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Composite Material Substitution in Formula 1 – Implications for Industry

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ABSTRACT

Formula One (F1) is arguably the World's highest technology sport with over 30% of sales reinvested in Research and Development. Performance in F1 is derived from a number of key first order performance drivers: engine, tyres and aerodynamics. Development of these key performance drivers is made possible with composite structures and the flexibility they allow designers. With composites making up over 80% by volume of an F1 car, this paper analyses the reasons why they are used so extensively. These reasons are primarily related to the rapid development cycles that deliver innovation, the methods that are used to mitigate risk that allow engineers to deliver designs that operate close to the limits of composite materials and the understanding of how integration of functions delivers innovation that is not always clear in the initial stages of a project.

While cost may initially inhibit the transfer of techniques and innovations, part of the technology transfer process will follow the reduction of complexity and the automation of the manufacturing value chain. Integration of components, structural health monitoring and experimental techniques for certifying composites will increase the confidence of industries to push the usage of composites further than before, with targets for weight saving in the order of 50%.

INTRODUCTION

This paper analyses the substitution of composites in Formula One (F1) and provides insights into how technology could transfer to other industries such as aerospace, defence and automotive. The most commonly used composites in F1 are continuous fibre, thermoset fabrics and uni-directional fibres fabricated with core materials such as aluminium honeycomb and foam, however the substitution of other varitations of composite materials may form part of the substitution into other industries.

F1 is the pinnacle of the motorsports world drawing TV audiences of more than 160 million viewers every weekend, travelling to 5 continents and 19 countries: it is the only regular, truly global sporting event in the world. Therefore the rewards from exposure and brand association from this glamorous business are very enticing to the world's largest companies. Budgets have climbed from around $10m in 1990 to the range $100-500m in the last decade driven by the entry automotive giants such as Mercedes Benz and Renault.

F1 is arguably the World's highest technology sport with over 30% of sales reinvested in Research and Development [1] and a large proportion of this is focussed on using composites which make up about 80% of the cars structure by volume [2].

F1's first order performance drivers are: engine, tyres and aerodynamics. Weight was a first order effect but it was artificially controlled in 1960's when a minimum weight limit of a car was introduced. Therefore the weight effect moved to a second order function related to the centre of gravities effect on cornering capability through the tyres sensitivity to vertical load and its proportional effect on lateral force generated in cornering.

When the minimum weight limit was introduced, engineers began to look for more efficient ways of using weight savings to deliver more performance by carrying what could be described in other industries as payload: more electronics for better understanding, increased safety, more complex dampers and other systems which can deliver more performance.

Throughout the 1970's further performance came in the form of increased chassis stiffness through the move to folded aluminium/sandwich panel design that continued the development of second order effects on handling performance of the vehicle. Subsequently McLaren International (an F1 team) introduced the first carbon fibre composite monocoque in 1981 with the support of Hercules Aerospace (U.S.A): a step change in performance. This was the beginning of the integration.

At this point it is worth clarifying the value of weight to F1 and comparing it to other industries which will go some way to explaining the drive for composite development. 1kg of weight reduction saves over 2,900 litres of fuel per year in single aisle plane [3] while a typical F1 car costs in the region of $US2m and weighs approximately 550kg without driver and fuel. This equates to approximately $3,600 per kg and allows a comparison to other industries using a cost trade-off Table from Ashby [4] which is shown below. The upper bound of the F1 car value is assumed to include development costs. As with the military aircraft reference in the table below, performance comes from other areas such as stiffness and torsional rigidity which composites provides.

Table 1 Cost trade-off

Sector	**Basis**	**US$ per kg**
Automotive	Fuel Saving	1-2
Truck	Payload	5-20
Civil Aircraft	Payload	100-500
Military Aircraft	Payload, Performance	500-1,000
Space	Payload	3,000-10,000
Formula One**	Payload, Performance	3,600-15,000

** Estimate for comparison

Formula One: “A Prototyping Competition”

In order to understand what drives the innovation cycle and why the costs of development are so high in F1 it is important to understand how the industry operates. The best way of understanding the sport is to imagine it as a “prototyping competition” with these basic numbers:

- Each team has two (2) cars at each race;
- With an average of three (3) sets of spare parts;
- Which means that there are only five (5) parts manufactured for any one version or design concept;
- With an average eight (8) week design and manufacturing cycle for each part;
- This allows the team to deliver over twenty (20) versions of each part per year.

