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Strategies for Managing Vehicle Mass throughout the Development Process and Vehicle Lifecycle

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ABSTRACT

Managing (minimizing and optimizing) the total mass of a vehicle is recognized as a critical task during the development of a new vehicle, as well as throughout its production lifecycle. This paper summarizes a literature review of, and investigation into, the strategies, methods and best practices for achieving low total mass in new vehicle programs, and/or mass reductions in existing production vehicle programs. Empirical and quantitative data and examples from the automotive manufacturers and suppliers are also provided in support of the material presented.

INTRODUCTION

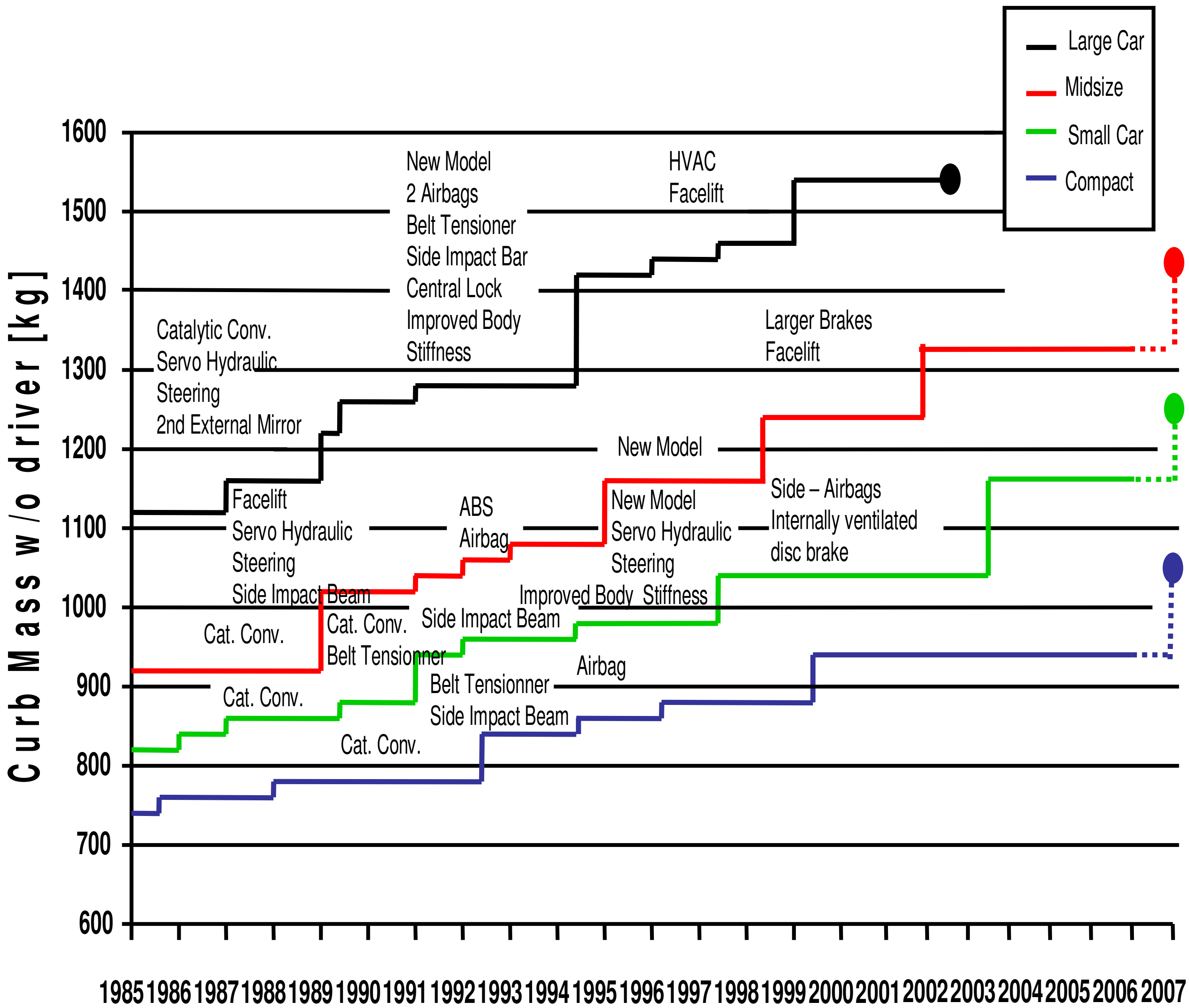
Recent increases in the price of gasoline in the North American market, and the subsequent importance of fuel economy in the minds of North American car and truck buyers, have led vehicle manufacturers to place renewed emphasis on the need to reduce or minimize vehicle mass. References to the importance of managing and controlling vehicle mass and its impact on fuel economy can be found in professional journals and trade publications dating back to the mid-1970's and earlier [1, 2, 16]. These previous articles, written during the gasoline supply shortages of the early to mid-1970s, focused on the fact that reducing vehicle weight can play a very significant and practical role in reducing fuel consumption. More recently, Guzzella has shown that while improvements of 10% in vehicle aerodynamics or rolling friction provide a 3% fuel economy improvement, that same magnitude of mass reduction provides a 7% increase in fuel economy [9]. Furthermore, the impact of vehicle mass extends beyond just fuel economy, and has a measurable effect on additional vehicles attributes such as performance, cargo capacity, ride and handling, cost, durability and ease of assembly. The impact of vehicle mass on developing and future technologies has also been the focus of investigation, with respect to both the positive and negative implications of mass reductions. For example, in their study on the fuel economy sensitivity of different powertrains to vehicle mass, Pagerit et al. established and quantified how the regenerative braking of a hybrid vehicle is affected with changes in vehicle mass [13]. Among other things, the study found that, although the amount of available energy that can be recovered diminishes with vehicle mass, a lighter vehicle will have less available braking power in excess of a given battery size, and the battery captures a larger portion of the total braking power (less energy wasted through the friction brakes). Furthermore, as the mass of the subject vehicle was decreased, the degree of hybridization increased. Therefore, while minimizing and optimizing the total mass of a vehicle remains a critical goal for many reasons when developing a new vehicle and throughout its lifecycle, the many implications of that mass reduction need to be fully understood and considered.

