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# ACCELERATING PROGRAM DELIVERY THROUGH OPTIMIZATION

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## ABSTRACT

*It is generally accepted that structural optimization has been responsible for achieving component and system weight reduction for multiple applications, but often these methods are considered only as a tool to reduce vehicle weight later in a vehicle design. This paper proposes earlier and broader application of the technology during a military vehicle program.*

*An optimization driven design approach will reduce development time, through fewer design iterations, while creating robust design directions not influenced by design history. The proactive use of optimization technologies throughout a development program yield benefits in terms of vehicle weight (and therefore increased payload), improve performance and protection while reducing material costs.*

## INTRODUCTION

The paper will discuss, through examples, how the application of structural optimization technology and a simulation driven processes can, in the context of a military ground vehicle program:

- **Reduce Development Time** – through fewer design iterations
- **Create Efficient Designs** – not influenced by historical directions
- **Increase communication** – provoke dialog among stakeholders (PM, Design, Validation, and Manufacturing) earlier in design process
- **Deliver Robust Designs** – with material aligned along load paths, thereby reducing stress concentrations

Although optimization technology is applied to military ground vehicle programs, the application is often limited to late program weight reduction exercises where little design freedom exists. Broader application of optimization throughout the program timeline offers new opportunities to explore trade-offs and earlier convergence to a robust design direction.

Initial vehicle level concept optimization studies can be performed before the existence of detailed CAD models, allowing program challenges to be quickly understood and planned for. As a design matures global performance optimization allows rapid exploration of changes to vehicle structural targets, dimensions, packaging or manufacturing strategy. Fast trade-off studies (e.g. mass versus performance) are also possible prior to prototyping and without significant CAD investment. Later in the program local performance optimization can be applied at the system level, prior to final mass optimization prior to component design release.

## STRUCTURAL OPTIMIZATION

Structural optimization is not a single technique, but a family of methods that can be applied to the improved protection, performance and payload military ground vehicles. These methods can be summarized as:

- Topology
- Topography
- Size
- Shape

### *Topology Optimization*

Topology optimizes the material layout within a given design space, for an applied set of loads and boundary conditions. This allows engineers to quickly develop a structural concept that will satisfy a set performance criteria.

After several years of success in the automotive industry, topology optimization has been introduced in other industries with great success. Design processes in the consumer products and aerospace industry for example, now benefit greatly from the use of topology optimization [1]. The introduction of manufacturing constraints made the technology even more broadly accepted and applicable.

### *Topography Optimization*

In sheet metal parts, beads are often used to reinforce the structures. For given allowable bead dimensions, topography optimization technology will generate a design proposal for the ideal bead pattern of reinforcement.

### *Size Optimization*

While topology optimization will provide a promising structural concept, a more detailed size optimization is used to refine the design to achieve the required performance. Size optimization defines ideal component parameters, such as material values, cross-section dimensions and thicknesses.

### *Shape Optimization*

Shape optimization is applied on existing components designs. This can be used to reduce high-stress concentrations. Through the use of a morphing technology (such as Altair HyperMesh) to prepare finite element meshes for optimization enables dramatic shape without mesh distortion. This technique allows design modifications without any underlying CAD data.

## OPTIMIZATION WITHIN A VEHICLE PROGRAM

The use of a CAE driven design process including the extensive use of optimization techniques is a well-documented and accepted method to minimize cost and weight whilst maintaining performance in the automotive industry [2]. The competitive nature of the automotive industry demands vehicle development times to be continually driven down to ensure early time to market, as well as minimizing development costs and the product Bill of Materials costs. Similar pressures are present in military ground vehicle programs.

Figure 1 shows a generic representation of the simulation driven design process. The phases indicate vehicle development stages and show the correlation to optimization methods:

- **Phase 1** – Concept Optimization
- **Phase 2** – Global Optimization
- **Phase 3** – Local Performance Optimization
- **Phase 4** – Mass Reduction/Payload Optimization

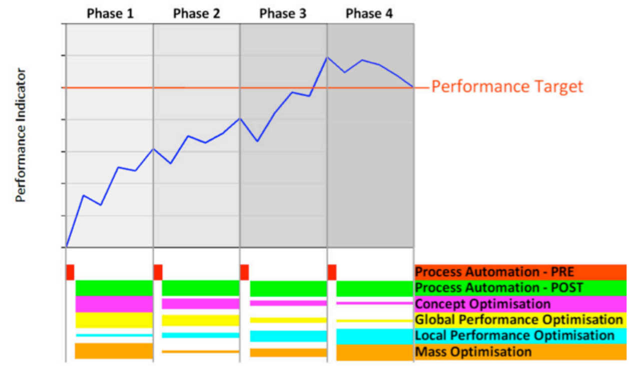


**Figure 1**: Elements of a Simulation Driven Design Vehicle Program

The performance indicator, shown on the Y axis, is a generic representation of the average performance of protection, performance and payload attributes. During a phase, the vehicle performance is developed through routine use of optimization analysis. In early phases it is used to define an efficient base structure. These activities are then ramped down in later phases while local performance optimization is ramped up as the design becomes more mature.

