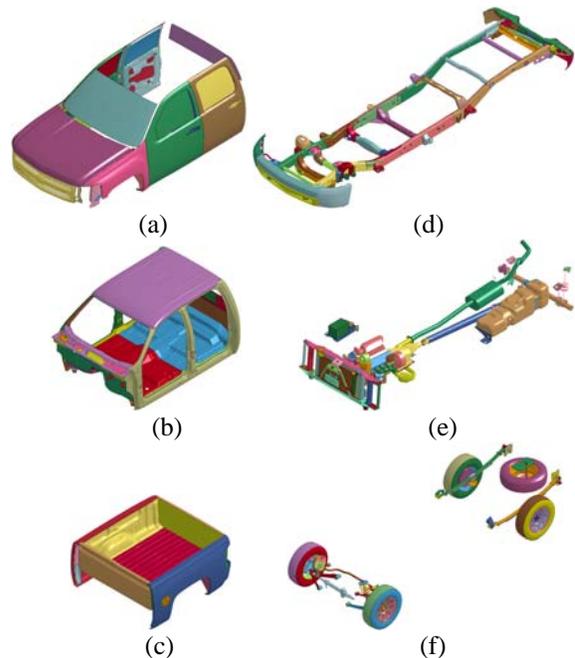


Figure 2. Assembly of the FE model of Silverado: (a) closures, (b) occupant compartment structure, (c) truck bed structure, (d) ladder frame structure, (e) power-train related, (f) suspension related.

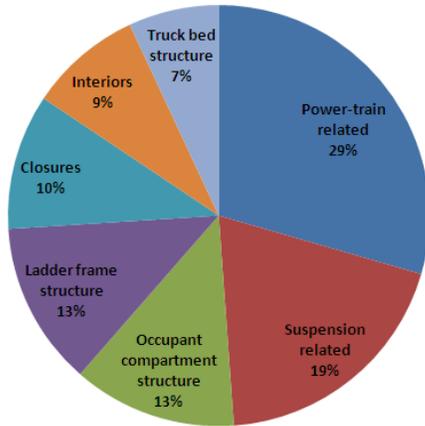


Figure 3. Mass breakdown of the FE model of Silverado.

### Light-Weighting Strategies

In order to light-weight the current vehicle model, three strategies were considered: material substitution, component change, and component removal.

**Material substitution** In order to reduce the vehicle weight, the steel material in the vehicle components was replaced with other lighter-weight materials. In particular, plastics and composites were used as a substitute for the steel material since these materials were primarily the main focus in this study. Plastics and composites have quite different material characteristics than steel. Steel material is isotropic and ductile, while plastics and composites are mostly anisotropic and brittle. So, the ACC-PD and some of its member chemical companies (SABIC, BASF, and Bayer) voluntarily participated in this study to provide information about available components that could be redesigned using plastics and composites. In addition, other available resources were utilized to gather information about the applications of light-weight materials.

When the steel material in the Silverado was replaced by plastics or composites, the components were re-designed by ACC-PD's chemical companies if a design change was deemed necessary. Otherwise, the steel material was simply replaced with the plastics or composites. Note that, in this study, only the frontal NCAP test of the light-weighted vehicle was considered for investigating the effect of weight reduction on the vehicle's crashworthiness. So, if any component was not engaged in the frontal NCAP test, the material substitution was realized by adjusting the weight of the particular component numerically without changing the component design.

It should be noted that plastics and composites are applied not only to non-structural components, but also to structural components in this study. Figure 4 shows the impact energy absorption of components of the Silverado in the frontal NCAP test. Some structural components, such as bumpers, fenders, frontal-end module and ladder frame, are changed to composites. Especially, the ladder frame of the Silverado was determined to be the primary structural member because the ladder frame was observed to absorb over 70% of impact energy in the frontal NCAP test. In addition to being evaluated using NCAP frontal crash test simulations, the new composite structural components are evaluated by component test simulations to prove that these new components provide equivalent structural performance to original components.

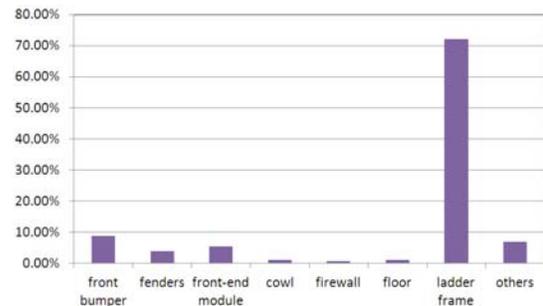


Figure 4. Impact energy absorption of components of the baseline (original) vehicle in NCAP test simulation.

When it was determined that there were no plastics or composites available for a given component but other light-weight materials were available, the original material was replaced with the other lighter-weight materials without undertaking a design change. For example, the steel material of the wheels and rear differential carrier were changed to aluminum and magnesium alloys, respectively.

**Component change** In the vehicle, there are many finished components, such as the engine, transmission, battery, and so on. It was decided that these existing components could be changed to light-weight ones to reduce the vehicle weight if it was determined that the new components could provide equivalent performance. Since the current vehicle weight was to be reduced, a smaller engine and transmission could be adopted. Additionally, a lighter weight battery could be adopted.

**Component removal** It was decided that any component which is not directly related to the vehicle operation could be removed to reduce the vehicle weight. Thus, for example, the spare tire and its

carrier in the current vehicle could be removed. This is a practice that already is being utilized by the industry.

## RESULTS

### Development of a Light-Weight Vehicle

The selected components of the Silverado were light-weighted by following the light-weighted strategies mentioned above. The detail description of each component is explained in the reference [52]. In this paper, several light-weighted components are explained.

**Front & rear bumpers** SABIC redesigned the front and rear bumpers. The original parts of the front bumper assembly were reduced from nine parts to five parts and those of the rear bumper assembly were reduced from six parts to three parts. The steel material was changed to a blend of semi-crystalline polyester and polycarbonate (i.e., a PBT(or PET)/PC blend) [53] and a polypropylene plastic [54]. The insert support is made of steel. The weights of the front and rear bumpers were reduced to 47% and 39% from their originals, respectively. The light-weighted bumpers are evaluated by component tests which show that their crash performance is equivalent to the baseline bumpers. These materials also are applied to roof and rear window.

**Front-end module** SABIC redesigned the front-end module. The original parts of the front-end module assembly were reduced from nine parts to one part. The steel material was changed to a long glass fiber reinforced polypropylene [55]. The weight of the front-end module was reduced 58% from its baseline weight.

**A- and B-pillar reinforcements** Composite inserts were applied to the A- and B-pillars and the thickness of steel pillars was reduced. BASF designed the composite inserts by using a 35% glass reinforced polyamide (PA6) [56]. Both pillars were gauged down 20%. The crash performance of composite inserts in vehicle structure was studied by Park *et al.* [57,58]. The light-weighted A- and B-

pillars were evaluated by component tests which show that their crash performance is equivalent to the originals. The 35% glass reinforced polyamide (PA6) is also applied to door beams, transmission crossbeam, and oil pans along with design changes.

