The Total Cost of Weight Revisited:

An Essay on Cost as a Function of Weight in Automobiles and the Use of Shot Peening to Reduce Both

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Editor's Note: Even though this article was written in the late 1980's, it is a relevant review of the challenges and opportunities that face the automotive industry and the benefits shot peening can provide.

Engineers have understood for years that "weight begets weight" in any efficiently designed machine. The heavier the working parts of the machine have to be to do their job, the sturdier must be the bearings and the support structure. Furthermore, the heavier the working parts are, the more severe the vibration problems become, which problems usually require the addition of still more weight in the base and supporting structure.

In the case of automobiles, aircraft and other self-propelled vehicles, the addition of weight in the working parts is substantially more important than in a stationary machine. All parts of the vehicle, including the working machinery and supporting structure, have to be propelled, accelerated and decelerated, and the overall weight of the vehicle directly determines the performance of the vehicle, including its fuel economy, acceleration, etc. The design weight of the very first subsystem designed, be it an aircraft spar or an automotive engine, largely determines what will be the weight of the other subsystems, and as such the vehicle as a whole.

Overall weight has a direct effect on cost. The weight and the material used for a component provide a starting point for most cost estimates. The relative cost of many similar machines, including automobiles, are often "guesstimated" by simply comparing their weights.

Finally, the weight of components can have a direct effect on the marketability of an automobile. Currently, the single greatest limiting factor today in the amount of horsepower which can be produced in four cylinder engines produced in the U.S. is the fatigue strength of connecting rods. This is due to the need to keep the secondary harmonic vibrations generated by the reciprocating mass in a four cylinder engine at as a low a level as possible, since the buying public will only tolerate certain low levels of vibration. Any increase in the weight of a connecting rod to allow meeting market demands for higher horsepower may be associated with lost sales due to higher vehicle vibration levels.

The fact that a weight increase in one part of an automobile causes weight increases in other parts of the car was quantified, and examples given, in a paper by Leo Artinian and S. L. Terry in March of 1961 before a national meeting of the Society of Automotive Engineers. The cumulative effect of weight increases were demonstrated by plotting the weight of several sizes of specific car components against the weight of the cars in which these components were used. That was done for a number of different components - the differential, the front and rear suspension (separate), the steering gear, the wheels and tires, the engine, the transmission, etc. See Table 1.

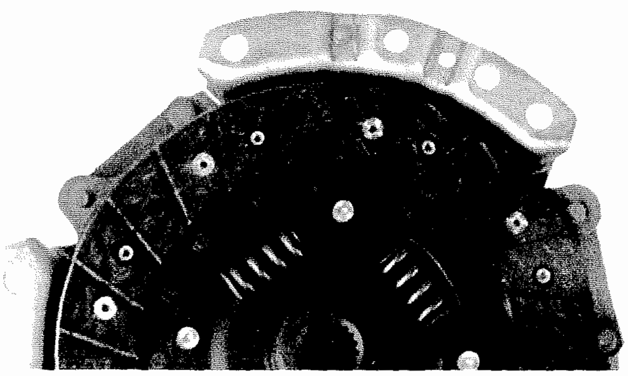
Naturally, each of these curves was a step function, since in some cases there were only two or three different component sizes for all of the different weight cars considered. But the cumulative curve for all of the different components was added, resulting in many small steps from which a straight line was derived. This revealed that for the data use, the addition of a pound of weight to the steering gear required the addition of 0.539 lbs. of weight to other working parts of the car. This is a surprisingly high number, but representative of the numbers arrived at for one pound increases in other portions of the car using the same empirical method.

