Technical Whitepaper: Crashworthiness and Crash Avoidance

Introduction

As vehicle designers are continuously challenged to explore new technologies in pursuit of the historically conflicting goals of vehicle weight reduction and safety, aluminum with its superior strength-to-weight ratio and unmatched design and manufacturing flexibility is a proven medium that provides safety and weight reduction at the same time. Recent data suggests that aluminum intensive vehicles (AIVs) can be designed to be safer than equivalent steel-based vehicles.

Specifically, the use of aluminum for crash energy management has many advantages over that of steel:

- The high strength-to-weight ratio of aluminum allows strong, yet lightweight body structures to be built
- Aluminum allows for larger crush zones which serve to reduce forces on vehicle occupants in a crash
- Aluminum structural members can be engineered to collapse in a predictable manner in severe impacts and, as a result, can be readily designed to provide the desired amount of crash energy absorption
- The superior corrosion resistance of aluminum minimizes deterioration of the crash energy absorption capabilities over the life of the vehicle
- Pound for pound, aluminum absorbs twice as much crash energy as typical automotive steel so that as vehicle weight reduction becomes inevitable, substituting aluminum for steel will provide simultaneous improvement in fuel economy, performance and safety, a truly compelling combination for vehicle manufacturers and their customers

The benefits of using aluminum in vehicle design allows automotive designers to maintain vehicle size and occupant safety while achieving significant vehicle weight savings. This paper discusses the attributes and advantages of aluminum to maintain and enhance the crashworthiness of motor vehicles, as well as to improve the ability of vehicles to avoid crashes.

Background-Crash Management

Before we explore the safety attributes and advantages of aluminum, it is important to understand the basics of vehicle crash management.

The basic idea is to design vehicle structures which minimize the amount of injury-causing crash energy that reaches the occupants. Generally, this is accomplished by developing structural zones that absorb crash energy outside the passenger compartment – these are called "crush zones" and they collapse in a prescribed way at specified loads, thereby providing the appropriate energy absorption and deceleration of the passenger compartment.

Meanwhile, passengers are protected inside the passenger compartment by restraint systems, i.e. seat belts and air bags. A great deal of research and development has been carried out over the years to design and integrate these systems. In the case of the crush zones, the energy is absorbed by the folding and bending deformation of the metal structure.

To the strongest extent, automotive engineers attempt to maximize the transmission of crash energy through the structure axially (from front to back) so that the structure folds like an accordion as it absorbs the crash energy. This design is sensible because frontal impacts are the most frequent vehicle crashes and cause the most injuries and fatalities.

In vehicle crashes, most of the crash energy is absorbed through the in-and-out folding of the side plates of the main energy absorbing structural beams during the collapse process. The longitudinal beams at the front end of a vehicle generally act as the main structural members for absorbing crash energy in a frontal impact, and the crushable length of these components defines the distance over which the crash energy can be absorbed.

Bumper-to-frame rail attachments are designed to transfer the impact force directly to the lower front rails. The upper rails also need to be part of the load path to absorb some of the impact energy, and to transfer some of the force of the crash in order to minimize vehicle bending moment.

The design objective for rails is to balance the load path into the passenger cell of the body structure so as to distribute the loads between the roof and the floor. The structure between the rails and the rockers also must be strong enough to resist plastic deflection into the passenger space. To allow proper functioning of the passenger restraint system, the bending moment on the passenger compartment must be limited to avoid collapse of the roof structure and floor bending.

Other than axial collapse resulting from front and rear end crashes, bending collapse is the other common mode of energy absorption in automotive structural components. A-pillars, windshield headers and roof side rails are typical structural members where combined forces cause bending mode collapse. Such collapse is typically caused either by buckling of the compressed surface or by cracking and tearing of the surface under tensile stress. Buckling is the preferred mode of collapse because it results in a more stable and predictable energy absorption.

Automotive Aluminum and Safety

Aluminum, just like steel, absorbs energy in a vehicle crash by folding and bending deformation of the metal structure. There are, however, important physical and metallurgical differences between the metals. Aluminum, for example, is much less dense than steel but it is typically used at 1.5 times the steel thickness in equivalent structural components. Because aluminum has a higher strength-to-weight ratio the resulting aluminum components are stronger but still have a much lower weight than their steel counterparts.

Pound-for-pound, aluminum will absorb almost twice the crash energy of typical automotive steel. It is estimated that for two vehicles of equal weight - one aluminum and one steel - the aluminum vehicle can be 20 percent larger. This allows designers to maximize overall vehicle size without weight penalties.

Since greater size provides the ability to design more crush space, the occupants of such a vehicle would be subjected to lower G forces and would be safer than occupants in a conventional vehicle of similar weight.