EVIDENCE OF, AND REASONS FOR, VEHICLE MASS INCREASES

Both recent and older studies have documented that total vehicle mass tends to increase as vehicles progress through their life cycle, in spite of very successful efforts at mass reduction involving those same vehicles [7]. Ventre, DeAndria and Rullier [16] of Renault demonstrated in 1980 a net increase of 1% annually, generally speaking, in the weight of European vehicles, even while efforts were implemented on many of those models to reduce total vehicle weight. More recently, Dereski of General Motors has presented similar data showing mass increases for a range of different-sized vehicles over the course of their respective lifecycles [8]. This data is shown in Fig. 1, which depicts the increases in mass for each of four vehicle lines over time as a step function. This chart also identifies the product features or content changes that were introduced to satisfy regulatory, performance, or customer demands, and the corresponding increase in mass. In general, new model or major changeovers resulted in an increase of 80-100 kg (177-221 lbs), while minor facelifts increased vehicle weight by 20-50 kg (44-110 lbs). As noted above, this is consistent with the experience of other manufacturers.

There are a number of recognized reasons for or causes of increased vehicle mass, some of which are customer or market-driven while others are often technical in nature or the result of the regulatory environment. Among the former, the addition or inclusion of customer-driven features such as rear passenger entertainment

Fig 1: HISTORICAL VEHICLE CURB MASS GROWTH



Reference: "Vehicle Mass Case Study", W. Dereski, September 2006 systems, trailer towing packages, and powered seats, doors, windows and liftgates, all add to the overall mass of the vehicle. Also included in this category would be safety enhancements desired by the customer, such as side curtain and side impact air bag systems, stability control, and anti-lock brakes. Increasing government safety regulations have resulted in the inclusion of protective features for rear impact, side impact, and roll-over protection. Governmental emission requirements have resulted in fuel delivery systems, engine controls, and exhaust systems that require additional hardware and the accompanying mass increases, while efforts to increase fuel economy have led to the use of transmissions with more gears for increased operational efficiency of the engine.