**Engine and transmission** Table 1 shows the specifications of three Silverado models. The Silverado has two kinds of engines: the V6 and V8 engines. Also, the Silverado has two body styles: the extended cab and crew pickups. The FE vehicle model was developed for the crew pickup with the V8 engine. The vehicle size of all three vehicles listed in Table 1 is similar, but there is a weight difference. In the extended cab pickup, there is an 84 kg weight difference depending on which engine is adopted. Basically, this weight difference comes from the change of engine, transmission, and connecting assemblies. In addition, the difference of the gross vehicle weight rating (GVWR) is 182 kg depending on which engine is adopted. This means it would be reasonable to assume that, if the vehicle weight is reduced 183 kg or more, the V8 engine can be replaced by the V6 engine.

In this study, the original V8 engine was replaced by the V6 engine. It was assumed that the engine, transmission, and their assemblies were not changed; but instead the material density was adjusted, although the actual size of V6 and V8 engines are different. Also, it was assumed that even the weight of the V6 engine could be made lighter by using newer technologies and lighter materials, such as aluminum and magnesium. With these assumptions, the substitutions led to a 100kg weight saving in the engine and transmission.

**Ladder frame** Previous studies have shown that fiber-reinforced plastic (FRP) composites offer a means to light-weight vehicle structural components [35-38]. The main advantages of FRP composites over the more conventional isotropic materials are the lower density, very high specific strength, specific stiffness, and specific energy absorption (SAE) that can be achieved. However, introducing the FRP composites into vehicle structural components should be achieved without sacrificing the current

**Table 1. Specifications of Silverado**

NCAP Test No.	Model	Year	Body Style	Engine Type	GVWR (kg)	Vehicle Weight (kg)	Wheel Base (mm)	Vehicle Length (mm)
6171	SILVERADO	2007	EXTENDED CAB PICKUP	4.3L V6 MPI	2903	2210	3654	5821
6174	SILVERADO	2007	EXTENDED CAB PICKUP	4.8L V8 SFI	3085	2294	3658	5824
6168	SILVERADO	2007	CREW PICKUP	4.8L V8 SFI	3085	2307	3660	5830

performance of crashworthiness and stiffness. Many studies have shown that composite structures deform in a manner different than that of similar structural components made of conventional materials like steel and aluminum [35-37, 59-61]. The micro-failure modes, such as matrix cracking, delamination, fiber breakage, etc., constitute the main failure modes of composite structures. These complex fracture mechanisms make it difficult to analytically and numerically model the collapse behavior of FRP composite structures. This has limited the application of composites for mass production in the automotive industry.

The commonly used FRP composites are unidirectional laminates and textile composites. In general, laminates have good in-plane properties, and textile composites, which include woven, knitted, and braided fabrics, have better dimensional stability, out-of-plane properties, and impact and delamination resistance. Braided composites have some advantages: (1) good impact resistance, (2) better fatigue life and strength, (3) low manufacturing cost, (4) good interlaminar shear properties, and (5) efficient reinforcement for torsional loads [39]. The numerous studies of braided composites have been performed and identified crushing behavior, energy absorption capability, and significant braiding parameters [62-65].

Actually, extensive material experiments of a carbon fiber-thermoset braided composite were performed in this study to identify the crushing behavior, energy absorption capability, and numerical material parameters [52]. Based on the result of material tests and simulations, the steel in side rails was changed to the carbon fiber-thermoset braided composite, which is explained in detail in the references [52,66]. The design of the ladder frame was not changed but the thickness of side rails was increased to twice the thickness of the original design in order to have equivalent stiffness and impact performance to that of the original steel ladder frame. The crashworthiness of the composite ladder frame is evaluated by component tests which show that their crash performance is equivalent to the original. Therefore, the weight of the ladder frame was reduced 32% from that of the original. If the composite material is applied to cross members and mount supporters and optimal design is adopted, the weight of ladder frame could be reduced even more.

Table 2 summarizes all the weight savings of components of the Silverado to develop a light-weighted vehicle. The total saving is 432.76 kg which is about 19% reduction of the original vehicle

weight. Thus, the weight of the light-weight vehicle becomes 1,874.24 kg. Today's average U.S. light vehicle contains plastics and composites that account for about 10% of the total vehicle weight [1,21]. Based on this fact, it can be assumed that the weight portion of plastics and composites in the original Silverado is about 10% (i.e., about 187.4 kg). Using this assumption, the total weight of plastics and composites in the light-weighted vehicle can be obtained by summing up the weight of existing plastics and composites (187.4 kg) and the weight of newly added plastics and composites (254.35 kg). In other words, the light-weight vehicle contains about 441.75 kg of plastics and composites, which is about 23.6% of the total light-weight vehicle weight.

### Frontal NCAP Test Simulations

The frontal NCAP test was simulated to evaluate the crash performance of the light-weighted vehicle developed above. In the full frontal NCAP test, a vehicle with two dummies in the front seats collides with the rigid barrier in the full overlap configuration at the impact speed of 56 km/h (35mph). In the full frontal NCAP simulation, dummies were considered as added masses. The LS-DYNA hydrocode is utilized for vehicle crash simulations [101].

Three vehicle configurations are considered; (1) the baseline (original) vehicle (2,307 kg), (2) the light-weighted vehicle with the original steel ladder frame referred to as LWV1 (1,949 kg, 16% weight reduction), and (3) the light-weighted vehicle with the composite ladder frame referred to as LWV2 (1,874 kg, 19% weight reduction). Since the ladder frame is the primary energy absorbing structure of the Silverado, its crash performance is of great interest. So, the two different light-weighted vehicles, LWV1 and LWV2, were considered for evaluation to determine if the composite ladder frame could provide equivalent crash performance as the original steel ladder frame. As stated above, the difference between the LWV1 and LWV2 is the material adoption of the composite ladder frame in the LWV2. The LWV2 is the lightest vehicle.

Figure 5 shows vehicle response histories in the frontal NCAP test. Figures 5a and 5b show the acceleration curves. The notable point in the acceleration curve of the baseline vehicle is a big drop at 27 msec, which is induced by the crumple zone deformation of side rails. This big drop in acceleration can be observed in LWV1 and LWV2 as well. Compared to the baseline, the LWV1 has higher peaks at an earlier time, and the LWV2 has a lower peak at an early time, but a higher peak at a later time.

**Table 2. Summary of weight savings**

components	old material	new material	weight saving (kg )	references
• material substitution with new design (using plastics and composites)				
A- & B-pillars	steel	downgauge, composite inserts	1.32	[56-58]
door beams	steel	composite	4.92 (55%)	[56]
tailgate	steel	plastic, composite	8.66 (44%)	[53,55]
front-end module	steel	composite	7.77 (58%)	[55]
front bumper	steel	plastic, composite	7.61 (47%)	[53,54]
rear bumper	steel	plastic, composite	6.32 (39%)	[53,54]
transmission crossbeam	steel	composite	4.40 (56%)	[56]
• material substitution only (using plastics and composites)				
roof	steel	plastic	8.82 (43%)	[53,54]
front fenders	steel	plastic	3.53 (45%)	[67]
rear fenders	steel	plastic	10.84 (45%)	[68,69]
rear window	glass	plastic	2.73 (42%)	[53,54]
oil pans	steel	composite	3.82 (51%)	[56,69]
stabilizer links	steel	composite	0.14 (40%)	[56]
IP retainer	steel	composite	4.10	[70-74]
truck bed	steel	composite	20.46 (31%)	[75,76]
drive shaft & yokes	steel	composite	3.69 (58%)	[77-80]
front brake disks	steel	composite	14.39 (50%)	[81]
leaf springs	steel	composite	34.73 (70%)	[82-84]
ladder frame	steel	composite	74.80 (32%)	[52,59-66]
• material substitution only (using other materials)				
rear differential carrier	steel	magnesium	8.80 (25%)	[85,86]
wheels	steel	aluminum	20.06 (40%)	[87]
• component change				
front & rear seat			10.00 (20%)	[88-91]
engine & transmission			100.00	[52]
door modules			2.00	[55,92]
battery	lead-acid	lithium-ion	10.76 (60%)	[93-96]
Tires			8.75 (10%)	[97,98]
• component removal				
spare tire & carrier			38.79 (100%)	[99,100]
Vehicle weight (kg)	baseline	2307.00	432.76 (19%)	
	light-weighted	1874.24		