Through the routine use of optimization, the objective is to exceed performance targets and allow more scope for mass optimization prior to engineering release. Also represented is the extensive application of process automation for the pre- and post-processing of simulation models.

In the context of a military ground vehicle program experience has shown that investing one to two months early in the concept phase to optimize the proper layout of a frame and cab union will save in the overall timing to delivery of an optimal structure of the vehicle's architecture. A sub-structure approach can be utilized to tackle the full vehicle. The front and rear sub-structures may be broken up and analyzed separately knowing the cab will be a fairly rigid structure due to blast requirements. The cab itself can be optimized individually for transferring the front and rear sub-structure loads and blast pulse absorption.

### *Variant Engineering*

Optimization technology offers methods to explore vehicle variants early in a program. The generic vehicle body shown in Figure 2 demonstrates one such technique.

The challenge in this case was to create an initial design direction for a long and short wheelbase version of a vehicle with similar mission profile. For manufacturing and maintainability/sustainability purposes the front and rear end structures of both variants should share a common topology, while the topology of middle section can be unique.

A solution is to consider both variants in one topology optimization model. This results in a quick study that demonstrates feasibility and design direction with pattern repetition.

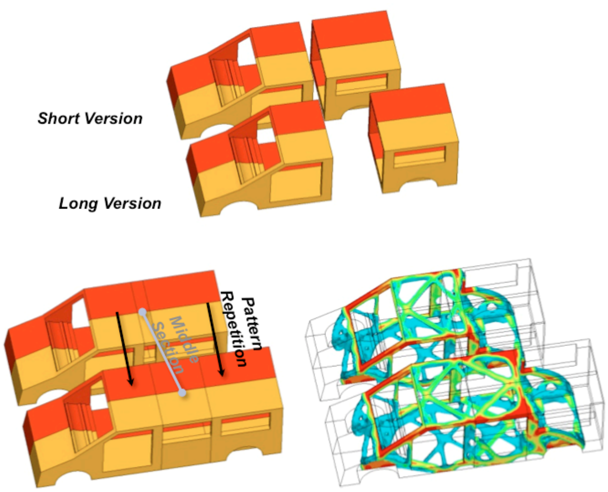


**Figure 2**: Elements of a Simulation Driven Design Vehicle Program

## CONCEPT OPTIMIZATION

During the early phases of a development program optimization techniques can be applied to the investigation of design options and derive concepts that satisfy available package constraints and performance targets. Areas of the structure that had not been defined allowed greater design freedom to use optimization methods such as topology to arrive at an optimum material distribution and size and shape to derive gauges and geometry definition.

### *Optimized Light Tactical Vehicle*

A successful example of concept optimization is the application to the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) Optimized Light Tactical Vehicle (O-LTV) program. This program set out to develop a vehicle to meet M-ATV mine blast requirements with commercial seats and current HMMWV crushbases. To achieve these constraints the invention of a new vehicle underbody shape to mitigate most of the energy produced by the mine was required [3].

A variation of the "moving boundary" optimization method [4] was employed to drive the vehicle geometry around the package constraints (including occupant and equipment space claims, powertrain requirements, ground clearance and suspension envelopes) and vehicle targets (including protection, threat, vehicle weight and payload) [5]. A threat blast wave was discretized as a series of piecewise static pressures and then a series of linear sub cases with different pressure loads and boundary conditions were used in a gradient based optimization to develop the optimal shape of the vehicle hull to minimize the energy transferred to the occupant compartment and floor intrusion.

The use of Altair OptiStruct inspired new design directions, with the fast exploration of new hull as shapes shown in Figure 3. Once promising hull designs were identified, a secondary application of topology optimization was used to drive the material placement of the hull structure.