This cycle of innovation allows the engineers in the industry many opportunities to experiment on theories. Experimentation and failure are part of the culture of development: much akin to the business world where start-ups in clusters like Silicon Valley are actively encouraged to experiment, fail, and most importantly, learn. “Fail fast and fail often” is a mantra taken from the open source community but can be equally applied in the world of F1.

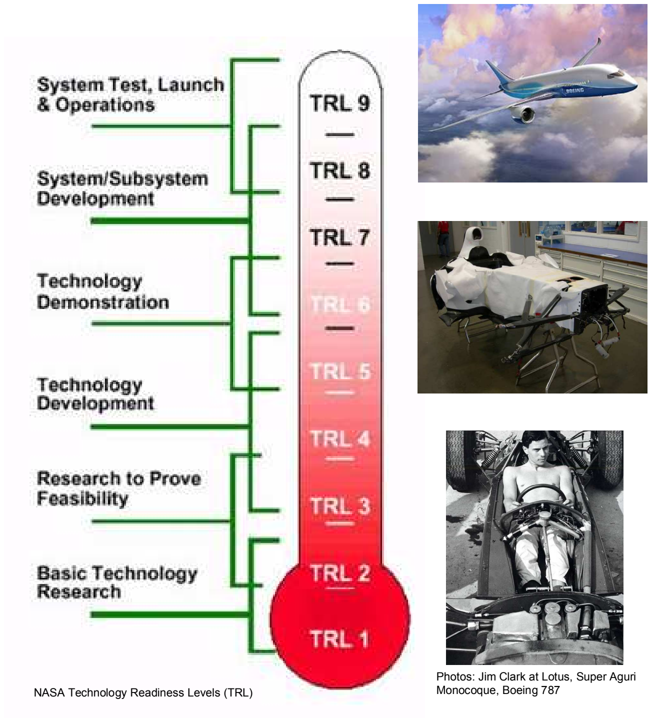
While the rate of experimentation is high, the capital intensity of a design cycle is relatively low in comparison to automotive and aerospace. The cost of design and tooling for a road car can approach US$2bn within an 18-36 month cycle. In comparison, each F1 car can cost around US$2m but with a total design cycle of approximately 3-6 months. These factors combine to drive experimentation and innovation. Development at this speed has inherent risks and mitigation of this risk is perhaps one of the key aspects of F1 that has changed over the past two decades. By understanding this change in risk management there may be lessons that can be transferred to other industries.

Risk

NASA’s Technology Readiness Levels (Figure 1) can be used as a visualisation of the differences between motorsports and aerospace/automotive where risk minimisation is a key element in any business model. Historically, motorsports was a dangerous industry with over 25 deaths occurring between 1954 and the present day. Engineers would literally think of a new idea, modify the car in the garage and then send the driver onto the track to carry out the experiment: in the figure below this is shown in the TRL Level Region 2-3. The figure helps to visualise how motorsports has moved towards the rigor of aerospace and automotive while still maintaining a level of experimentation and innovation that would be described as high risk in any other industry.

Risk is composed of two elements: uncertainty (probability of success/failure) and consequences (of an event) [5]. Failure can be the result of performance (to achieve performance requirements) or programmatic functions (such as cost and timing). Part of the change in the sport came with the arrival of automotive companies who focus on minimising uncertainty. This provided the drive towards more process innovation: the use of simulation, rigs, non-destructive inspection techniques and higher levels of quality control bringing the sport to where it is today with companies such as Ferrari and Mercedes Benz still involved with the sport.