Since the application of lightweight engineering practices follows “well-defined and optimized engineering principles”, it would seem that an engineering solution optimized for mass should be readily achievable. However, “compromises between styling, packaging, availability, manufacturability, noise-vibration-harshness, and aerodynamics complicate the quest for the perfectly engineered structure. Thus, the full potential of lightweight engineering can be realized only in rare cases, necessitating the consideration of additional lightweight solutions.” [14]

For these and many other reasons, efforts to reduce the total weight of a vehicle frequently result in no net gain to the total vehicle mass, and often only reduce the amount of mass increase that would have otherwise occurred. In fact, providing vehicles that satisfy consumer wants and needs, regulatory requirements, and environmental and societal needs without inflationary growth in vehicle mass, continues to be regarded as one of the toughest challenges facing the automotive industry.

VEHICLE MASS TARGET SETTING

A key element of any strategy to manage or reduce vehicle mass is to establish target values for vehicle weight early on in a program, and to treat those targets as program requirements throughout the vehicle’s development and lifecycle. Setting meaningful and defensible targets/requirements is often achieved using one of the following methods:

Benchmarking

Benchmarking consists of a rigorous comparison of one product to a similar product for the purpose of making competitive assessments. In the case of mass analysis and comparison, a competitive production vehicle would be weighed while fully assembled, and then disassembled, with each subsystem and/or component identified, weighed, and observations noted regarding characteristics or features that might be of interest or value to the engineers making the assessment. Once the disassembly is completed, the mass data and other relevant information is analyzed and summarized, and used in the setting of component, subsystem, system and total vehicle mass targets. This exercise is also useful in identifying or discovering new features or technologies that might be of use in reducing mass in the vehicle for which mass targets are being generated.