Overall, all three acceleration curves are not much different. Figures 5c and 5d show the velocity curves. All vehicles exhibited a similar rebounding speed and slope. The LWV1 and LWV2 have earlier velocity zero time than the baseline as shown in Figure 5c.

Figures 5e and 5f show the wall force curves. The force curve of the baseline vehicle has five peaks within a certain force range. The LWV1 shows similar wall force to the baseline except the lower peak at the late time, which is because of the lower weight of LWV1. On the other hand, the wall force curve of the LWV2 has just two peaks, which is clearly indicative that the composite ladder frame in the LWV2 makes a big change in the crash mode of the LWV2, compared to the baseline with the original steel ladder frame.

Table 3 summarizes the single response values of vehicles in the frontal NCAP test simulations. In terms of the maximum crush, the LWV1 has a lower crush value than the baseline, but the LWV2 exhibited a similar crush value to the baseline. The

weight reduction in the LWV1 possibly leads to lower vehicle crush. However, adopting the composite ladder frame in the LWV2 causes more vehicle crush than the LWV1 although the vehicle weight of the LWV2 is lighter than the LWV1. The vehicle stiffnesses, i.e., the crush-work stiffness ( $K_w400$ ) [102] and the global energy-equivalent stiffness ( $K_E$ ) [103], were calculated using the wall force curves in Figure 5f. The LWV1 stiffnesses become softer than the baseline vehicle, which may be the effect of weight reduction. The LWV2 stiffnesses become further softer than the LWV1, which should be the effect of using the composite ladder frame. Thus, using the composite ladder frame leads to the vehicle stiffness being softer but to similar vehicle crush as the baseline. In other words, the composite ladder frame in the LWV2 provides the required crash performance to keep the crashworthiness of the LWV2 equivalent to the baseline.

Figure 6 describes the measurement points of occupant compartment intrusion. The intrusions at

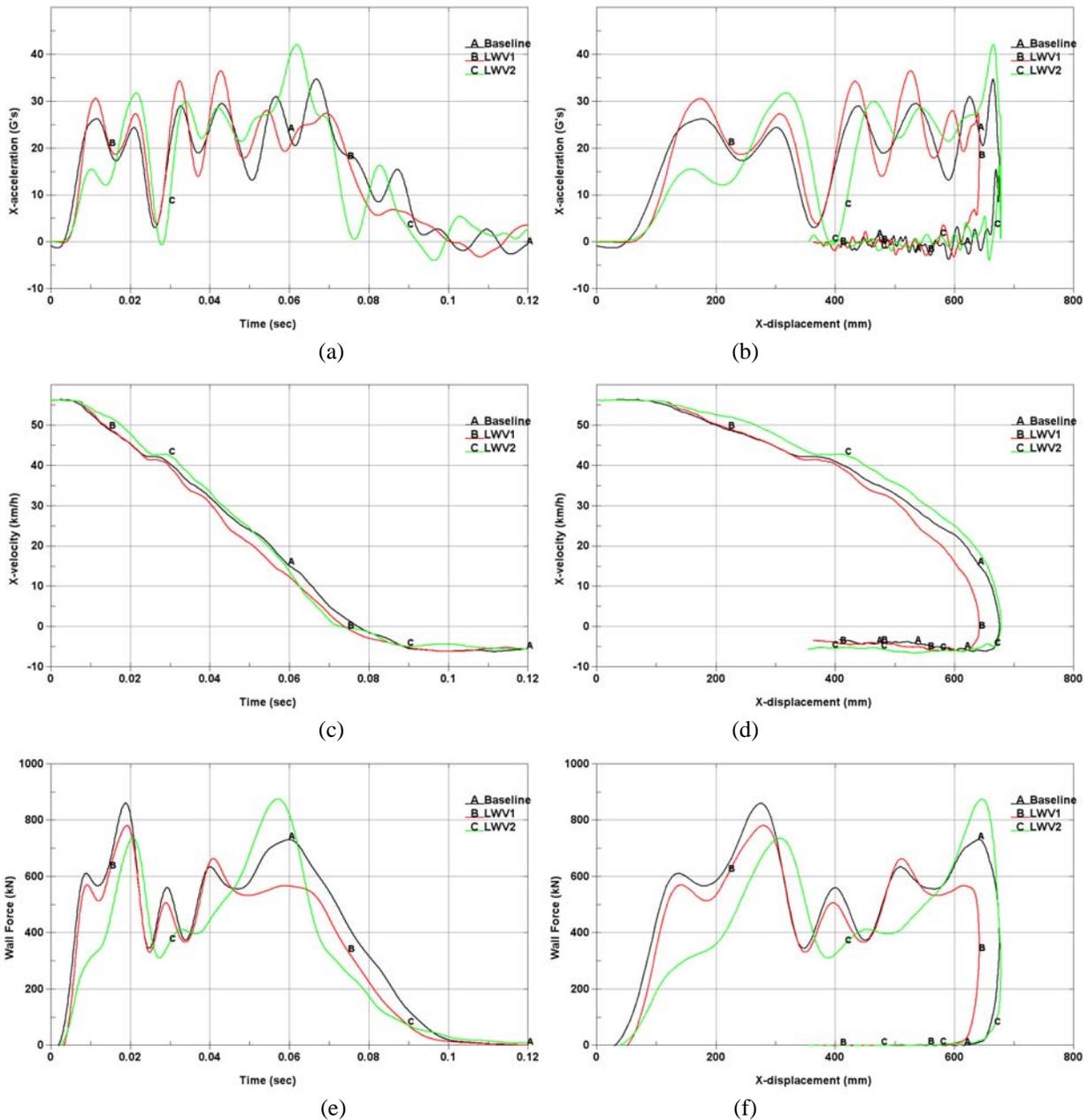


Figure 5. Vehicle response histories in frontal NCAP tests; (a) acceleration in time, (b) acceleration in displacement, (c) velocity in time, (d) velocity in displacement, (e) wall force in time, (f) wall force in displacement.