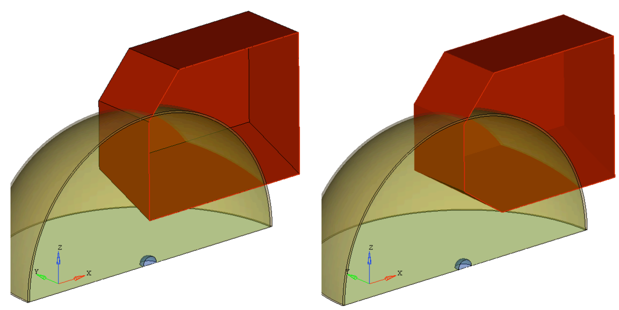

**Figure 3**: Shapes Explored for a Vehicle Hull Optimization

## GLOBAL OPTIMIZATION

The objective of the global optimization analysis is to define as early as possible in the design process critical areas of the structure that require development to meet vehicle level program targets. An overview of the process is described in Figure 4. In this example a tactical trailer is shown. The method was used in the development of a strategy for Army semitrailer modernization by creating a scalable (modular) semitrailer or Family of Scalable Trailers (FAST) that could replace a variety of different models. Improved trailers are more able to match the capabilities of today's improved tractors or tactical vehicles.

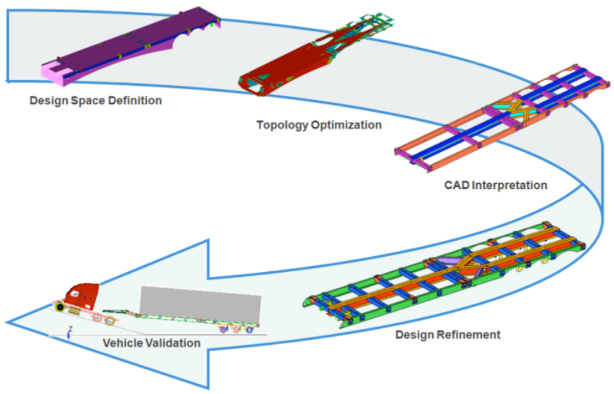


**Figure 4**: Structural Optimization Process

### *Design Space Definition*

The first step in the process is to develop a design space, shown in Figure 5, based on dimensional constraints. A 3D space claim volume was developed defining the CAD model in which the frame structure could reside. The volume was developed by removing volumes defined by the surrounding systems. For example, a volume was removed to ensure sufficient clearances to the suspension system, the ramp break over requirement and the deck height requirement.

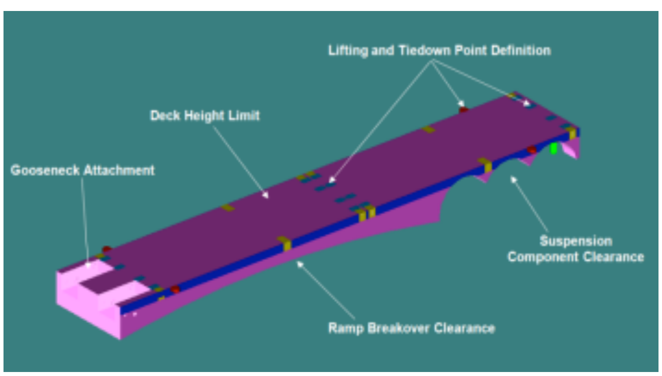


**Figure 5**: FAST Trailer Design Space used for Topology Optimization

### *Load definition*

Next, the vehicle loads were identified. First the required cargos for the FAST program were listed. A compatibility matrix was constructed to assess the capability of the trailer to transport the cargos based on axle and fifth wheel loading.

For the design of the FAST Trailer, the Altair team generated a matrix of loads including those generated by the suspension, different cargo types, landing gear, cargo tie downs, and trailer lifting and tie down provisions. These loads were then applied to the design space.

Suspension loads were developed through an analytical vehicle model driven over road events (such as 10" Half Round). Other loads were defined by vehicle specification and specific loading events (i.e. lifting and tie downs MIL-STD-209K). Vehicle dynamic events such as the NATO lane change event were simulated as well.

### *Topology optimization*

Using Altair OptiStruct the load paths in the structure were identified. These initial results are shown in Figure 6.

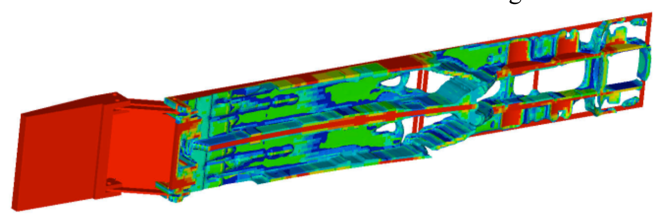

**Figure 5**: FAST Trailer Topology Results

### *Topology Interpretation*

Next the topology results were interpreted within a CAD system and the major resulting load paths were defined. These load paths defined the most mass efficient architecture and set up the geometry for further design refinement (size, shape and gauge optimization). See Figure 6 for the initial CAD interpretation of the topology results.