The amount of weight added to the rest of the car varies widely with some components. It is clear that a change in the weight of the connecting rods, for example, has a very great influence on the weight of all of the major structural elements in the engine: the crankshaft, the block, the bearings, etc. It is even possible that the overall dimensions of the engine can be

Table 1.
Components affected by car weight changes

Weight increase in any part of the car causes adverse functional effects or weight increase in:

- **Engine**
- **Transmission**
- **Torque converter**
- **Clutch**
- **Final drive**
- **Brakes**
- **Steering**
- **Front suspension**
- **Rear suspension**
- **Exhaust system**
- **Fuel system**
- **Wheels and tires**



reduced if lighter connecting rods can be made to work satisfactorily, and in such a case a pound reduction in connecting rod weight could make possible the saving of as much as 20 pounds of engine weight, which could save still another ten pounds or so of chassis weight. No attempt was made in the reference paper to break any of the principal car components into detailed parts because of the obviously complicated nature of such a study, but engineers familiar with engine design, for example, estimate savings of at least 10 to 1 are available for every pound saved in connecting rod weight.

On the other hand, a pound of weight added in a stiffening body panel has an effect on the weight of the rest of the car, but to a much smaller extent. Each component has a different degree of effect on overall car weight, with some of the more important elements, like the connecting rod, being orders of magnitude more important than others.

Auto engineers have their own "rules of thumb" as to the cumulative weight effect of weight reductions in various specific components. Suspension engineers have said that a pound of unsprung weight saved (wheel, tire and portions of the brake and suspension system) will allow up to a ten pound saving in the rest of the car.

Much as engineers would like to quantify precisely the cumulative weight effects in the car due to weight savings in specific components, they have so far not been successful in this effort, at least as far as the authors are aware.

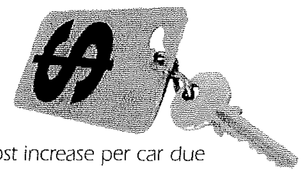
Terry and Artinian, in their paper, sought to connect the weight penalty in the rest of the car to dollars and cents penalty in order to be able to make better day-to-day decisions when material options are being considered. To stay on the conservative side (that is, to be sure not to overvalue the cost of weight) they used only the average cost of the material to which they added a freight cost addition (parts shipments as well as cost of shipping the entire car). No cost associated with manufacturing the parts was included. The results using the 1955 economics ran from $0.088 to $0.219 per pound, with the figure running $0.126 per pound for the steering gear, which was the original part analyzed. All of these were for the 1960 Plymouth car line. Examples of possible substitutions of aluminum for iron in parts like the transmission housing were given, which showed that while the substitution of aluminum for iron might indicate a substantial penalty on the face of it because of the higher material cost, the weight saving made possible would more than offset the penalty with savings in the rest of the car.

On the basis of using 1986 dollars, this says that today a pound taken out of the steering gear would save $0.309 in the cost of the rest of the car.[2]

Table 2 shows the affects, represented in 1986 dollars, for weight reductions for the various parts of an automobile interactively affected by weight.[1] (Editor's note: We added the 2004 U.S. dollar numbers based on a CPI calculator.)

Unfortunately, during the 1960's, this concept was never made more than that – a concept. Even though the logic was there, the potential cost savings never were exploited in the U.S. to any extent until the enactment of The National Energy Conservation Act which required companies to meet rigid fuel economy standards. Among other provisions, the Act required companies to meet rigid Corporate Average Fuel Economy (CAFE) standards, and levied substantial fines on those companies who failed to meet the CAFE standards set by Congress. These standards required that companies