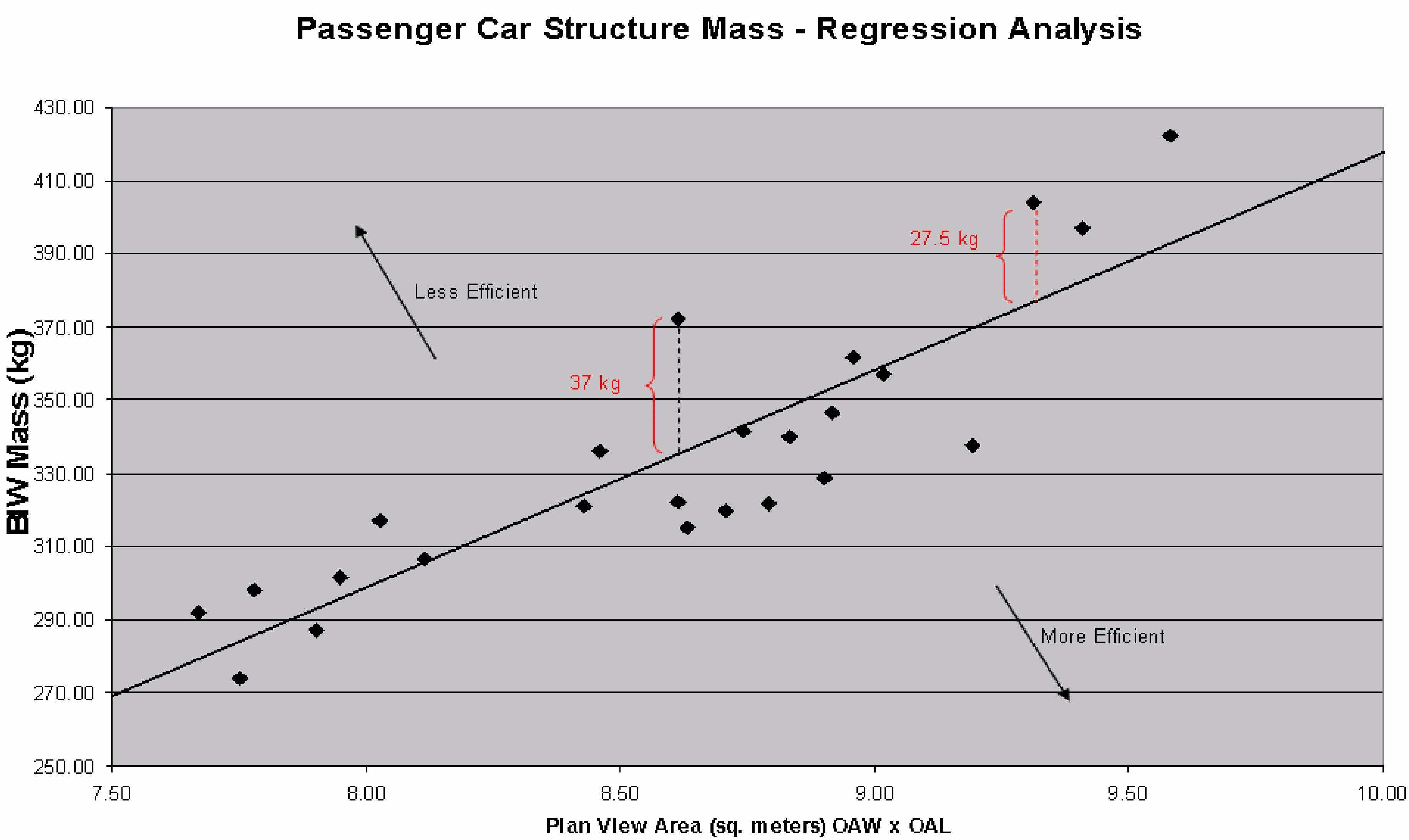
Seed vehicle walk-ups

Although similar in approach to benchmarking, seed vehicle walk-ups usually involve an existing or near-production vehicle from the same supplier or manufacturer as the vehicle for whom the mass targets are being set. While the focus of the benchmarking assessment is to identify the mass of vehicles already on the market that the new vehicle being developed will compete with, the seed vehicle walk-up is intended to do a comparison to a similar vehicle about which the manufacturer already has knowledge. This seed vehicle can then be used as a “starting point” as the development of the new vehicle begins [5]. It is also used to identify those areas or features of the vehicle where known changes are planned, such as the structure for safety reasons, or the interior for addition of an entertainment system. The anticipated increases in mass for the components or parts to be added or removed in light of these changes can then be added or subtracted, or “walked up”, from the starting point that the seed vehicle provides. Seed vehicle walk-ups are often considered an inexpensive yet credible way of estimating potential mass changes with known part or subsystem data, which when coupled with good engineering judgment results in mass estimates of high fidelity

Regression analysis

Regression analysis is an analytical prediction that utilizes exiting measured data from a large population of appropriate current and past production vehicles to generate a mathematical relationship between vehicle mass and some other characteristic(s) of those vehicles. This method has been in use in near-identical formats and with similar variables by various automobile manufacturers since at least the 1970s [16]. Fig. 2 is a regression that compares the measured weight of the Body-In-White (BIW) for a population of vehicles (plotted on the vertical axis) as a function of the plan view (overall length x overall width in meters squared) of the BIW (plotted along the horizontal axis). Using this regression for the appropriate population, the developers of a new vehicle could use the plan view to predict the weight of the BIW for their planned vehicle. A similar approach could be and is often used for vehicles as a whole. In an attempt to improve upon these regression analysis tools, other parameters for use on the horizontal axis have been developed, including some that are based upon complex proprietary formulas made up of various vehicle characteristics and attributes, to establish a relationship with the vehicle mass. Using appropriate sample sizes, studies have shown a correlation coefficient of 0.94 or higher [16] for some regressions, indicating that the correlation with the appropriate parameters can be significant.