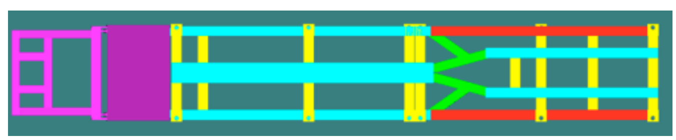

**Figure 6**: Initial CAD Interpretation of Topology

### *Design Refinement*

Lastly additional design refinement was executed, refining the surrounding system design as well as the topology driven frame design. Utilizing 'off the shelf', readily available materials, a general design was developed. Validation of this design was accomplished with the use of additional FEA tool and techniques. A finite element model of the baseline design was developed and refined. Global and local loadings were considered. A baseline structural analysis was performed and reviewed. Considering cost and manufacturing constraints, the overall design was developed. See Figure 7 for a comparison of the final prototype CAD vs. the topology results.

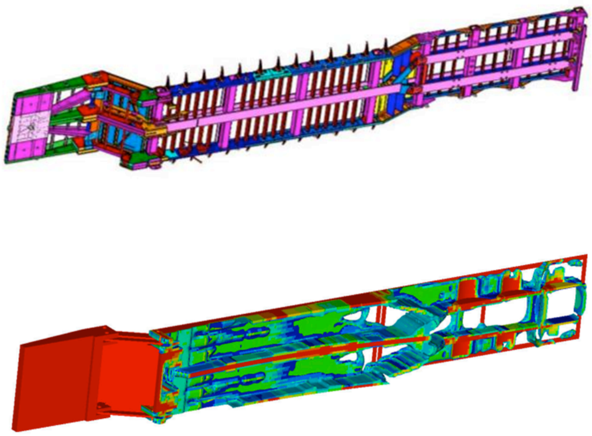

**Figure 7**: Topology vs. Final CAD (Main Frame Only)

## LOCAL PERFORMANCE OPTIMIZATION

As the design of the vehicle became more mature, concept and global optimization activities are replaced by more detailed, local, design optimization activities. An example of this work for military ground vehicle was the redesign of a chassis component by Altair ProductDesign for a supplier. The component was based on a successful commercial vehicle product, but required substantial weight reduction and performance enhancement to meet the needs of military vehicle OEMs. The commercial ferrous component weighed more than 23lb, the military spec version is 13.3 lb, well below the customer target of 16.7 lb. A simulation and optimization driven process was used to design the new version.

Initial study included material selection (aluminum, titanium, or magnesium). Thermal requirements including the use of high temperature coatings and brake cooling, in addition to operation with steel tension bolts used in the assembly and of course cost were considered. Topology was used to explore solutions that offered single or multiple piece construction, superior serviceability and manufacturing efficiency with minimum weight, while achieving less deflection than the ferrous part for all operational loads.

The use of topology allowed design ideas (and material usage for each) to be shared early in the process without investment in CAD representations. This enabled quick “buy-in” from the product team, manufacturing and other stake-holders and convergence on an engineering direction.

## MASS REDUCTION/PAYLOAD OPTIMIZATION

Too often the first phase in which optimization technology is applied is this late opportunity to reduce the mass of mature designs. When used as the last stage in a simulation driven processes, where generally more attributes meet or and exceed targets, there is greater opportunity to reduce the mass of the structure whilst still maintaining target performance.

The results of one military ground vehicle in which Altair ProductDesign was engaged as part of an effort to reduce the mass of a baseline chassis design as summarized in Figure 8. This was not a program that has followed a simulation driven process. The structural space claims had already been performed by the different groups, but there was still enough package space existing to perform size and shape optimization on select massive parts within the global structure.