Table 2. Table of Weight-Cost Factors

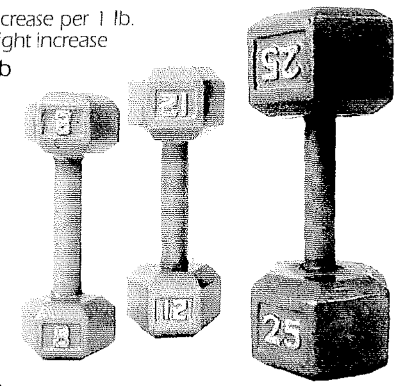


1 lb increase in weight of this component	Cost increase per car due to compounding effect of weight: 1986 U.S. dollars	2004 U.S. dollars*
Body in white	$0.248	$0.424
Front end sheet metal	$0.322	$0.550
Front structure	$0.322	$0.550
Glass	$0.248	$0.424
Exterior ornamentation	$0.248	$0.424
Operating hardware	$0.248	$0.424
Grille	$0.322	$0.550
Front bumper	$0.322	$0.550
Rear bumper	$0.241	$0.412
Instrument panel	$0.248	$0.424
Interior trim	$0.248	$0.424
Chassis electrical	$0.248	$0.424
Engine	$0.371	$0.634
Transmission	$0.253	$0.432
Torque converter	$0.381	$0.651
Clutch and flywheel	$0.538	$0.919
Final drive	$0.280	$0.478
Brakes	$0.238	$0.406
Steering system	$0.309	$0.528
Front suspension	$0.297	$0.507
Rear suspension	$0.216	$0.369
Exhaust system	$0.236	$0.403
Fuel system	$0.246	$0.420
Wheels and tires	$0.275	$0.470

* Figures based on Consumer Price Index and Inflation Rates.
For an easy-to-use CPI calculator, go to http://woodrow.mpls.frb.fed.us/research/data/us/calc/

Table 3. Compounding Weight Factors

Component	Compounded weight 1 lb.increase per 1 lb. of steering system weight increase
Engine	0.150 lb/lb
Transmission	0.081
Torque converter	0.005
Final drive	0.025
Brakes	0.050
Front suspension	0.050
Rear suspension	0.020
Exhaust system	0.031
Fuel system	0.007
Wheels and tires	0.120
Total:	0.539 lb/lb



approximately double the average fuel economy of the fleet of new car they sold in 1975 .

Suddenly the importance of car weight changed from low priority to extremely high priority, for weight reduction is the most important factor the engineer has to work with to increase fuel economy. Today the U.S. new car fleet fuel economy is approximately twice what it was in 1973 when the gas shortages first hit (26 to 13 mpg), and although the political and congressional pressure has subsided from fuel economy for the moment, U.S. auto engineers assume that energy problems will persist well into the next century. Accordingly, engineers are extremely interested in any developments that have the potential of substantial weight reductions.

Recent developments in shot peening provide that potential. Work at Advanced Material Process, including basic research funded by the U.S. Dept. of Defense and process development performed in conjunction with U.S. auto manufacturers on the use of shot peening as a means of increasing the design strength of automotive components, indicates that the Weibul B-10 fatigue strengths of the working and highly stressed parts of the car can be consistently increased by at least 20%. This strength increase is over and above the strength of the finished parts in production; after they have been heat treated and otherwise finished.

If these weight savings are then carried forth into the design of the rest of the working components of the car, the compounding effect can be multiplied many times, as each additional part is reduced in weight, not only from the increase in strength resulting from shot peening it, but also from the reductions in the loads it must carry due to weight savings already made elsewhere due to the same process. The total potential savings possible are almost mind-boggling, but to achieve this type of systematic weight reduction through the use of a very advanced form of shot peening the auto designer must start with a "clean sheet of paper".

For the purpose of illustration let us assume that the use of shot peening in an automotive steering system part weighing 4 lbs, yields a 25% increase in fatigue strength of the part. Let us also assume that this can be directly converted into a 25% weight reduction, or a 3 lb shot peened component which have the same fatigue strength as a 4 lb unpeened component. Table 3 predicts a concurrent .539 lb weight reduction and associated cost savings throughout the other component systems of the vehicle.[1] These other component systems can also concurrently utilize the shot peening process to reduce weight and cost, and have the same leveraging effect, including weight and cost reduction in the steering system.

The cost of processing must be subtracted from the cost savings to gain a true picture of net effect on cost. This is a difficult task as the cost of production processing will be reflected in the physical complexity of the part, the size and complexity of the area to be peened, the volume of parts, the optimum process parameter levels and acceptable cumulative tolerances, and many others. It is the authors' conclusion, however, that the cost of processing is consistently lower than the potential cost savings on associated material cost for the peened workpiece alone. Leveraged weight reduction and cost savings further increase the net cost reduction. As such, if systematically utilized, the cost of producing an auto using a numerically engineered shot peening process should be significantly lower than not using it, with the weight reduction benefits of using this type of shot peening being substantial.