The trade-off between performance and timing is an interesting one. Unlike other industries, the first race of the season will still take place even if one of the competing teams/companies is not ready. Hence, the trade-off between increasing performance and an unmovable timing plan has the unfortunate effect of driving up costs. Constant improvement of processes has helped to contain these costs through the use of the aforementioned simulation and testing procedures that have been developed in the industry.



NASA Technology Readiness Levels (TRL)

Photos: Jim Clark at Lotus, Super Aguri Monocoque, Boeing 787

Figure 1 NASA Technology Readiness Levels applied to F1/Industry Comparison

Certification and Quality

In order to minimise risk and maximise performance, F1 has developed quality processes and certification expertise that not only allows engineers to shorten development cycles but also run the parts closer to the limits of materials such as composites which are relatively new in the history of aerospace and automotive. As a minimum, F1 runs aerospace/automotive levels of quality assurance with certification of materials and traceability of manufacturing processes: much of this brought about with the arrival of the aforementioned automotive manufacturers who demanded more rigour in their teams.

At this point F1 has more in common with aerospace than automotive. F1 can have short interval inspection cycles and 100% inspection criteria with the minimum time between inspection intervals which is only limited by the distance/time of a race: approximately 500 km or two (2) hours of operation. While at first this may seem to reduce risk levels, it also allows engineers to push closer to the limits of the materials and structures. The more understanding of a component, the closer it can be run to the ultimate failure or fatigue loading.

The high cycle time for inspection, hours rather than seconds or minutes, in F1 allows components to be subjected to extensive certification processes in order to reduce risk and increase confidence. Acoustic emission [6] of parts undergoing load testing provides a robust methodology for understanding the operating limits of a component. The paper by Rowland et al. describes the acoustic emission technique and gives an example of how it can be applied to the certification of components such as the wings on an F1 car which are loaded to around 600-750kg. The acoustic emission technique provides an indication of the damage occurring in part under loading when it is not detectable by any other process.

Although inspection techniques such as X-Ray and ultrasonic testing can highlight problems in manufacturing they do not tell the engineers and designers how close a part is to the limit. Although metallic finite element analysis (FEA) can provide very accurate predictions of fatigue and ultimate failure, composite analysis is not at this level at this point in time. This analysis can also be applied to manufacturing process development. By varying the process control parameters it is then possible to give an indication of how these parameters affect the quality/strength of the components.

Added to this, the automotive/aerospace industries have created testing methodologies that have been developed over the last century to a point that certification methodologies give a high degree of confidence in both the design and the processes for manufacturing and certification. However, with composites, these tried and true methodologies do not always crossover. This means that composite design is often conservative with the result that predictions of weight saving are not always as expected.

Formtech uses the acoustic emission technique in combination with FEA and other non-destrcutive (NDT) techniques to design and develop structures with a high degree of confidence. At this point in the development of the industry this is an area where F1 methodologies can be used to understand how close design/FEA are to the actual limits and how production quality issues affect the longevity of a component.

In order to deliver this performance gain to other industries it may be necessary to develop in-service continuous structural health monitoring. Only in this way will it be possible to speed up the process of learning that is taking place in the automotive/aerospace industries and deliver the weight savings that are theoretically possible.

Complexity

The route of substitution of metallic for composite parts is combined with another aspect of risk: complexity. The figure below shows the order of components substitution in F1, starting with bodywork and then moving towards gearboxes and engines. After plotting the history of substitution, a pattern emerges. Large, lightly loaded parts are the first to be substituted: for example bodywork. Front and rear wings were next, and although often quite highly loaded, they were simple in their design. Initially they were simple aerodynamic shapes, effectively uniformly loaded beams in bending. Next was the monocoque.

