face to face with Paul Stewart

Design process leader and consultant

A perspective on simulation in the automotive industry

by Kathleen Grant
EnginSoft

From his studies in Systems Design Engineering and Naval Architecture Dr Paul Stewart has an extensive background in CAD surface mathematics and fluid dynamics as they relate to the design process. He began working at the Ford Research Lab where he was the first to apply shape morphing to automotive CFD (computational fluid dynamics) and then continued on with EXA and eventually Altair, creating virtual design technologies involving advanced surface modelling, response analytics, and advanced visualization. During this time he has worked on production design projects and processes with almost every automotive and heavy truck manufacturer worldwide.

Paul is currently consulting with CAE providers looking to find their place in the design process and Design and Engineering companies looking to take their design process to the next level. Futurities interviewed him about his thoughts on the evolution of simulation in the automotive industry and the likely impact of new technologies.

The roles of design and engineering in automotive

The sinuous lines of a sand dune, the poetic simplicity of the curve of a feather, the power and adrenaline of a galloping stallion - these are the sources of inspiration for car designers. The design has to evoke an experience or make an identity statement for the eventual car buyer … and the car's shape captures the essence of that theme.

Yet it is also just the beginning of the automotive design process with the emphasis being on "Design" and not "Art" because the vehicle manufacturers set a large number of rigid objectives for the final product, thousands of which constrain the designers. These are fixed numbers to be achieved in multiple areas, such as aerodynamics where their design shape must satisfy a specific drag count to achieve the fuel economy necessary to be able to sell the vehicle model. Since an automotive company will cancel a programme rather than manufacture a product that does not meet its numbers, this places great pressure on the designers and engineers to meet these constraints.

According to Stewart, this is where a lot of the friction between designers and engineers arises: "Designers and engineers both think of themselves as the designers of the car. However, engineers generally concentrate on the specific technical constraints - thermal problems, aerodynamics, emissions, manufacturability, and so on - while studio designers are the group in the company tasked with creating a shape that meets or facilitates almost all the 5,000+ constraints that any car design must achieve for commercial viability.

Beyond that, to truly succeed the studio designers must do this with a shape that that the client loves," states Stewart. "Engineers often talk in terms of optimization, but vehicle programme management will tell you it's all about compromise. What's good for aerodynamics is bad for thermal cooling, what's good for thermal cooling is bad for crash-ability, and so on. Optimizing for any single engineering requirement will certainly degrade others. The studio designer has to weave a solution among all the constraints while simultaneously satisfying the aesthetics required for the vehicle."

Stewart views the designer's role as somewhat similar to an orchestra conductor's – combining all the elements in harmony where each element or instrument succeeds, and their combination captures and conveys the brand image that they set out to create originally. "While an orchestra conductor is likely to be an expert in most instruments, the designer must rely on the individual engineers for their expertise. That creates friction and explains why the designer's job is so challenging," he says.

> Automobile design is about achieving an acceptable compromise between all the constraints while satisfying the aesthetic requirement for the vehicle.

According to Stewart, CFD engineers may often have the tendency to run some simulations, identify changes to the car design to correct the aerodynamics, and propose the modified design to the design team as "the fix" to their problems. This generally causes frustration and irritation among design teams: "In fact, parts of the studio design process are built as an obstacle to engineers' attempts to tamper with their design language."

Changing perceptions

Stewart's perception of the roles of the automotive designer in the studio and the automotive engineer have evolved significantly over his career.
In the 11 years he spent in Ford Research Lab (FRL) he was able to observe the automotive design process first-hand and develop design technology from the automotive company's perspective, particularly the design studio. His next 20 years were spent with software companies supplying CFD design process technology to the industry and participating in production design projects.

"In the beginning I viewed both engineers and studio designers as 'designers', each with their individual design tasks to complete. While they naturally needed to work in partnership, each had their own design responsibility. Over time and with the help of a few studio mentors, I came to understand the unique, central role of the designer and my perception evolved to view the engineer's role as being to support the designers by helping them to understand how and why air interacts with the surface they're designing," he explains.

"If engineers can guide designers to intuitively understand how air works over the surface, the designers can integrate that knowledge into their design language as they go through their creative process," he says, specifying that guidance by the engineer is the critical step in the process. "Designers do not need to understand air flow mathematically (Bernoulli's equation, pressure gradients on the surface, etc.), but rather instinctively, so they can anticipate its behaviour as it moves over their surface."