Fig. 2: Mass Regression Analysis of Passenger Car Structure



Although the credibility and value of this approach is grounded in the fact that it is based upon measured data of production vehicles, it's use in predicting the mass of new or future vehicles must be tempered with the recognition that this is historical data and represents the relationship of mass to the plan view (or whatever vehicle criteria is chosen) of current and past vehicles and technologies. Therefore, vehicle programs that are intended to improve upon or "leapfrog" past and current products would need to achieve a mass that is below the regression line for a given horizontal-axis independent variable. In a similar fashion, vehicles that are expected to incorporate additional convenience, entertainment, safety or regulatory features that add content and mass beyond what would typically be found in this vehicle population, will either demonstrate a competitive disadvantage for mass to the rest of the population, or will require new and innovative mass-reducing designs and technologies to compensate for those added features.

MANAGING TO TARGETS AND REQUIREMENTS

Once vehicle and subsystem mass targets/requirements have been identified and communicated to the engineering team, rigorous and disciplined processes must be in place to ensure that the requirements are met. The fact that such processes often do not receive the required management support, or are dismissed as not being as critical to the product's success as are other vehicle criteria, has been documented in previous program management studies, and often results in either unsatisfactory results for the vehicle's final mass, or costly solutions to achieve it. As previously stated by Kim and Wilemon, "Whilst it is recognized that the front-end process is critical for new product success, companies still poorly manage this phase of the development process" [12]. It is therefore critical that program management implement the necessary processes for establishing these mass targets, the tools and strategies for achieving them, and the discipline and accountability among the engineering team to ensure that they are considered requirements that must be met. One example of such a tool, and the resultant discipline that accompanies it in a well managed and executed program, is that of a change management structure and process. As discussed by Batchelor, et al., in a case study of a successful program by one automotive OEM [4], a critical element of that success was "…a change management process that not only project managed the issues, but also enabled the change in key metrics such as…weight to be analyzed simultaneously across the issues." A strong change management process, in which decisions and changes affecting component and/or vehicle mass are controlled and communicated in a coordinated manner, eliminates confusion and provides clear direction to the team. Tracking models, in-depth reviews (known as "deep dives"), and gate reviews at key points in the development program are additional tools utilized in a well-managed and disciplined development program for managing or reducing weight to requirements. These are beyond the scope of this paper. However, and are therefore mentioned only for reference and will not be considered further.

The discussion up to this point established the importance of optimizing and/or reducing the total vehicle mass throughout a vehicle's development and life cycle, and the tools and strategies for setting and achieving vehicle mass targets and requirements (during development) or mass reduction targets (during production). The remainder of this paper summarizes the strategies and processes that have been identified for implementation by various Original Equipment Manufacturers (OEMs), suppliers and researchers, and discussed in past professional publications and trade journals. Empirical and quantitative data are also provided in support of the material presented.

STRATEGIES FOR MANAGING VEHICLE MASS

The strategies, methods and best practices for managing vehicle mass that have been identified by this investigation and literature review include:

- Selecting lighter or lower density materials
- Optimizing or improving existing designs
- Combining or eliminating parts, assemblies, and/or their function
- Re-sizing parts and systems
- Removing content or features from the vehicle
- Revising manufacturing or assembly operations

The decision of which of these strategies, or which combinations of strategies, to apply to a given vehicle program will depend on a variety of factors, including the resources available for the mass management effort, the magnitude of the mass reduction required, and where in the development or production cycle a given program finds itself.