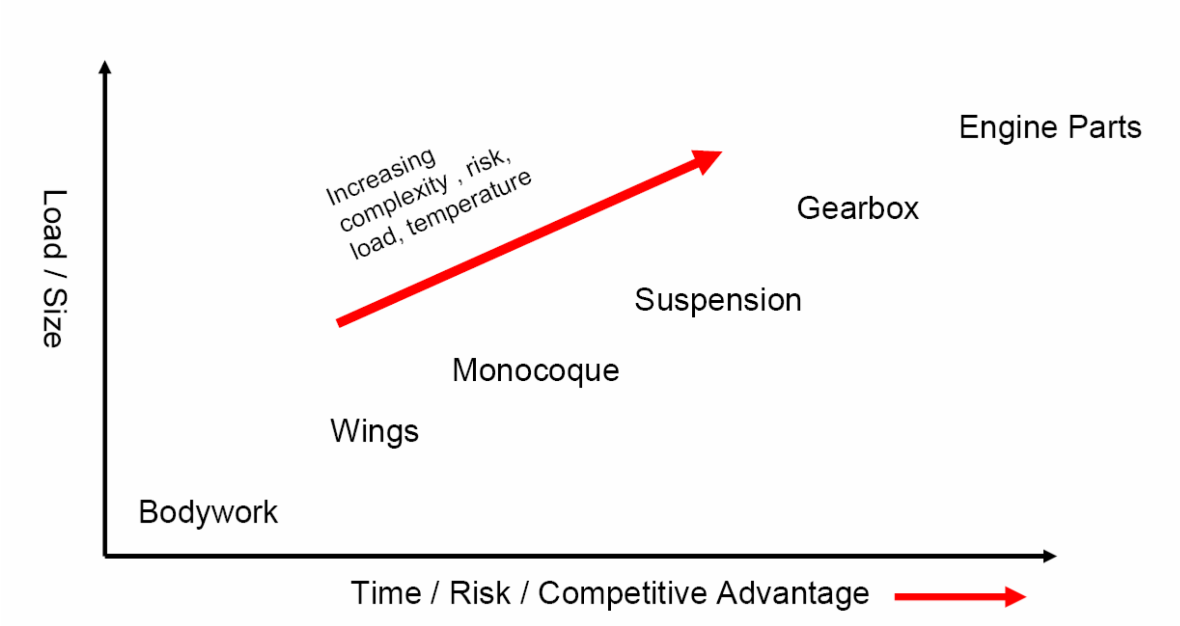


Figure 2 Substitution of Composites in F1

The monocoque is an interesting example of integration of functions. Initially it was simply about performance. Space frames are still cheap to manufacture, but the performance gains from adding panels between the tubes increased the efficiency of the structure in torsion and bending. The replacement of aluminium with carbon fibre was simply due to the large increase in specific stiffness.

However, the integration and consolidation of parts that carbon fibre designs allowed started to give secondary benefits. For example, the monocoque not only did the job of the chassis, it also included the integration of suspension mounts, inboard suspension, bodywork, and fuel cell. Another was the integration of a safety cell.

The integration of the safety cell has two important conclusions. Without the increase in performance that was created by composite substitution, it would not have been possible to develop a monocoque that can withstand 350+ kN of frontal impact loading and 250 kN of side impact loading. Only with a moulded carbon fibre monocoque is it possible to deliver this in such as small and light package.

The second aspect of the safety cell integration is that it effectively created an artificial technology barrier that means that returning the old performance levels associated with early F1 cars is just not possible. It is unrealistic to now develop a metallic monocoque that can deliver the levels of torsional rigidity, integration, weight and safety. Using this knowledge it may be possible to create a barrier to entry in another market whereby new entrants cannot start at a lower specification level and base their products on cost. This aspect will most likely deliver the same business advantages to companies in other industries and should form part of a strategic materials substitution to composites.