The evolution of CAD and CAE with free-form deformation

Historically, another barrier between design and engineering was the amount of time it would take engineers to respond with a design analysis: "In the past, it would take a CFD department two weeks or more to turn the designer's outer body geometry into something that could be simulated and analysed, by which time the designers would have moved in a different direction," he says. This meant early CFD was used primarily in the late stages of design, after the intensive studio work, when the body shape was more or less final but still needed testing to meet its performance targets.

This use of CFD was faster to react to ad hoc tests than the wind tunnel, but it meant simulation was only being used for testing, as a score card to measure pass/fail and improvement, rather than for actual design. According to Stewart, this is where the studio designer's frustration would reach its peak: "At this late stage meeting performance targets is critical, and "fixes" proposed by engineering most often take priority over the aesthetics of the design. Once the manufacturing tooling process is underway, all changes are expensive and the designer has very little flexibility left to save their design," Stewart says.

He believes CAE can only contribute its potential value to automotive design if it keeps pace with the speed of the design process at its earliest stages. "The design process is very rigid to allow the myriad of related dependencies to be resolved in the correct order from the outset. The timing of every milestone is marked out years in advance, and missed deadlines are measured in millions of dollars per day.

> This type of volumetric morphing allowed us to keep pace with the design team and marked the transition of CFD from testing to design.

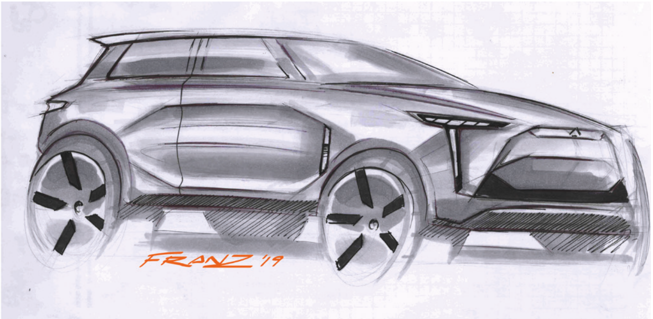
Your assigned task may have a six-week window to begin and complete a particular design decision and if the CAE can't keep up, it can't add value. The decision will be made on deadline with whatever information is available," he says, explaining that this leads to overly conservative decisions being made. "The vehicle must perform and be safe, certainly, but conservative, conventional, and over-designed is not a winning approach in a style-driven industry with small profit margins."
In his last few years at Ford in the late 1990s, Stewart saw an opportunity to bring simulation turnaround times closer to automotive design's pace. The Ford CFD department had approached him with a typical problem to solve: adjust the CAD model to tilt a windscreen and adjust the wrap radius (the curve of the windscreen as it moves outboard to the A pillar). "This was simple enough - until they explained that they wanted to perform a design of experiments (DoE) with 30 different models, and they needed the 30 models in less than a day to have the time to run the simulations and still meet their design process milestone! We believed it was impossible, especially if we worked directly on the NURBS of the CAD model," he says.

The enormity of the problem forced what was, for that time, a radical solution: the mathematics modelling literature at the time was covering new methods of shape modelling, many of which were the first seeds of the development of CGI animation at companies like Pixar. One method in particular, from Thomas Sederberg, professor of Computer Science at Brigham Young University in Utah in the USA, warped rigid curves by encasing them in a lattice which was then bent to "morph" the curve into a new shape without constraint from the mathematical form of the original curve.

This inspired Stewart to rethink the approach to modelling: "We abandoned the CAD model or, rather, converted the baseline model to a CAE mesh, and we used this as a baseline that was then morphed into derivative shapes.

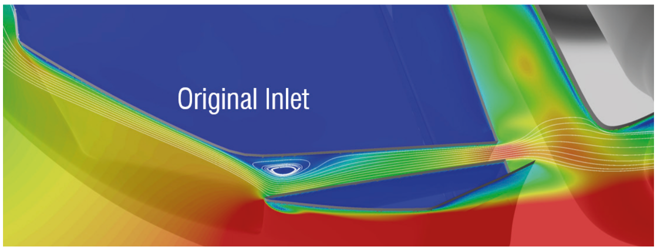
We enhanced the early morphing work by creating individual lattices for each DoE design element and parameterizing the lattice morphing from 0-100%. Once the individual morphing lattices were complete (a few hours work) we could take the baseline mesh model, apply the three windscreen design parameters automatically, according to a DoE table, and create the 30 simulation-ready CAE models - all in about 10 minutes," he explains.