It is important to note at this point that all data available to the authors indicates that the use of shot peening in this manner requires a far greater numeric understanding of process variable cause-effect relationship on the fatigue life of the particular component in question and positive control of these variables within values known to generate acceptable fatigue strength benefits, than has been historically applied in shot peening. While this type of systematically leveraged benefit throughout a vehicle was impractical with the shot peening technology state-of-the-art as recently as 1980, and has yet to be applied in such a manner, the technical tools for doing so which were unavailable then are available now. [3,4,5,6,7,8]

Since beginning design from a truly "clean sheet of paper" only happens about once during the average engineer's career, it is perhaps more useful and certainly more practical to consider the more immediate benefits that can be achieved through utilizing recent advances in shot peening technical understanding and process control. Auto engineers are constantly faced with increasing loads on components that were originally designed for much lower loads. Since the original design was naturally done as efficiently as possible at the time, there is theoretically no way to increase loading without causing failure in many of the highly stressed parts.

Knowing that cars tend to increase in weight over the years, and engine output always goes up, never down, engineers know that they have to provide factors of safety in the original car. These are usually 20% to 30% of fatigue strength for highly stressed parts. Doing so does increase the original weight and cost of the product, but not to do so would severely limit the life cycle of the car, the number of years it could be "improved".

New components that increase loads far beyond the factors of safety contemplated in the original design are, however, constantly appearing. A new V-6 engine mated to the same transmission as the 4 cylinder engine it is replacing is such an example. Adding a turbo-charger to the engine is another. Many power train parts in today's U.S. model lineups are being loaded to twice their original design load. Suspensions have to carry bigger engines and transmissions, and axles have to carry higher torques.

Naturally, engineers are being pressed for solutions. If a transmission cannot carry the torque of a new engine, a larger transmission must be used. If the company has a suitable transmission available, it will naturally cost many more dollars. If they have to buy one outside, it will cost even more. If they decide to design and tool a new higher capacity transmission and manufacture it themselves, the costs alone for this today can run as high as half a billion U.S. dollars.

Thus, there is an enormous incentive for the engineers and planners to work out a way to strengthen the original transmission so it can be used with the new engine.

This is the immediate value of a technically well defined, highly controlled shot peening process. For most components, an increase in design fatigue strength would require no further engineering other than the quantification of optimum shot peening parameter values through a well-organized iterative test program, and implementation of the results into production.

One caveat has to be addressed before the auto engineer utilizes shot peening to reduce or prevent an increase in the weight of components. This is that 30 years of process history and all data produced by the authors over the past several years indicates that the utilization of conventional "controlled" shot peening in this manner will not provide the desired result. A far broader and more in depth numeric description of process specification and control is required.

To merely say that the process of shot peening is now "controlled" is insufficient. During the period 1950 - 1980, the state-of-the-art in the shot peening process precluded its use in weight reduction or design performance increase in an automotive production environment due to the very large fatigue scatter of peened parts processed in this manner. Even though purveyors of the art were touting "controlled" shot peening decades ago, the authors' experience has been that while mean fatigue life values dramatically increased during fatigue testing specimens peened in this manner, when utilized in high production volumes, low fatigue life values were no better than unpeened. As such, the statistical prediction of Weibul B-10 fatigue life for a peened component was no better, and sometimes worse than, an unpeened component.

While it is not the purpose of this paper to examine the technical process requirements for use of the shot peening process in increasing component design strength, qualitative approaches, expert opinions, and inviting words like "controlled" will not suffice. A clear numeric understanding of process design and specification requirements obtained through a well-organized test program, and positive process variable control, through statistical process control and/or electronic machine control systems, within these requirements, are essential.

Without doing any more, however, than adding a quantitatively engineered, highly controlled shot peening processes to finished parts, particularly in the most highly stressed areas where the failures are or would be occurring if loading was increased, the load capacity of that part can be increased 20% to 40% - with the authors' experience that it can be increased sometimes by as much as 70%. In many cases, this simple processing addition can prolong the life cycle of a major component system, and in the process save the car maker many millions of dollars.

Best of all, the process costs little more than conventional "controlled" shot peening and even less than most heat treating processes. A technically well-defined and positively-controlled shot peening process provides a new and enormously useful tool for the auto manufacturing industry. The process may even mark a milestone in the engineering and development of more efficient transportation vehicles.

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