**Table 3. Summary of vehicle responses in frontal NCAP test simulations**

Vehicle	baseline	LWV1	LWV2
Maximum X-crush (mm)	675.8	642.1 (-5%)	678.7 (0%)
$K_{W400}$ (MPa)	2413.4	2180.8 (-10%)	1768.2 (-27%)
$K_E$ (MPa)	1530.8	1453.2 (-5%)	1255.8 (-18%)

the fifteen cross-points of five Y-lines and three Z-lines were measured at the end of the simulation time. Only the driver-side intrusion was investigated. Z1 was located 100 mm above the vehicle floor. Figure 7 shows the intrusion profiles of the three vehicles.

Both light-weighted vehicles, the LWV1 and the LWV2, show smaller X- and Z-intrusions than the baseline vehicle, which could be attributed to the effect of weight reduction.

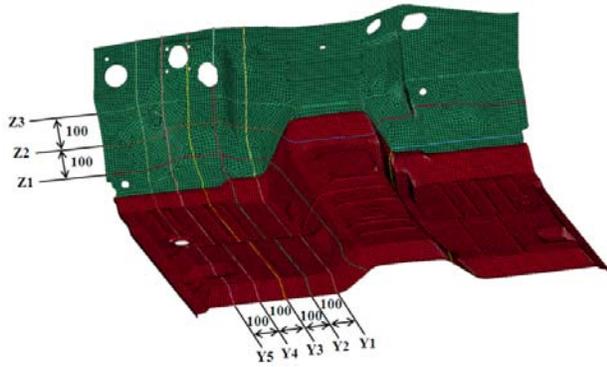


Figure 6. Measurement points of vehicle intrusion (unit: mm).

Figures 8 through 10 show the deformations of three vehicles. The deformation of the baseline vehicle is shown in Figure 8. A folding deformation mode of the steel ladder frame is observed. The deformation

of the steel ladder frame reaches a location that is behind the engine as indicated by green arrow in Figure 8a. The deformation of the LWV1 is shown in Figure 9. Since the LWV1 has the original steel ladder frame, the deformation of the LWV1 is similar to that of the baseline. The deformation of the LWV2 is shown in Figure 10. Since the LWV2 has the composite ladder frame, the deformation mode is quite different from the baseline. The brittle fracture mode of the composite ladder frame can be observed. The bending fracture of the composite side rails also occurs at a location around the transmission crossbeam as indicated by the green arrows in Figure 10b.

## DISCUSSION

As part of implementing the PCIV safety roadmap of the NHTSA, this study investigates the opportunities

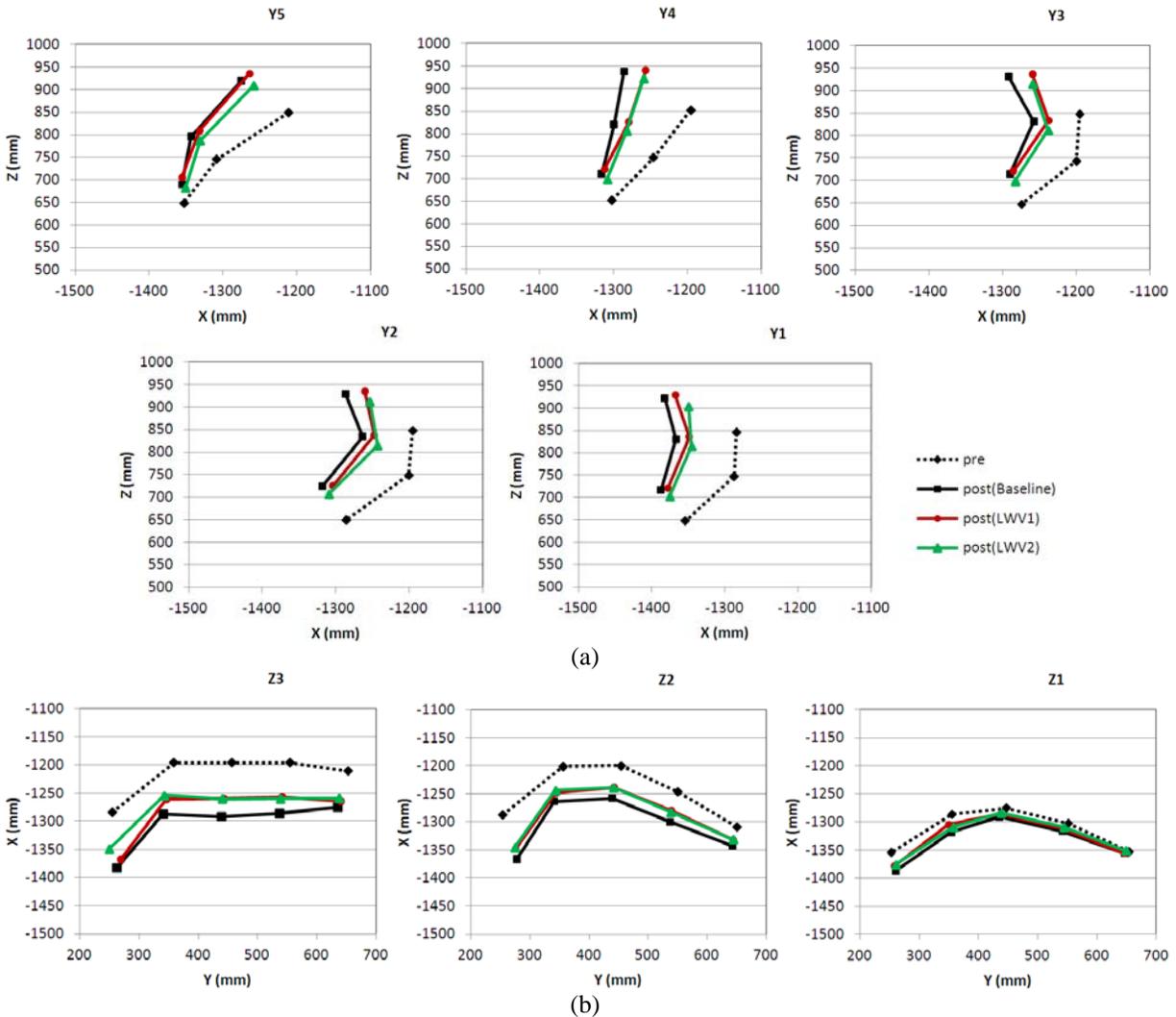


Figure 7. Vehicle intrusions; (a) vertical profile, (b) horizontal profile.

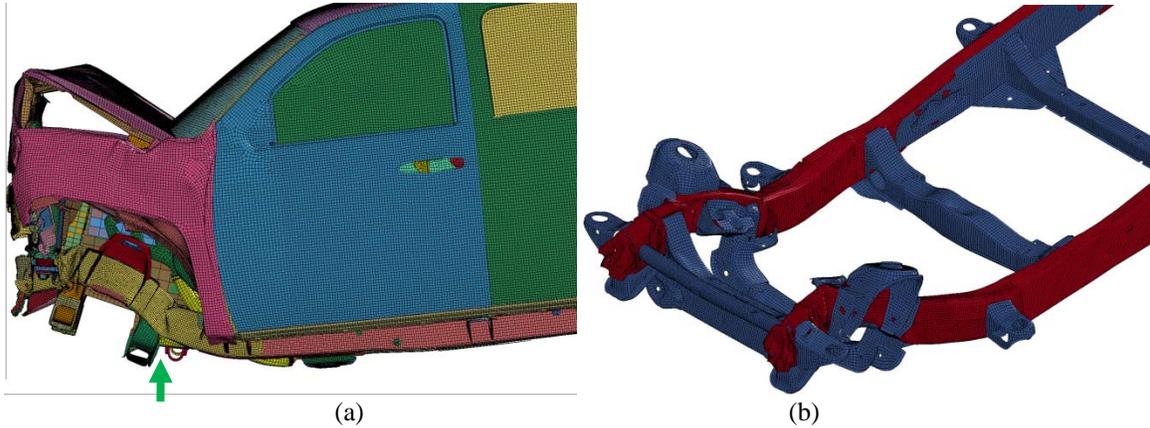


Figure 8. Deformation of the baseline vehicle; (a) frontal area (wheel hidden), (b) ladder frame.