"This type of volumetric morphing allowed us to keep pace with the design team and marked the transition of CFD from testing to design. A CFD department could generate large numbers of complex shapes in a small fraction of the time, change and add design parameters without having to manually rework the geometry, and perform a more reasoned study of performance than they could using the previous approach of trial and error," he says. "Even if a DoE wasn't being applied, we could morph significant design changes to all parts of the car in half a day and produce a new design analysis each morning instead of the two weeks required to work from CAD. This approach provided significant value to the design team and changed the business significantly. It was ground-breaking to apply Sederberg's science in that way," he states.

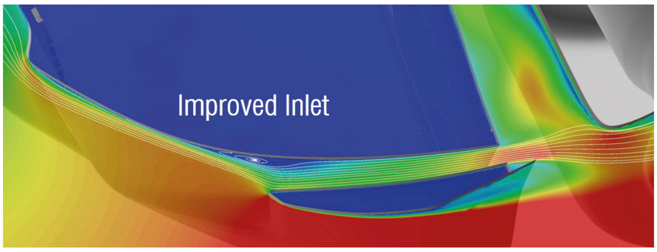


Arc SUV design courtesy of Francesco Di Giuseppe

The interior surfaces of ducts are usually tuned to optimize air flow during the later stages of design. However, maximum duct potential is governed by the visible shape of the inlet and frozen in the early stages of design.



Most ducts inlets have significant recirculation. But if the designer understands the flow paths over the fascia while creating the design concept shape the result can be a duct with twice the flow potential.



The interior of this improved duct was later tuned with a parametric design space analytics resulting in more than twice the performance possible with the original.

Shortly after this first project, EXA, who supplied their flagship CAE product, PowerFLOW, to the simulation department, realized the value and licensed all the morphing technology from Ford, and in the early 2000s Stewart joined the company to produce what became PowerCLAY, "the first parametric morphing tool applied to CAE". This work eventually expanded to include template-based meshing, response surface analysis, and adaptive sampling to reduce the number of simulations required by 50-70% v. a DoE.

Over time, engineers at all automotive manufacturers began applying these techniques while other CAE meshing tools adopted similar morphing technology, culminating in a perhaps unfortunate effect: all cars started looking the same. Since the morphing tools were applied primarily by the engineers whose primary goal was to meet their specific performance criteria, they all carefully rounded the front fenders and tuned boat tails and applied all the shape changes known to have worked in the past, smoothing away anything that might interfere with the flow. In a short time, car manufacturers' designs started to converge.

Stewart believes two things are missing in the design-engineer partnership: "First, engineers need to 'teach, not tell' and explain to designers how and why flow moves as it does over a design shape; in other words, describe what engineers try to achieve with flow, but in intuitive and spatial terms designers can relate to. This puts the designer back in the central position of creating a shape that integrates all needs, including aesthetics. Armed with this knowledge, it's been my experience that they can offer much more creative shape solutions than engineers - and definitely alternatives that capture not only the needs of the physics, but also fit coherently into the design language of the vehicle," he says.

The second missing piece is a design tool that allows designers to rapidly create parametric shape alternatives, similar to morphing parameters, but with a mathematical elegance more closely related to the character lines and design language of their vehicle. "These tools aren't there today, but the need is great because designers are introducing more distinguishing forms back into design. There are many regions in cars where a very smooth form only improves drag very slightly.

With this knowledge, designers can explore shapes with more character such as using aggressive details in the stagnation regions (where flow stagnates regardless of shape) and along the sides (where the flow is already turbulent from the wheel wakes and may not be significantly affected). We're getting back to focusing on the aesthetics. But better design tools are needed to complete this step," comments Stewart.

When Dassault acquired EXA, Stewart joined Altair where he re-built his parametric-design process vision including the volumetric morphing, and added a significant new piece based on the subdivision surfacing mathematics of Inspire Studio. Sub-division surfaces, sometimes referred to as polygonal modelling, are an alternative to conventional NURBS surfacing mathematics and, as mentioned earlier, are extensively used in CGI software to create shapes for movie animation and gaming. Although not as precise as NURBS for tight tolerance manufacturing, designers can directly use sub-division surfaces to create and modify detailed concept shapes in significantly less time. This makes them ideal as a design format to feed early-stage CAE analysis, according to Stewart.

My journey with aerodynamics and design began when learning to sail at 10 years old. At first imagining the wind moving through the sails to make the boat go forward and later, when teaching racing, helping students think about the air moving over the shape of the sail surfaces as we learned to trim them to maximize boat speed. Yes, the mathematics and physics are important, but ultimately good design comes from a natural understanding of behavior. This is what we, as engineers, should provide.