SELECTING LIGHTER OR LOWER DENSITY MATERIALS

The primary material for use in automobile and truck manufacturing has typically been mild steel, but manufacturers are now investigating applications utilizing alternatives such as high-strength steel (HSS) and advanced high-strength-steel (AHSS), which are considered enablers to the design and manufacturing part of the development process. Conventional mild steel and some HSS grades restrict component complexity with severe limits in formability of the steel. However, the reduced limitations of AHSS with respect to formability provide significant opportunities for the designer to optimize part shape and combine components and features. This results in designs that increase mass efficiency by placing the materials where they are most effective at achieving performance requirements with minimum mass. A study by Shaw and Roth demonstrated a 20% to 25% reduction in vehicle mass at no relative cost increase when compared to benchmark vehicles in a recent ULSAB program [15].

In addition to AHSS, other alternative materials, such as aluminum, titanium, magnesium and composite materials are also being looked at as a means for reducing vehicle mass. Although these materials and their mass-saving potential have been known to the auto industry for years, their lack of cost-competitiveness has prevented them from being considered for production vehicles. With today's higher fuel costs, however, their contribution to improving fuel economy, safety and other vehicle attributes may be sufficient to offset the higher costs [7].

Aluminum's relatively low material density makes it an excellent choice as a way to lower the mass of parts such as bumper reinforcement beams, especially when it is extruded or formed so that the wall thickness in the cross-section is no more than what is needed to meet the application's requirements [10]. Critical to the use of such alternative materials, however, is the employment of alternative construction and joining techniques, such as the use of rivets, adhesives and using castings in place of stamped sheet metal for aluminum extrusions. In fact, the critical factor in achieving desirable results with alternative materials is to design and engineer the components with the alternative material and its properties in mind, rather than just substituting one material for another in the exact same design. Jaguar engineers have learned to substitute alternate constructions as needed, rather than just replacing sheets of, say, steel with aluminum. "We've changed subtly how we design our cars," says Mark White, Manager of Body Structures at Jaguar. "We use castings now where we used to use multiple-sheet construction…Casting the part lets engineers vary its thickness as needed, so it is neither too flimsy nor too heavy." [7]

Among composite materials, the 2005 Chevrolet Corvette utilized a unique construction consisting of an SMC (sheet molded compound) skin enclosing a balsa wood core for the floor panel. The subsequent C6 model switched to a carbon-fiber covering for the balsa core [7].

OPTIMIZING OR IMPROVING EXISTING DESIGNS

Redesigns are another approach that can be employed to reduce mass, and may range from the simple removal of unnecessary material through engineering or test analysis, to the combining of existing or modified parts that results in an equivalent or superior, yet lighter, module or system. One approach involves utilizing hybrid bumper systems that not only optimize the design of the individual components, but also leverage the manufacturing process and material selection for the entire bumper system. This steel hybrid design proposed by Glasgow, et al., incorporates a bumper beam whose cross-section is varied along the length of the beam [10]. This provides a higher bending stiffness where needed at the center of the beam's span by increasing the thickness there, satisfying performance requirements while reducing the thickness at each end to reduce mass. In addition, the material thickness and grade of the roll-formed and stamped components can be varied by design as well, enabling further mass reductions while meeting overall system requirements. Implementing these design, material and manufacturing ideas resulted in a front bumper system that was 30% lighter over the current production design utilizing roll-formed steel. A hybrid steel and plastic rear bumper system that also utilized optimized designs, materials and manufacturing processes from a systems perspective achieved a 20% mass reduction. Both hybrid solutions successfully demonstrated that hybrid design concepts for bumper reinforcement beams could be developed to meet performance requirements while achieving significant mass savings.

On occasion, the physical dimensions and gauge required for stiffness in a carbon steel part have been less than what was required for strength in that same part, requiring a redesign of the part. In those cases, "the traditional approach has been to increase the material gauge resulting in a higher part weight. However, in lightweight design, the use of a higher strength material is considered before increasing the material gauge." [14] This will often permit a design that achieves stiffness, strength and/or combinations of other requirements, without a corresponding increase in component mass.