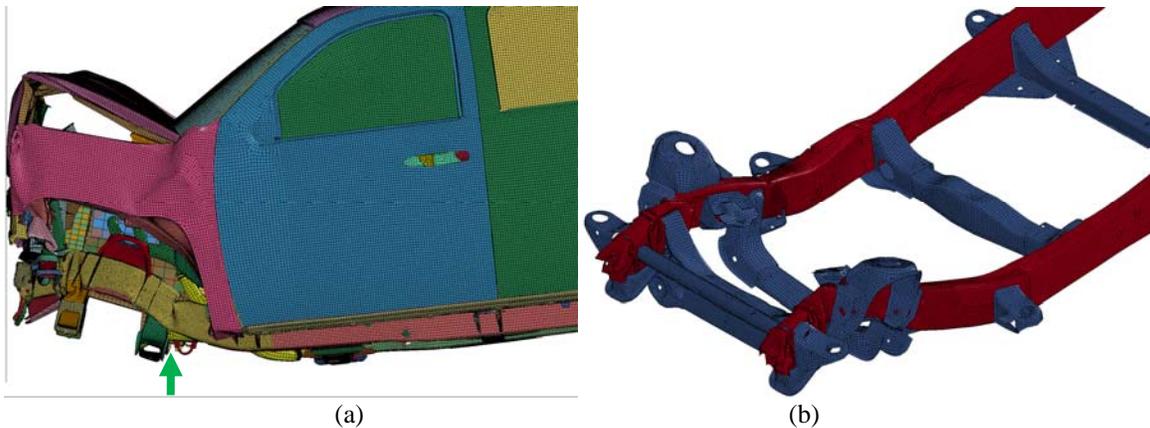


Figure 9. Deformation of the LWV1 vehicle; (a) frontal area (wheel hidden), (b) ladder frame.

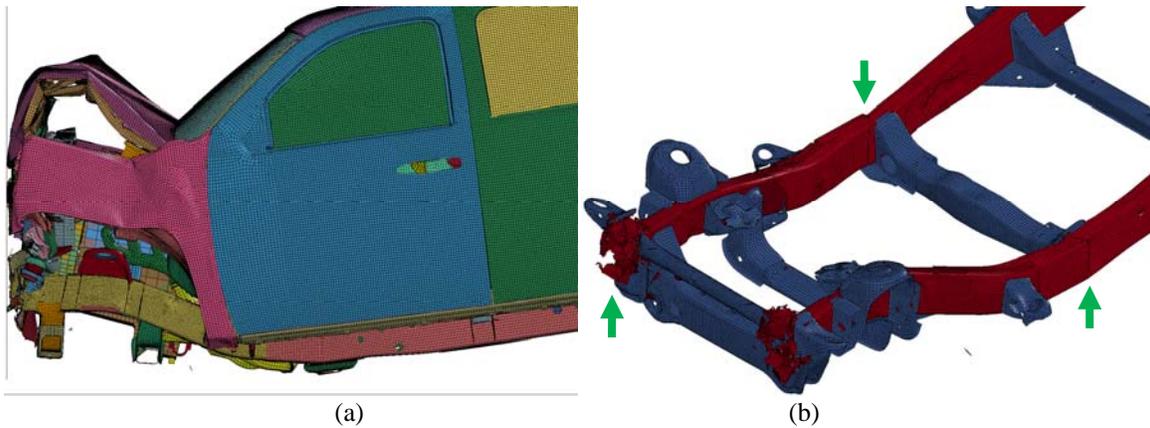


Figure 10. Deformation of the LWV2 vehicle; (a) frontal area (wheel hidden), (b) ladder frame.

for light-weighting a current body-on-frame type vehicle using advanced plastics and composites. In addition, the safety benefits of structural plastics and composites applications in future lighter vehicles is identified and evaluated by frontal impact simulations.

Over 25 components of the Silverado were light-weighted by using plastics and composites primarily. In consequence, the original vehicle weight, 2,307 kg, was reduced to 1,874 kg, which is about a 19% decrease. The light-weight vehicle contains about 442 kg of plastic and composites, which represents about 23.6% of the total weight of the light-weight vehicle. To reach or exceed a 30% content of plastics and

composites in the development of a PCIV, additional applications of plastics and composites to the vehicle structural components, especially occupant compartment and closures, would be required. Also, adopting optimally sophisticated design can reduce more mass in the light-weighted components. Particularly, the ladder frame can be further reduced if composite material is applied to crossbeams and optimal design is used.

Those light-weighted components include non-structural as well as structural members, such as bumpers, pillar reinforcements, door beams, and ladder frame. Especially, the ladder frame was determined to be the main energy absorbing structure and was changed to a carbon fiber-thermoset braided composite. The crashworthiness of the composite structural members was evaluated by frontal NCAP simulations. Only frontal impact configuration was considered in this study. The simulation results of the light-weighted vehicles show that (1) the vehicle mass reduction contributes to a decrease in the vehicle frontal intrusion, (2) the deceleration of a vehicle was more likely to be dependent on the vehicle stiffness and crash mechanisms, rather than vehicle mass reduction, and (3) overall, the light-weighted vehicles using advanced plastics and composites provide equivalent structural performance (intrusion and crash pulse) to the baseline vehicle in the full frontal impact condition.

In conclusion, this study demonstrates that (1) using plastics and composites can reduce the vehicle weight efficiently, and (2) the light-weighted Silverado using advanced plastics and composites provides equivalent structural performance in the frontal impact condition. Especially, carbon-FRP composites show good structural performance. Also, this study recommends further research, such that (1) undertaking a clean sheet design from the ground up (rather than the less optimal component redesign approach) to provide an maximal approach for light-weighting, (2) the evaluation of the crashworthiness of light-weighted vehicles in other crash configurations (side and rear impacts, roof crush, etc.), (3) the study of cost analysis, and vehicle repair and maintenance issues of plastics and composites components, and (4) the enrichment of material database of plastics and composite.