His process could take a proverbial sketch on a napkin to a fully detailed, open-grille vehicle model, including all the gaps and fillets necessary for accurate CFD, in one day; present an aero analysis the next morning; and then follow up with a re-design and analysis the morning after.

This was further augmented by directly adding parametric control of the designer's character lines, thus almost completely eliminating the need for the more complex volumetric morphing. "This approach is the next step to moving CAE all the way forward into the concept and even pre-concept design stages," he says.

How are the evolution of CAD and CAE intertwined?

"As an undergrad, I didn't understand how pervasive surface mathematics were," Stewart says, "But in my graduate research in CAD mathematics I soon realized that we live our lives in and around objects defined this way. Virtually everything we touch every day was described with a mathematical surface at some point, starting back with shoe companies that had to produce the same shoe for all foot sizes," he says. Applied research into surface mathematics really flourished in the automotive and manufacturing sectors.

"Automotive companies had the budgets for such work and the extremely difficult problem of transferring complex, freeform designs from paper to mass production where high volumes and tight tolerances make customized manufacturing prohibitive," Stewart explains, "A science was needed to faithfully translate the design idea quickly and accurately for manufacturing, which led to the creation of CAD."

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Ultimately two types of CAD emerged: constructive solid geometry (CSG) to describe parts with Boolean combinations of solid primitives, and boundary representations (B-Reps) to describe complex and freeform shapes by stitching together individual patches, usually NURBS, into a quilt describing the surface boundary of a volume. "A B-Rep NURBS has a more versatile shape that can be faired to a few thousandths of an inch to achieve the near-perfect continuities required for smooth surfaces, as well as elegant highlight or reflection lines," says Stewart. "However, while the B-Rep is great for describing an abstract design idea, its construction and design-change process can be very labour intensive for manufacturing."

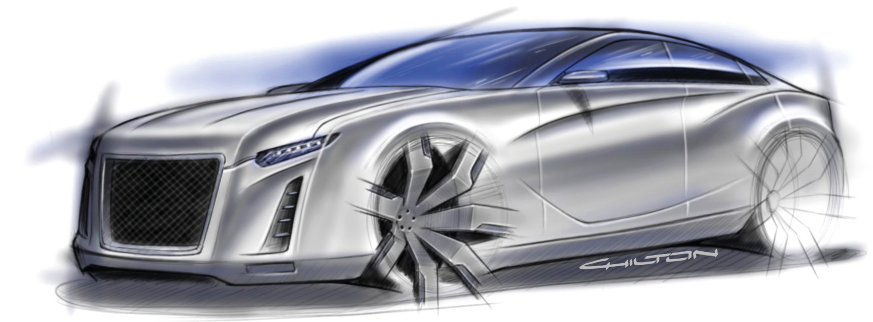
He continues, "Consider class-A surfaces. These free-form surfaces of cars, such as the stamped sheet metal and plastic body parts, are both aesthetic and critical to many of the vehicle's physical performance criteria. Expertly skilled math-modelers (a new profession, similar to a clay modeller, that evolved just to create these shapes) can create a reasonable outer skin of vehicle hood (or bonnet) in about half a day.

This painstaking process proceeds one NURBS patch at a time, with each depending on its neighbours in a critical and complex hierarchy such that an entire vehicle can take up to two weeks to be fully stitched with all of the critical details necessary for accurate simulation. Any design changes further compound this problem because even a small change may cascade to many layers of surrounding surfaces, requiring extensive re-work. These time delays make it impossible for CAE to keep pace with a rapidly evolving design and for this reason CAE was initially applied at a relatively later stage in the design process once the design was stable when it helped to avoid significant physical testing costs and rescued programmes with critical corrections," Stewart explains.

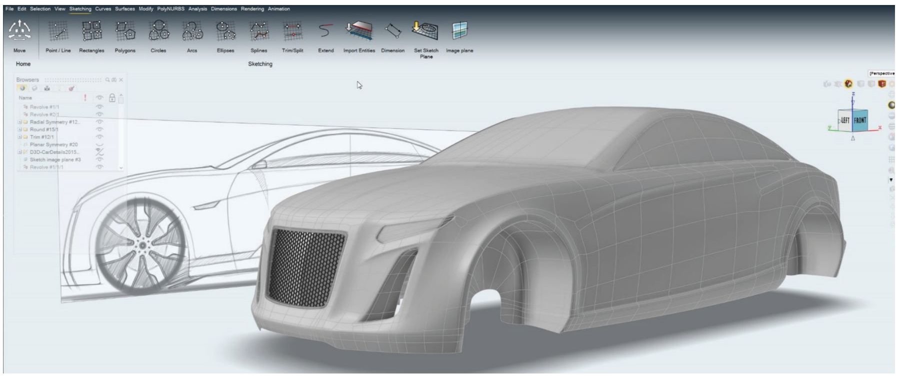
"A typical new vehicle programme may start with seven or more alternatives that quickly explore aesthetic themes and technologies. Over a matter of months, these are narrowed down until one design theme is then perfected in the studio," he says. "This early pace is simply too rapid for CAE that depends on a complete model description in CAD - even with the significant efforts to automate and reduce the time to create a simulation-ready mesh from CAD, the time required to create the CAD is still prohibitive and unnecessary considering that the manufacturing-quality CAD only becomes important once the final theme is selected," says Stewart.