Another approach is to use the benefits of engineering software and computer modeling to optimize designs. The commercial vehicles systems group of one major Tier One supplier to truck OEMs (Original Equipment Manufacturer) has utilized engineering technology advancements such as proprietary shape optimization software with its CAD (Computer Assisted Design) applications. Computer analysis tools like these have resulted in designs that minimize material and reduce mass while still meeting performance requirements [5]. Examples of successful mass reduction component design solutions include 146mm (5 ¾ inch) axle tubes that save 13.5 kg (30 lbs) per axle compared to a traditional 127mm (5 inch) axle tube. The supplier also reports the added benefit of improved tire wear and fuel economy resulting from the reduced axle deflection.

COMBINING OR ELIMINATING PARTS, ASSEMBLIES, AND/OR THEIR FUNCTION

Birkland [5] reports on efforts to reduce mass by creating one component to perform the function of two. This led to the design introduction of a new drive axle system by a Tier One supplier to the trucking industry that combines a single drive axle with a reconfigurable tag axle. This 6x2 drive and tag combination eliminated over 90 kg (200 lbs) of extra weight and complexity compared to a traditional tandem axle design, resulting in a vehicle mass reduction of about 1%.

Design features that reduce the number of parts in the assembling of systems and modules are another opportunity for combining parts. The 1.2L Diesel engine designed and used in the Ford PRODIGY hybrid vehicle featured an innovative method of using through-bolts to clamp the head, block and girdle together. This resulted in a reduction in the material required to provide the engine's structure with the necessary strength and rigidity. Additional weight savings were achieved in this engine by selecting aluminum as the material for the head, block and girdle, while the valve cover and oil pan utilized a lightweight metal matrix material. [11]

The starter/alternator (S/A) systems that are found on many of the emerging hybrid designs represent a significant incremental weight reduction. Since the S/A assembly is designed to replace the conventional starter motor, alternator, and flywheel on an engine, parts can be integrated and combined to reduce the total part count and mass. In addition, the lower mass of an S/A in a hybrid propulsion system allows resizing the heat engine to be smaller, which further reduces the weight of the vehicle. [11]

Another example utilizing one material or component to replace or supplement another can be found in the seat fabric being developed by a Tier One supplier to the automotive industry. In this case, an elastomeric fabric has been designed that eliminates the need for a good portion of the seat foam. This material acts as a suspension element, rather than just a covering for the seat foam, which allows the seat manufacturer to reduce the amount of foam, and the accompanying mass, from the seat. Lighter-weight foams are also being developed which have less density, but durability is an issue that still needs to be assessed. [6]

Mass management or reduction efforts can sometimes affect, or be affected by, the styling of a vehicle. Hidden headlights were long a styling trademark of the Chevrolet Corvette, but many of today's high performance cars have incorporated low-profile fixed headlamps. By making a switch to a similar design on the Corvette, the manufacturer was able to reduce mass by eliminating the headlamp actuation system, although not without some arguments over the merits of the new style [7].

Finally, new emerging technologies can often lead to mass reduction opportunities by replacing functions that are no longer needed. As an example, spare tire assemblies, and the associated hardware for securing and installing the tire, represent a significant mass increase to the vehicle. The switch to "space-saver" tires in past years was an attempt to reduce the mass of the spare tire, but not eliminate it. The development of tire repair and/or inflator kits that could be installed in the vehicle reduced the weight penalty further by replacing one system with another of greater mass efficiency. Finally, the development and implementation of "run flat" tire technology represents an attempt to eliminate the spare tire completely and the inconvenience to the customer of having the replace or repair the tire as well. However, this solution adds mass of its own to the design of the tires that arrive with the car, as well as an accompanying increase in cost.

RE-SIZING PARTS AND SYSTEMS

As mentioned in the section above, the combining of the alternator and starter into one module on a hybrid-equipped vehicle reduces the mass over what you would have with individual starter and alternator assemblies, which reduces the weight of the vehicle. This in turn allows a smaller heat engine to be used (resizing) for a given vehicle application, which reduces the total mass of the vehicle further.