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## REFERENCES

- [1] S.C. Davis, S.W. Diegel, and R.G. Boundy, "Transportation energy data book: edition 30", ORNL-6986, Vehicle Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, 2011.
- [2] U.S. Environmental Protection Agency, "Inventory of U.S. greenhouse gas emissions and sinks: 1990 – 2010", EPA-430-R-12-001, 2012.
- [3] BBC Research, "Lightweight materials in transportation", A BCC research advanced materials report, Report ID # AVM056B, 2011.
- [4] J.A. Carpenter, "Overview of freedomCAR and its composites crash-energy management work", The Safety Characterization of Future Plastics and Composite-Intensive Vehicles (PCIVs) Workshop, Cambridge, MA, USA, 2008.
- [5] L.W. Cheah, "Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the U.S.", Ph.D. Dissertation, Massachusetts Institute of Technology, 2010.
- [6] U. Vaidya, "Composites for automotive, truck and mass transit", DEStech Publications, Inc., Lancaster, PA, USA, 2011.
- [7] U.S. Environmental Protection Agency and U.S. Department of Transportation, "Light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards; final rule", Federal Register, 2010, 75(88):25324-25728.
- [8] U.S. Environmental Protection Agency, "Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2011", EPA-420-R-12-001a, 2012.
- [9] A. Burnham, M. Wang, and Y. Wu, "Development and applications of GREET 2.7 - the transportation vehicle-cycle model", ANL/ESD/06-5, 2006.
- [10] G. Keoleian, S. Miller, R.D. Kleine, A. Fang, and J. Mosley, "Life cycle material data update for GREET model", Report No. CSS12-12, 2012.
- [11] A. Bandivadekar, K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, and M. Weiss, "On the road in 2035: reducing transportation's petroleum consumption and GHG emissions", Report No.

- LFEE 2008-05 RP, Massachusetts Institute of Technology, 2008.
- [12] Center for Automotive Research, “Automotive technology: greener products, changing skills – lightweight materials & forming report”, 2011.
- [13] N.P. Lutsey, “Review of technical literature and trends related to automobile mass-reduction technology”, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-10-10, 2010.
- [14] H. Singh, “Light-weighting options for vehicle structures for model year 2020”, SAE 2012 Government/Industry Meeting, Washington, DC, USA, 2012.
- [15] L. Schewel, “Triple safety: lightweighting automobiles to improve occupant, highway, and global safety”, SAE Technical Paper # 2008-01-1282, 2008.
- [16] K. Chan-Lizardo, A.B. Lovins, L. Schewel, and M. Simpson, “Ultralight vehicles – non-linear correlations between weight and safety”, International Crashworthiness Conference, Leesburg, VA, USA, 2011.
- [17] National Highway Traffic Safety Administration, “NHTSA workshop on vehicle mass-size-safety”, Washington, DC, USA, 2011, <http://www.nhtsa.gov/Laws+&+Regulations/CAFE++Fuel+Economy/NHTSA+Workshop+on+Vehicle+Mass-Size-Safety>, accessed August 2012.
- [18] F.J. Tahan, C.K. Park, R.M. Morgan, C. Cui, C.D. Kan, B. Brar, and K. Shanks, “The effect of reduced mass on crashworthiness”, International Crashworthiness Conference, # 2012-089, Milan, Italy, 2012.
- [19] U.S. Congress, “Committee reports, 109th Congress (2005-2006), Senate report 109-293 – transportation, treasury, housing and urban development, the judiciary, and related agencies appropriations bill, 2007”, The Library of Congress.
- [20] Research and Innovative Technology Administration - U.S. Department of Transportation, “A summary of proceedings for the safety characterization of future plastic and composite intensive vehicles (PCIVs)”, 2008, [http://ntl.bts.gov/lib/32000/32200/32205/summary\\_pciv\\_workshop.pdf](http://ntl.bts.gov/lib/32000/32200/32205/summary_pciv_workshop.pdf).
- [21] American Chemistry Council Plastics Division, “Plastic and composite intensive vehicles: an innovation platform for achieving national priorities”, 2009, <http://www.plastics-car.com/pcivs>, accessed August 2012.
- [22] A. Brecher, “A safety roadmap for future plastics and composites intensive vehicles (PCIV)”, Report No. DOT HS 810 863, Volpe National Transportation Systems Center, 2007.
- [23] A. Brecher, J. Brewer, S. Summers, and S. Patel, “Characterizing and enhancing the safety of future plastic and composite intensive vehicles (PCIVs)”, The 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany, 2009.
- [24] G. Barnes, I. Coles, R. Roberts, S.O. Adams, and D.M. Garner, “Crash safety assurance strategies for future plastic and composite intensive vehicles (PCIVs)”, Report No. DOT-VNTSC-NHTSA-10-01, Volpe National Transportation Systems Center, 2010.
- [25] M. Fisher and B. Cundiff, “APC vision and technology roadmap for the automotive market-defining priority research for plastics in 21st century vehicles”, SAE Technical Paper # 2002-01-1890, 2002.
- [26] M. Fisher, J. Kolb, and S. Cole, “Enhancing Future Automotive Safety with Plastics”, The 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper # 07-0451, Lyon, France, 2007.
- [27] American Chemistry Council Plastics Division (ACC PD), “Plastic in automotive markets technology roadmap – a new vision for the road ahead”, 2009, [http://www.plastics-car.com/roadmap\\_fullversion](http://www.plastics-car.com/roadmap_fullversion), accessed August 2012.
- [28] Automotive Composite Alliance, “History of automotive composites”, <http://www.autocomposites.org/composites101/history.cfm>, accessed August 2012.
- [29] B. Tang, “Fiber reinforced polymer composites applications in USA”, The First Korea/U.S.A. Road Workshop, 1997, <http://www.fhwa.dot.gov/bridge/frp/frp197.cfm>, accessed August 2012.
- [30] K. Sehanobish, Engineering Plastics and Plastic Composites in Automotive Applications, Warrendale, PA, USA, SAE International, 2009.
- [31] S. Das, “The cost of automotive polymer composites: a review and assessment of DOE’s lightweight materials composites research”, ORNL/TM-2000/283, 2001.
- [32] D.R. Cramer and D.F. Taggart, “Design and manufacturing of an affordable advanced-composite automotive body structure”, The Proceedings of The 19<sup>th</sup> International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, Busan, South Korea, 2002.
- [33] N. Tucker and K. Linsey, “An introduction to automotive composites”, Rapra Technology Limited, Shawbury, UK, 2002.
- [34] H.A. Jahnle, “Feasibility study of plastic automotive structure”, Report No. DOT-HS-801-771, U.S. Department of Transportation, 1975.
- [35] P. Beardmore and C.F. Johnson, “The potential for composites in structural automotive applications”, Composites Science and Technology, 1986, 26:251-281.
- [36] P.H. Thornton and R.A. Jeryan, “Crash energy management in composite automotive structures”, International Journal of Impact Engineering, 1988, 7(2):167-180.
- [37] G.C. Jacob, J.F. Fellers, S. Simunovic, and J.M. Starbuck, “Energy absorption in polymer composites for automotive crashworthiness”, Journal of composite materials, 2002, 36:813-850.
- [38] E. Mangino, J. Carruthers, and G. Pitarresi, “The future use of structural composite materials in the automotive industry”, International Journal of vehicle design, 2007, 44(3/4):211-232.
- [39] R.E. Bonnett, H. Kulkarni, G. Lim, P. Beardmore, and R. Knight, “Design and fabrication of automotive components in graphite fiber-reinforced composites”, SAE Technical Paper # 790031, 1979.
- [40] P. beardmore, J.J Harwood, and E.J. Horton, “Design and fabrication of a GrFRP concept automobile”, The 3rd International Conference on Composite Materials, 1980.
- [41] R.G. Boeman and N.L. Johnson, “Development of a cost competitive, composite intensive, body-in-white”, SAE Technical Paper # 2002-01-1905, 2002.