| | | | Size/shape Optimization of current design | | | Topology driven design change | | |
|---|---|---|---|---|---|---|---|---|
| Part Description | Quantity per Chassis | Original Mass per part [kg] | New Mass [kg] | Δ Mass [kg] | Δ mass [%] | New Mass [kg] | Δ Mass [kg] | Δ mass [%] |
| Part A | 1 | 63.2 | 51.3 | 11.9 | 18.8 | 47.6 | 15.6 | 24.7 |
| Part B | 1 | 63.2 | 51.3 | 11.9 | 18.8 | 47.6 | 15.6 | 24.7 |
| Part C | 1 | 52.6 | 47.6 | 4.9 | 9.4 | | | |
| Part D | 1 | 18.1 | 15.6 | 2.5 | 13.8 | | | |
| Part E | 1 | 18.1 | 15.6 | 2.5 | 13.8 | | | |
| Part F | 1 | 5.1 | 5.1 | | | | | |
| Part G | 2 | 5.1 | 5.1 | | | | | |
| Part H | 1 | 49.1 | 43.2 | 5.8 | 11.9 | 42.6 | 6.5 | 13.1 |
| Part I | 1 | 49.1 | 43.2 | 5.8 | 11.9 | 42.6 | 6.5 | 13.1 |
| Part J | | 29.5 | 24.0 | 5.5 | 18.5 | | | |
| Part K | 1 | 5.7 | 4.0 | 1.7 | 29.8 | | | |
| Part L | 1 | 5.7 | 4.0 | 1.7 | 29.8 | | | |
| Part M | 1 | 65.4 | 59.7 | 5.8 | 8.8 | | | |
| TOTAL | | | | 60.1 | 16.9 | | 68.7 | 18.2 |
| | | | | 132.4 lbs. | | | 151.4 lbs. | |

**Figure 8**: Table of Weight Savings

The total mass saving potential identified within the baseline design by applying size and shape optimization methods was 132.4lbs. The application of topology to the current design identified a design change that offered the opportunity to increase the total mass reduction to 151.4lb.

An existing global finite element model can be utilized to perform this optimization of subassemblies. These tasks have taken between 1 – 4 weeks to perform and have resulted in 5 – 30% mass reduction. The significant mass savings have been seen in major components such as frame members, shock towers, roof and drive train support structure. The overall development time is usually shortened, even with weight reduction campaigns on a mature design due to less time spent iterating between CAE and CAD.

## EFFECTIVE IMPLEMENTATION

Integration of an optimization driven philosophy into current development processes can be a challenge. The design of military ground vehicles is complicated, often requiring the trade-off of many conflicting requirements to be satisfied. The challenge is to introduce leading edge technology whilst mitigating risk. A method that has been used at multiple organizations in the aerospace and automotive industries is the establishment of Optimization Centers. This approach to implementing new technologies and exploring how to incorporate them into an established design process with maximum impact and minimal disruption has proved effective. The Optimization Center is a focused 'Centre of Excellence' for weight reduction, performance enhancement and collaborative multi-disciplinary product development.

The Center through application and advocacy of optimization methods and through working with program teams can determine the areas where optimization can bring the biggest benefit to the design process. Creating this type of resource within a military ground vehicle organization will promote the proactive use of optimization technologies throughout a development program and yield the benefits of better vehicle weight/payload, improved performance and protection while reducing material costs.

Existing Optimization Centers are staffed with a combination of optimization experts, and engineers from within the vehicle prime organization and its partners. Optimization Center staff carry out individual design optimization projects, provide mentoring and perform training in the application of these methods. Not only does the Center aid in the implementation of design optimization methods in the program Prime's product development process but, when accessible to the supply base, provides efficiencies to all structural designs in the vehicle.

### *Successful Optimization Centers*

Altair has learnt many lessons from the successful initiation and sustainment of multiple Optimization Centers, such as the team supporting the Airbus A350XWB aircraft.

At a high level these lessons may be summarized as:

- **Gain support from a senior champion** – Ensure visibility of the Center to the program teams and attribute leaders
- **Demonstrate quick wins** – Screen components with large weight reduction potential to provide immediate value to the product development
- **Interact extensively with the design team** – Quickly break the circle of design then analyze, through fast definition of best practice to integrate optimization into program processes
- **Use the Center to pilot new methodologies** – Not only to assess how optimization methods can be integrated into existing production design process, but to assist process roll-out for consistent execution

Although the main charter of the Optimization Center is to improve the development process and assist in the creation new engineering methods, they are also available to help address urgent program concerns. Current Centers have expanded beyond the application of topography, topology, size and shape optimization and are a resource for applying Design of Experiment (DoE) methods, Stochastic (Monte Carlo) techniques, Multiple Disciplinary Optimization (MDO) and composites ply optimization to design problems.

## CONCLUSION

Through the increased and earlier application of optimization technology, military ground vehicle programs would have greater opportunity to explore design trade-offs while achieving earlier convergence to a robust structural design.

The examples in this paper have illustrated that the application of structural optimization technology will not increase development time, but has actually reduced design and engineering time through fewer design iterations and increased early discussion of new design proposals on previous programs. The lack of embedded knowledge of design history and typical practices ensures that structural optimization tools can inspire innovation in the industry, while delivering robust solutions.

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