Structural Forms

The mass efficiency and production cost of specific components often requires that the components be of a particular form. The most efficient form might be an extrusion, a casting, or a box beam fabricated from sheet. In other cases a combination of those elements might be dictated. Aluminum’s superior castability and ease of extrusion allows each component to be designed for maximum energy absorption while remaining compatible with mating components. Flexibility of fabrication as well as high strength-to-weight ratio provide aluminum with significant advantages for vehicle construction.

The Crash Pulse

It is neither cost-effective, nor safe, for a vehicle to be designed so rigid or heavy as to survive any collision imaginable without damage. The human body can only withstand deceleration to a certain limit, beyond which severe internal injury or death occurs. A crashworthy vehicle must be designed to deform according to a deceleration-time response, or crash pulse. Ideally, engineers try to design the deformation of the structure to achieve a uniform deceleration, for example 20-25 G's when measured in a fixed barrier, frontal crash at 30 mph (where G is the pull of gravity). During that very short time period (in milliseconds), the kinetic energy must be absorbed primarily by the vehicle's crush zone.

Vehicle engineers design crush zones to satisfy a number of disparate regulatory requirements and consumer information programs.

To provide examples for frontal impacts, the U.S. National Highway Traffic Safety Administration's (NHTSA) Federal Motor Vehicle Safety Standards (FMVSS) specify that a 30 mph full-frontal impact into a rigid barrier while the highly publicized Insurance Institute for Highway Safety (IIHS) tests crash vehicles at 40 mph into a deformable offset barrier; the U.S. New Car Assessment Program (NCAP) requires a 35 mph full-frontal impact; the European NCAP program tests at 40 mph into a 40 percent offset deformable barrier; and European regulations require a 37 mph impact into a 40 percent deformable offset, barrier.

These various tests measure deceleration response and establish head injury criteria (HIC), chest G's, femur loads and other measures as indicators of the level of injuries an occupant might receive. A vehicle designed for the global market must be able to satisfy this whole spectrum of testing requirements without being unduly complex and massive. Furthermore, the United States. and the European regulatory authorities appear to be developing additional testing requirements virtually on a continuous basis.

Aluminum Intensive Crash Performance

Aluminum use in autos has doubled in the last decade and this growth is expected to accelerate in the future. With this rapid conversion of steel to aluminum, there is a natural concern in part of the public that vehicle safety could be affected. Happily, this is not the case. In fact, AIVs have demonstrated superior crash performance. Most notably, the aluminum intensive Audi A8 has been crash tested by NHTSA under its NCAP program and achieved NHTSA's top five-star rating for both front occupants, the only luxury sedan to achieve the top dual five-star safety rating for 1998. One scheme to integrate all available safety data (and published in the Wall Street Journal on 10/12/99) has rated the Audi A8 as the safest car in the world.

Ford Motor Company has also conducted crash tests on their AIV, specifically, the regular steel production Taurus/Sable on which the design of the AIV was based.

The results show similar, and in many instances improved performance for the AIV than for the regular steel production vehicle. Of particular note is the AIVs chest-acceleration g-measurement of 37, versus 53 for the steel Taurus. Also, femur loads in the AIV are dramatically lower than those in the production Taurus/Sable, itself having received high NHTSA crash ratings.

The General Motors aluminum-structured EV1 electric car also had a satisfactory rating in the NHTSA NCAP 1997 crash test, matching the performance of many larger and heavier vehicles. This is a remarkable achievement given the EV1s extremely light structure coupled with its extremely heavy load of batteries.

Vehicle Size and Weight

Today, the issue of vehicle safety is more important to vehicle purchasers. The sales trends during the last two decades have certainly been a consequence of this consumer sentiment. Thus, light trucks have taken an increasingly large share of the United States market while the smallest car segments have continuously declined over the same period. It is not clear when this weight-size spiral will abate but it is clear that the trend is seriously impacting other national and societal priorities, i.e. pollution control, global warming, energy conservation, congestion, etc. Not surprisingly, this situation has created a serious dilemma for vehicle manufacturers as indicated recently by no less a personage than William Clay Ford, the chairman of Ford Motor Company.

There is little doubt that larger and heavier vehicles provide more safety for their occupants. In fact, there is a great deal of data which bears this out in the various statistical data bases on highway injuries and fatalities. However, it has been much more difficult to separate the effects of size and weight from a statistical point of view. But, in actuality it is now possible to separate size and weight, by replacing steel with aluminum.

While not a new concern, discrepancies in size and weight between cars, light trucks and other vehicles on the road are getting increasing attention by the highway safety community. Called Vehicle Compatibility, the goal is to design vehicles that would be sufficiently compatible in body structure, bumper height, center of gravity, and crush zones so that crashes between larger vehicles and smaller ones would not result in such an uneven distribution of damage and risk as exists today.

It is also well known among safety experts that the effects of size and weight are quite different from a societal point of view. Thus, one of the effects of increasing weight is to shift the risk from the heavier vehicle to any other vehicle that may collide with it. The concern is that vehicle purchasers, acting in their own self interest, will cause this risk shifting to continue even further.