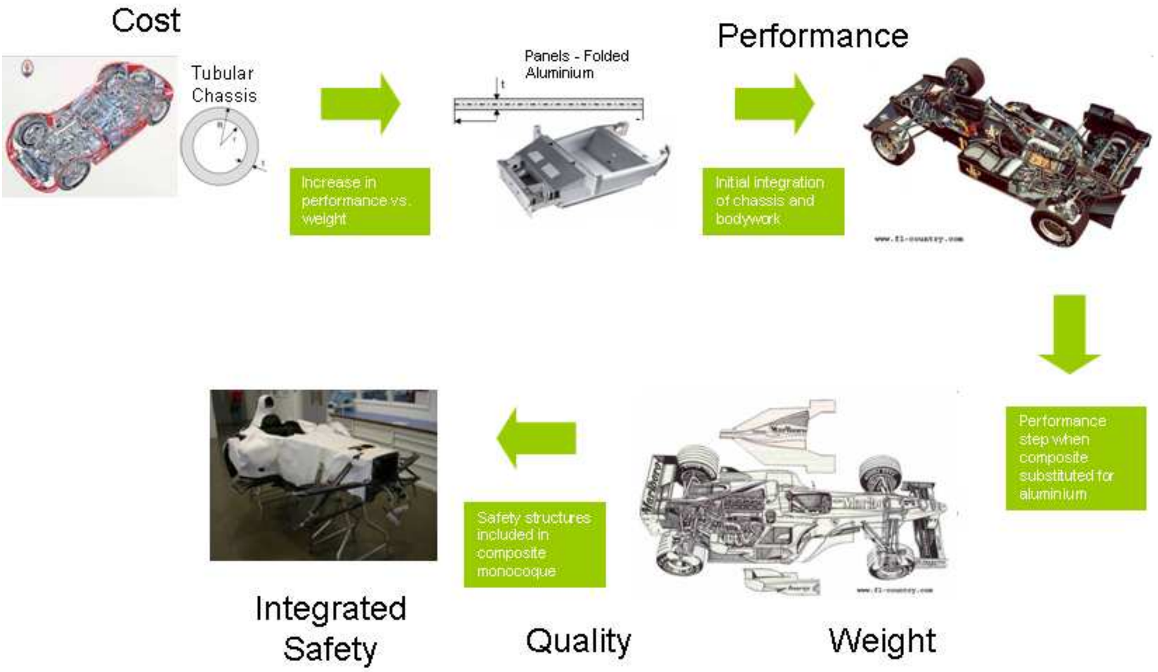


Figure 3 History of Integration of an F1 Monocoque

This type of “innovation” is inherent in the development of F1 cars. There are many cases where new development paths are discovered when technology is pushed to the limits within an environment which encourages innovation and provides mechanisms for allowing experimentation.

Although integration in other industries gives the potential for reduction of overall complexity, when including part count in the analysis, the subsequent increase in piece price of integrated components must be traded-off against modularity for repair etc.

This reduction in system complexity does come at a price.

Within F1 the benefits of integration of function mean that every surface on the car delivers other benefits. In the past, a wing was constructed with two separate parts: a central load carrying beam, often metallic tubes with aluminium fabricated aerodynamic surfaces. With the introduction of composites the two functions were quickly integrated giving large increases in the efficiency of the aerodynamic aspects at the same time as delivering lighter more tailored structures (aero-elasticity is a whole other aspect). Appendix A gives an example of a rear suspension component from an F1 car that has perhaps taken the best step towards integration, weight reduction and cost reduction through the removal of process steps, reduction in certification requirements and therefore reduction in price.

Double curvature designs with integrated functions allow an incredible amout of design freedom. These freeform shapes are where the increase in performance is being found in F1 at the moment. These advantages can also be discovered in other industries, but the complexity of manufacture has the obvious effects on price and maximum volume.

The figure below shows an updated analysis of complexity vs. productivity presented by [7] SGL highlighting the need for automation. This figure has an estimate where the manufacture of F1 components fit in the analysis: highly complex, with a low rate of production. Productivity is a measure of the time it takes to manufacture a kilogram of composite component. The complexity indicates the shape factor of the parts in question. A very simple indication is given of the types of shape factors associated with the four segments of complexity indicated here. Simple flat plates and other 2D processes that current tape laying machines can deliver. Circular shapes which can be automated through filament winding and angled shapes that lend themselves to metallic processes such as pultruision. Double curvatures and fully enclosed parts are seen at the upper end of the spectrum.