- [42] H. Fuchs, "Design and structural performance assessment of a composite intensive passenger vehicle", The 6th Annual SPE Automotive Composites Conference, Troy, MI, USA, 2006.
- [43] A. Deb, P. Lakshmanan, D.K. Kharat, and S.C. Lakkad, "Composite versus steel rails for vehicle front impact safety", The IMPLAST 2010 Conference, Providence, RI, USA, 2010.
- [44] P. Sklad, "Lightweight SUV frame design development", Altair Engineering, 2003, <http://altairlighten.com/wp-content/uploads/2011/12/Lightweight-SUV-Frame-Design-Development.pdf>.
- [45] S.M. Summers, A. Prasad, and W.T. Hollowell, "NHTSA's research program for vehicle aggressivity and fleet compatibility", The 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper # 249, Amsterdam, The Netherlands, 2001.
- [46] S.M. Summers, W.T. Hollowell, and A. Prasad, "NHTSA's research program for vehicle compatibility", The 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper # 307, Nagoya, Japan, 2003.
- [47] J. Blum, P. Scullion, R.M. Morgan, K. Digges, and C.D. Kan, "Structural attributes of the striking vehicle that control aggressivity toward the struck-vehicle in frontal collisions", IRCOBI Conference, York, UK, 2009.
- [48] National Crash Analysis Center/The George Washington University, "Finite element model archive: vehicle models", <http://www.ncac.gwu.edu/vml/models.html>, accessed August 2012.
- [49] D. Marzougui, R.R. Samaha, C. Cui, and C-D Kan, "Extended validation of the finite element model for the 2007 Chevrolet Silverado pick-up truck", NCAC 2012-W-003, National Crash Analysis Center, The George Washington University, 2012, <http://www.ncac.gwu.edu/research/pubs/NCAC-2012-W-003.pdf>.
- [50] P. Mohan, D. Marzougui, E. Arispe, C. Story, "Component and full-scale tests of the 2007 Chevrolet Silverado Suspension System", NCAC 2009-W-004, National Crash Analysis Center, The George Washington University, 2009, <http://www.ncac.gwu.edu/research/pubs/NCAC-2009-W-004.pdf>.
- [51] P. Mohan, M. Ritter, D. Marzougui, D. Brown, C.D. Kan, K. Opiela, "Modeling, testing, and validation of the 2007 Chevy Silverado finite element model", NCAC 2009-W-005, National Crash Analysis Center, The George Washington University, 2009, <http://www.ncac.gwu.edu/research/pubs/NCAC-2009-W-005.pdf>.
- [52] C.K. Park, C.D. Kan, W.T. Hollowell, and S.I. Hill, "Investigation of Opportunities for Light-Weighting Vehicles Using Advanced Plastics and Composites", Report No. DOT HS 811 692, National Highway Traffic Safety Administration, December 2012.
- [53] SABIC, "Xenoy resin", <http://www.sabic-ip.com/gep/Plastics/en/ProductsAndServices/ProductLine/xenoy.html>, accessed August 2012.
- [54] SABIC, "Lexan resin", <http://www.sabic-ip.com/gep/Plastics/en/ProductsAndServices/ProductLine/lexan.html>, accessed August 2012.
- [55] SABIC, "SABIC innovative plastics" SABIC STAMAX long glass fiber PP helps Hyundai Sonata's plastic door module win 2010 SPE innovation award", 2010, [http://www.sabic-ip.com/gep/en/NewsRoom/PressReleaseDetail/november\\_1\\_0\\_2010\\_sabicinnovativeplasticssabic.html](http://www.sabic-ip.com/gep/en/NewsRoom/PressReleaseDetail/november_1_0_2010_sabicinnovativeplasticssabic.html), accessed August 2012.
- [56] BASF, "Ultramid® B3ZG7 OSI (Optimized for Stone Impact) PA6 (Polyamide 6)", <http://www2.basf.us/PLASTICSWEB/displayanyfile?id=0901a5e1801631d8>, accessed August 2012.
- [57] C.K. Park, C.D. Kan, S. Reagan, and B. Deshpande, "Crashworthiness of composite insert in vehicle structure", International Journal of Crashworthiness, 2012, 17(6): 665-675.
- [58] C.K. Park, C.D. Kan, S. Reagan, B. Deshpande, and P. Mohan, "Crashworthiness and numerical analysis of composite inserts in vehicle structure", SAE International Journal of Passenger Cars- Mechanical Systems, 2012, 5(2): 727-736; SAE Technical Paper # 2012-01-0049.
- [59] D. Hull, "A unified approach to progressive crushing of fiber-reinforced composite tubes", Composites Science and Technology, 1991, 40:377-421.
- [60] G.L. Farley and R.M. Jones, "Crushing characteristics of continuous fiber-reinforced composite tubes", Journal of Composite Materials, 1992, 26:37-50.
- [61] A.G. Mamalis, D.E. Manolacos, G.A. Demosthenous, and M.B. Ioannidis, Crashworthiness of Composite Thin-Walled Structural Components, Boca Raton, FL, USA, CRC Press, 1998.
- [62] C.H. Chiu, C.K. Lu, and C.M. Wu, "Crushing characteristics of 3-D braided composite square tubes", Journal of Composite Materials, 1997, 31:2309-2327.
- [63] H. Hamada, "Crushing behavior of braided composites", ASME International Mechanical Engineering Congress and Exposition, AMD-Vol. 250/MD-Vol. 96, pp. 33-40, New York, NY, USA, 2001.
- [64] S.J. Beard and F.K. Chang, "Energy absorption of braided composite tubes", International Journal of Crashworthiness, 2002, 7(2):191-206.
- [65] M. Okano, A. Nakai, and H. Hamada, "Axial crushing performance of braided composite tubes", International Journal of Crashworthiness, 2005, 10(3):287-294.
- [66] C.K. Park, C.D. Kan, and W.T. Hollowell, "Evaluation of crashworthiness of composite ladder frame in a body-on-frame vehicle", International Crashworthiness Conference, #2012-118, Milan, Italy, 2012.
- [67] SABIC, "Noryl GTX resin", <http://www.sabic-ip.com/gep/Plastics/en/ProductsAndServices/ProductLine/norylgtx.html>, accessed August 2012.
- [68] SABIC, "SABIC innovative plastics helps GM create first thermoplastic fenders in a North American truck platform with 2006 HUMMER", [http://kbam.geampod.com/KBAM/Reflection/Assets/9816\\_5.pdf](http://kbam.geampod.com/KBAM/Reflection/Assets/9816_5.pdf), accessed August 2012.
- [69] Smock D, "Plastic oil pans present major integration opportunity", Design News, 2009, [http://www.designnews.com/document.asp?doc\\_id=228511](http://www.designnews.com/document.asp?doc_id=228511), accessed August 2012.