However, aluminum offers the real possibility of changing the size-weight paradigm so that size and weight can be separated. In contrast to the effects of weight, it is expected that size differences will have very little effect on the aforementioned risk shifting especially with proper vehicle design.

The greater the mass of the vehicle, the greater the momentum (mass times velocity) that is transferred to the other vehicle in a crash. The ratio of masses between two vehicles has a strong influence on the aggressivity (the opposite of compatibility) and is a matter of great concern.

Lowered aggressivity means less energy transferred in a crash, translating in turn to less-serious injuries for occupants of the other vehicle. Reducing weight through the use of aluminum body structures (especially when applied to larger vehicles) achieves such results, as illustrated by tests conducted by the German auto magazine, *auto motor und sport.*

The magazine evaluated aggressivity by crashing two larger vehicles - an Audi A8 and a similar-sized but heavier steel vehicle - into two smaller ones. For the Audi crash test, the smaller vehicle was a VW Polo. The study concluded the Polo occupants would survive this serious head-on collision with the Audi A8 without life-threatening injuries. In contrast, occupants in the other small vehicle that crashed with the heavier steel vehicle would have sustained substantial and probably life-threatening injuries.

Vehicle Handling

An often overlooked factor in crash management is vehicle handling. It is fairly obvious that improved handling enhances a vehicle's ability to avoid crashes altogether. A certain number of vehicle crashes occur because one - or both - vehicles are unable to be maneuvered around the point of contact. The cornering limits of vehicles also affect their ability to be steered away from potential crashes. Reduced weight leads to improved stability and turning response as well as a decrease in slip angle between the tire and the road for any given turning (i.e. lateral acceleration) situation.

Lower weight should allow a vehicle to respond more directly and predictably to steering inputs other things being equal.

Acceleration and Braking

The reason for such performance differences is the combination of light weight and structural stiffness that can be obtained with aluminum. As a vehicle travels over uneven surfaces or changes direction, forces act to bend (twist) the body structure. However, the combination of lightness (which reduces the reaction forces) and high stiffness (which reduces the amount of twisting) reduces the steering correction necessary due to less flexing of the vehicle structure.

A vehicle's acceleration and braking also contribute to crash avoidance, and aluminum-structured vehicles have important benefits in these areas. The lightness inherent in AIVs improves their capability to accelerate. For instance, a conventional mid-sized sedan weighing 3,400 pounds, which can accelerate from 0 to 60 mph in 10.0 seconds, would weigh only 2,600 pounds if made from aluminum, and given the same drivetrain, could accelerate from 0 to 60 in 8.2 seconds. There are, of course, a number of crashes that could be avoided with such increased ability to accelerate away from danger.

The light weight of AIVs also improves braking capability, another important factor in crash-avoidance. Thus, with the same braking force applied by the driver, the AIV, with its lower kinetic energy, will stop in a shorter distance than a similarly equipped conventional vehicle made of the heavier, traditional material.

Cast Components

Drivetrain and suspension components are being rapidly converted from cast iron to cast aluminum. The primary motivations for these conversions is fuel economy improvement through weight reduction and performance improvement, but significant improvements in safety are also achieved in these changes.

One of the big obstacles in achieving a smooth crash pulse is the heavy iron powertrain. When the large mass of the engine is de-accelerated during a crash, and then "bottoms out" on the firewall. Aluminum blocks, heads, intake manifolds, transmission housings, etc., greatly reduce the drivetrain mass and thereby smooth out the crash pulse relative to a vehicle with heavier iron components.

In addition, aluminum suspension components, improve crash avoidance characteristics by reducing unsprung mass, thereby improving handling, ride and braking particularly on uneven surfaces. It is also expected that increased aluminum use in the future in structural and exterior panels can be used to lower the vehicle center of gravity which would be expected to reduce rollover accidents.

Conclusion

Automotive use of aluminum offers benefits that greatly enhance highway safety through effective crash-energy management and improved vehicle handling. Unlike traditional materials, aluminum's high strength-to-weight ratio and superior ability to absorb energy allow the weight of vehicle structures to be reduced while maintaining vehicle size and the ability of the structure to absorb crash energy. In addition, its light weight, coupled with the structural rigidity, also improves steering responsiveness, braking and acceleration, thereby helping drivers avoid potential collisions.

Furthermore, once, an effective crash management body structure has been designed and executed, aluminum's unmatched corrosion resistance ensures that the effectiveness will be maintained throughout the life of the vehicle.

Looking to the future, it is clear that the public, automakers and regulators all seek vehicles with improvements in efficiency, pollution control, performance and safety.

The only practical way these formerly contradictory improvements can be accomplished simultaneously is by substituting aluminum for steel. To the extent this substitution is applied to trucks and larger passenger cars, vehicle compatibility will also be improved. It is aluminum's superior strength-to-weight ratio that makes all this possible.