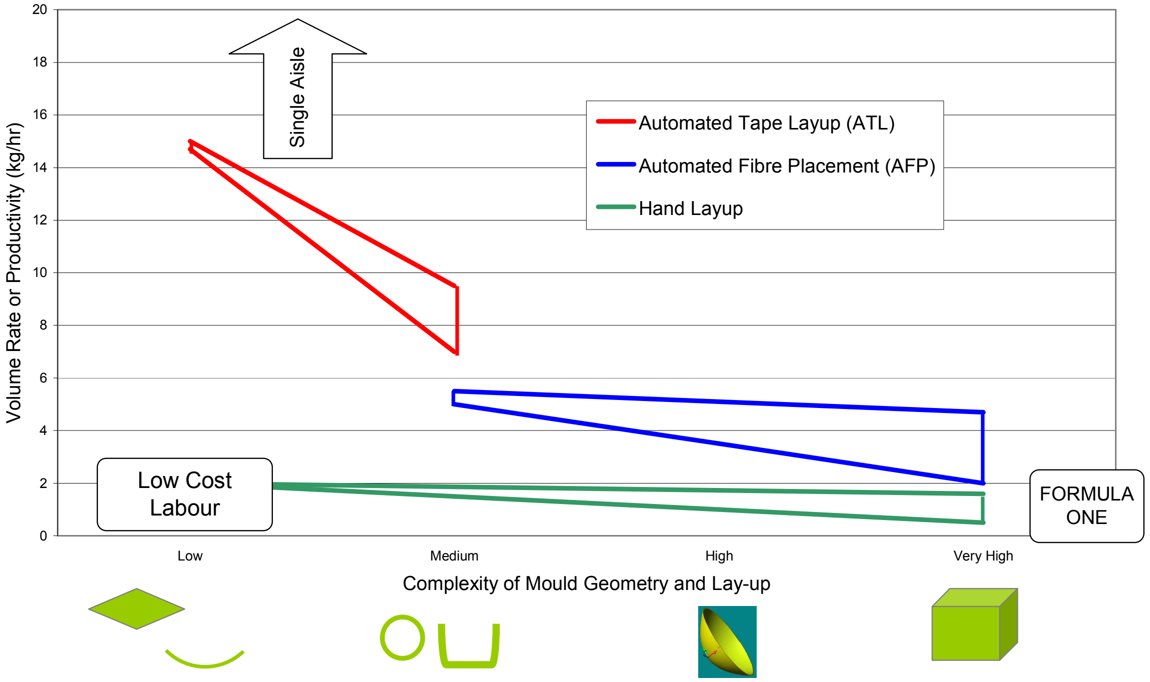


Figure 4 Complexity vs. Productivity

The green line indicates the approximate limit of hand labour and the red and blue lines indicates the approximate limit of automated processing. The figure also indicates where the lower end of the value chain where low capital investment is made and parts a fabricated by hand in large volumes.

The calculation for F1 came from the example of the monocoque. Average numbers have been used in the calculation and can vary depending on team. A typical monocoque could weigh around 65kg and take around 400-600 hours of labour to produce: 0.015kg/hour.

Compare this with the targets for the new single aisle aircraft that are targeted for manufacture later this decade and it is soon obvious that automation is paramount to delivering substitution of composites in aerospace.

In order for a number of the F1 examples of integrated structures to find their way to volume manufacture, automation will need to become part of the process. Developments in this area include net shape composites using stitching techniques such as pre-forms.

SUMMARY

The following table provides an overall summary of the various aspects discussed in this paper.

Table 2 Industry Comparison Summary

Comparison	**Formula One**	**Industry**
Performance/Payload	1st order driver of the business model	Drivers different in each sector: aerospace = weight, safety, efficiency
Risk	Prototyping Competition Higher level of risk although expensive procedures to mitigate, more mitigation in recent past	Very sensitive, market does not forgive failures: automotive = Toyota
Quality	Quality reduces risk and increases performance – trade off against pure performance	Quality is major driver with subsequent effects on cost. Requirements for certified quality systems to deal with large volumes. Repeatability, reliability
Cycle Time – Volume	Up to 400 hours per monocoque	Ranging from 5,000 annual (high-end auto) to 250,000+ (VW Golf). Targets around 1 minute per part
Cycle Time – Design and Prototype	8 weeks for full cycle	1.5-10 years before SOP
Integration	Drives performance, weight reduction and complexity	Weight reduction and cost of assembly traded off against higher piece price and replacement problems.
Business Model	*Start-up culture, experimentation matters. Relatively lower capital intensity*	*Minimisation of risks: consequences of failure, capital intensity of development*