- [70] Bayer MaterialScience, “Bayblend® T88 GF-10 and T88 GF-2”,  
[http://plastics.bayer.com/plastics/emea/en/library/newpublications/docId-2903947/PCS-3018\\_en\\_Bayblend\\_T88\\_GF-10\\_and\\_T88\\_GF-20.pdf](http://plastics.bayer.com/plastics/emea/en/library/newpublications/docId-2903947/PCS-3018_en_Bayblend_T88_GF-10_and_T88_GF-20.pdf), accessed August 2012.
- [71] Slik G, “Evolution of structural instrumental panels”, SAE Paper No. 2002-01-1270, 2002.
- [72] Jahn T, Baudouin I, Vatel P, Karnik S, Perez O, Cue JM, Benichou HP, Dittmar H, Sengbusch J, and Kurcz M, “Development of Lightweight, Hybrid Steel / GMT Composite IP Carrier to Meet World Crash Requirements on Passenger Vehicles”, The 5<sup>th</sup> Annual SPE Automotive Composites Conference, Troy MI, USA, 2005.
- [73] Marks M, “Long glass fiber-polypropylene light weight instrument panel retainers & door modules”, SPE Automotive Composites Conference & Exhibition, Troy MI, USA, 2008.
- [74] Melzig J and Lehner M, “Lightweight construction due to thermoplastic foams as exemplified in an instrument-panel support”, SAE Paper No. 2006-01-1404, 2006.
- [75] Seagrave TD, “Structural RIM choices for today’s automotive design”, The 3<sup>rd</sup> Annual SPE Automotive Composites Conference, Troy MI, USA, 2003.
- [76] U.S. Department of Energy, “Composite materials production methods developed”, Vehicle Technologies Program, 2001,  
[http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/composite\\_mtls\\_mar\\_2001\\_2.pdf](http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/composite_mtls_mar_2001_2.pdf).
- [77] American Chemistry Council, “Composite drive shafts can increase torque and can help prevent injuries”,  
<http://www.plastics-car.com/driveshafts>, accessed August 2012.
- [78] BAC Technology LTD., “Carbon fiber driveshafts”,  
<http://www.bactechnologies.com/shafts.htm>, accessed August 2012.
- [79] Ogando J, “Carbon-fiber drives shaft systems”, Design News, 2003,  
[http://www.designnews.com/document.asp?doc\\_id=222235](http://www.designnews.com/document.asp?doc_id=222235), accessed August 2012.
- [80] Strongwell, “Composite driveshafts”,  
[http://www.strongwell.com/selected\\_markets/comp\\_driveshaft/](http://www.strongwell.com/selected_markets/comp_driveshaft/), accessed August 2012.
- [81] SGL Group, “Carbon-ceramic brake disks”,  
[http://www.sglgroup.com/cms/international/products/product-groups/bd/carbon-ceramic-brake-disks/index.html?\\_locale=en](http://www.sglgroup.com/cms/international/products/product-groups/bd/carbon-ceramic-brake-disks/index.html?_locale=en), accessed August 2012.
- [82] Hexcel, “New cost optimized axle module for composite leaf springs - from Magna Steyr, composite trends”, 2006,  
<http://www.hexcel.com/news/newsletters/letter-20060401.pdf>, accessed August 2012.
- [83] HYPERCO, “Composite leaf springs”,  
<http://www.hypercoils.com/products/hyperco-composite-leaf-springs.aspx>, accessed August 2012.
- [84] Siddaramanna G, Shankar S, and Vijayarangan S, “Mono composite leaf spring for light weight vehicle – design, end joint analysis and testing”, Materials Science, 2006, 12(3):220-225.
- [85] Kulekci MK, “Magnesium and its alloys applications in automotive industry”, The International Journal of Advanced Manufacturing Technology, 2008, 39(9-10):851-865, DOI: 10.1007/s00170-007-1279-2.
- [86] Magnesium Elektron, “Magnesium in automotive”,  
<http://www.magnesium-elektron.com/markets-applications.asp?ID=7>, accessed August 2012.
- [87] Langsdorf J, “Weight savings: steel vs. aluminum wheels”,  
[http://www.ehow.com/about\\_5664238\\_weight-steel-vs\\_-aluminum-wheels.html](http://www.ehow.com/about_5664238_weight-steel-vs_-aluminum-wheels.html), accessed August 2012.
- [88] Hojnacki HE and Taka G, “Lightweight automotive seating system”, SAE Paper No. 2011-01-0424, 2011.
- [89] Naughton P, Shembekar P, Lokhande A, Kauffman K, Rathod S, and Malunjkar G, “Eco-friendly automotive plastic seat design”, SAE Paper No. 2009-26-0087, 2009.
- [90] LOTUS engineering, “Vehicle mass reduction opportunities”, 2010,  
[http://www.epa.gov/air/caaac/mstrs/oct2010/5\\_peterson.pdf](http://www.epa.gov/air/caaac/mstrs/oct2010/5_peterson.pdf)
- [91] Plott J, Personal communication, BASF, June 2011.
- [92] Marks MD, Personal communication, SABIC, July 2011.
- [93] Energy Efficiency & Technology, 2011, “Lithium technology comes to car batteries”,  
[http://eetweb.com/power-supplies/lithium\\_batteries\\_3411/](http://eetweb.com/power-supplies/lithium_batteries_3411/)
- [94] Lithiummoto, “Lithium high performance replacement batteries”, 2011,  
<http://www.lithiummoto.com/index.html>, accessed August 2012.
- [95] Motor Sports Newswire, “Racing batteries USA sparks agreements with the California superbike school & zippy racing”, 2011,  
<http://motorsportsnewswire.wordpress.com/tag/lightweight-batteries/>, accessed August 2012.
- [96] Porsche, “New lightweight battery option for the Porsche 911 GT3, 911 GT3 RS and Boxster Spyder”, 2009,  
<http://press.porsche.com/news/release.php?id=510>, accessed August 2012.
- [97] DuPont, “20% less weight: Revolutionary ultra-lightweight concept tire from Dunlop with DuPont”, 2009,  
[http://www2.dupont.com/EMEA\\_Media/en\\_GB/newsreleases\\_2009/article20090303a.html](http://www2.dupont.com/EMEA_Media/en_GB/newsreleases_2009/article20090303a.html), accessed August 2012.
- [98] ExxonMobil, “Exxcore DVA resin”,  
<http://www.exxonmobilchemical.com/Chem-English/brands/butyl-rubber-exxcore-dva-resin.aspx?ln=productservices>, accessed August 2012.
- [99] AAA, “Vehicles without a spare tire”,  
[http://www.aaa.com/AAA/corpcomm/socialmedia/No\\_Spare-Tires.pdf](http://www.aaa.com/AAA/corpcomm/socialmedia/No_Spare-Tires.pdf), accessed August 2012.
- [100] Williams D, “GM offering tire inflator kits instead of spare tires on some models”, 2011,  
<http://www.everycarlisted.com/blog/2011/05/gm-offering-tire-inflator-kits-instead-of-spare-tires-on-some-models/>, accessed August 2012.
- [101] Livermore Software Technology Corporation, LS-DYNA Keyword User’s Manual, Version 971, 2009.
- [102] P. Mohan and D.L. Smith, “Finite element analysis of compatibility metrics in frontal collisions”, The 20<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France, 2007.
- [103] G.S. Nusholtz, L. Xu, Y. Shi, and L.D. Domenico, “Vehicle mass, stiffness and their relationship”, The 19<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, DC, USA, 2005.