Cooling systems are another area of the vehicle where mass reductions beget additional mass reductions via resizing. For example, because the 1.2L Diesel engine used in the Ford PRODIGY vehicle could be sized to be smaller than the typical engine in this size vehicle, the engine radiator that was chosen could be physically smaller as well, because the cooling requirements were less. In addition, the radiator was constructed of aluminum, as were some of the cooling lines, all of which added to the eventual total mass reduction. In addition to the cooling system, the battery used in the PRODIGY was reduced in size and mass, again due to the lightweight nature of the vehicle compared to what would be required in a hybrid that had not benefited from extensive weight reduction initiatives [11].

REMOVING CONTENT OR FEATURES FROM THE VEHICLE

Removing content from a vehicle is often viewed as one of the quickest and easiest ways to achieve the desired decrease in mass, and usually has the added benefit of reducing the cost of the vehicle as well. Items that are usually the first to be considered include the obvious ones, such as floor and trunk mats, interior and exterior trim pieces, and vanity mirrors and lighting on sun visors. It may even progress to the consideration of removing features that customers may not be aware of but will miss if they have grown accustomed to them, such as under-the-seat heating ducts for rear seat passengers and insulation mats for reducing vehicle NVH (noise, vibration and harshness) levels. The key consideration when assessing such opportunities must be the value that the customer perceives for the feature, and how it will impact the image and overall performance of the vehicle. Such efforts usually must be conducted with the involvement of other functional areas within the organization, such as ergonomics, human factors engineering, and marketing. A more holistic approach to mass management or reduction is usually better able to achieve the goals of the mass management effort rather than focusing on individual features and content in an isolated fashion.

IMPROVING MANUFACTURING OR ASSEMBLY OPERATIONS

A design constraint for some commonly used manufacturing processes, such as conventional roll-forming, is that the cross-section of the part is constant for the entire length of the beam. The tailor rolling technology, however, presents a huge potential opportunity to reduce the weight of the Body-In-White (BIW) by varying the thickness of the steel in a continuous, uninterrupted manner. This allows the material thickness to be adjusted exactly to meet the material performance required of the part [3].

Another process that can be utilized to form thin-wall steel is hydroforming. This manufacturing technique results in a more efficient use of the steel material, and it can be used with high-strength or ultra-high-strength steels where the application requires it.

Manufacturing and assembly must also be taken into consideration when material changes or substitutions are being considered. As an example, aluminum may provide significant mass reduction opportunities in the BIW assembly, but spot-welding of aluminum, especially in a production environment can be very difficult without the necessary process controls and capability. “The Japanese are very, very good at process control,” says Mark White of Jaguar, commenting on Honda’s extensive use of aluminum in constructing the NSX sports car. “If you are going to spot-weld aluminum, you need [very] good process control.” [7]

Finally, in addition to reducing part or vehicle mass, some lightweight manufacturing solutions may actually lead to further savings in operational costs. An example of this cited by Pfestorf and van Rensburg is the use of laser blanks to consolidate or replace multiple stampings. Such a strategy requires the consideration of all costs associated with a given manufacturing process when evaluating the use of lightweight engineering and manufacturing solutions. [14]

CONCLUSIONS

The need for lightweight vehicles, and the weight-management challenges that they represent throughout their development and lifecycle, is an issue that the automotive industry will continue to need to address. Past efforts to manage or reduce net vehicle mass have met with limited success, for a variety of reasons, in spite of significant advances in technology, materials and design tools. The recurring issue of high fuel prices in North America and elsewhere will continue to keep pressure on those working to minimize vehicle mass while meeting vehicle-level performance requirements including fuel economy, safety, durability and reliability, governmental regulation, and customer satisfaction.

This paper presented an overview of the recent history of vehicle mass increases and the reasons for it, the challenges and opportunities faced while trying to manage mass as a vehicle requirement during the development process, and the strategies, methods and tools available for executing a mass management or reduction plan. Although six specific approaches or “strategies” were presented and reviewed, along with examples of technologies and methods for reducing mass, the most successful vehicle-level strategies will encompass overlapping and complementary elements from each of these enablers.

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