CONCLUSIONS

Formula One is arguably the most extensive user of composites in industry using over 80% by volume in its product. This paper begins to look at the reasons why this is the case including risk, certification, complexity, cost and productivity. Integration of functions leads to reduce in weight and increases in performance as well as barriers to entry for new entrants to given markets. An understanding of the effect of integration on complexity highlights the need for development in automation which will drive the substitutuion by composites in other sectors. Rapid development cycles increase the chance to experiment and hence increase the likeihood of innovation breakthroughs while inherent risks are minimised through a deep understanding of the correlation of saftey factors with real world situations. These correlations are brought about by a combination of process innovation in simulation methodologies such as FEA in combination with certification techqniques such as acoustic emission non-destructive testing and can have an equally beneficial role to play as composite materials become increasingly adopted within wider industry.

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APPENDIX A – Suspension

Probably one of the clearest examples of the development and integration of composites in a metallic substitution is the Rear Top Wishbone (suspension member) of a Formula One (F1) car shown in the figure below.

Traditionally this part has had a number of design constraints dictating that part was made of fabricated steel, specifically the temperature from the exhaust pipes that run from the engine to the rear of the car. With shielding from the exhausts it is possible to make carbon fibre parts work, although the joints are normally a weak link.

The first step towards reducing weight in the part is to introduce carbon legs and retain bonded metallic end pieces to deal with the stress concentrations around the bolted spherical joints. The subsequent increase in cost was the main drawback of the design dictated by the change to titanium end fittings and the introduction of more processes to manufacture: changes from a fabrication to a complex moulded, final machined product with interim machining processes to prepare for bonding.

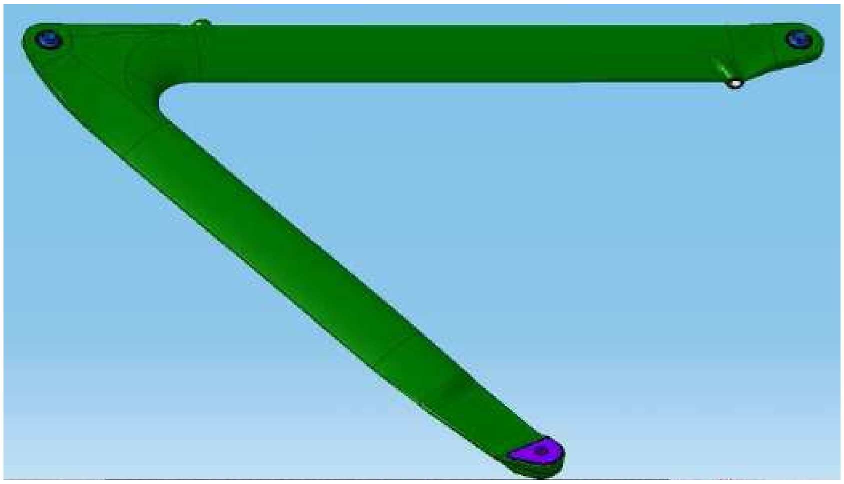

Figure 5 Rear Top Wishbone

Table 3 Rear Top Wishbone – Development

Design Iteration	**Normalised Mass**
Fabricated Steel baseline	1.000
Combination metallic and composites	0.527
Full composite	0.417

The current iteration is a full carbon wishbone, with fewer manufacturing processes and reduced complexity including the removal of bonded joints which require complex sign off processes. The bolts and joints a mounted into the carbon by way of top-hats. The integration of parts reduced costs, reduced the need for certification of bonded joints and removed more weight.