"However, that's not to say applying CAE once the final theme has been selected is without value. On the contrary, avoiding a problem during intensive studio work on the selected theme can be one or two orders of magnitude cheaper to correct than a problem found late in the programme when corrections often cascade to surrounding parts and include expensive re-tooling costs," he comments.
He believes that CAE has still greater potential if it can move even further upstream in design: "The guiding principle of successful design is to manage risk. As I already mentioned, to be noticed, a new vehicle or any product, must introduce bold customer-visible advancements. But manufacturers cannot afford to commit to any unsuccessful idea that may prevent the product from reaching the market.

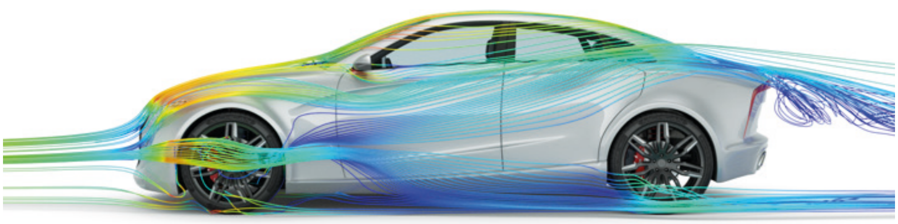
These bold risks are evaluated during the earliest stages of design and, unless they can



CX1 Sedan design courtesy of Darren Chilton



When sub-division surface modeling software is tailored for CAE a detailed open grille vehicle model can go from an idea on paper to a fully detailed simulation mesh in one business day.



This time advantage allows the designer to review an interactive, animated flow study the next morning while the design concepts are still relevant.

be proven to be very likely to succeed, they will be removed from the programme. It is here, when the concepts themselves are still vague, that CAE, at its best, can add enormous value - by allowing radical new concepts to be explored and refined to an acceptable level of risk."

According to Stewart this was the vision for simulation to fulfil its long-held promise: "To achieve it we required a new mathematical shape model capable of capturing form specifically for simulation - at the point when the idea was still only an image on a wall or a pencil sketch on a notepad. The success of PowerCLAY and volumetric morphing demonstrated the value of a modelling technique specifically for simulation that avoided significant portions of the meshing process and facilitated parametric-shape studies.

Working directly on the simulation mesh created a general-purpose approach that allowed CAE to significantly contribute to design. Yet that technique had drawbacks too because the baseline mesh still came from CAD, and morphing skills are not commonplace for either designers or engineers," he says. He continues, "Automotive design required a tool that could capture shape fast, run a simulation, and revert quickly to designers with the required feedback. In other words, a mathematical format that allowed designers to easily ideate a shape that was already (or very close to) a simulation-ready mesh. As mentioned, Hollywood provided inspiration for the answer."

The sub-division surfacing techniques of movie CGI have been incorporated into effective concept design tools like MAYA from Alias, which Stewart and his team experimented with successfully at EXA. In his time at Altair, Stewart was able to further improve on this by introducing parameterized shape features into Inspire Studio, which allowed a designer to create a fully detailed vehicle including open grille and fully filleted edges from scratch in a day (math modeler not required); this could then be simulated in CFD overnight and the same vehicle could be parameterized the following day to drive a complete parametric analysis by the end of the week.

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Stewart acknowledges that sub-division surfaces are generally not precise enough to be considered manufacturing quality but says they can capture the significant design details required for analysis: "Coupled with easy and rapid shape iteration and direct input into CAE it offers a significant advantage over traditional CAD modelling." Ultimately, he believes the design process will evolve to perform thousands of design iterations for concept evaluation and engineering design using sub-division surfaces and that the finalized shapes will then be transferred to traditional CAD modelling to prepare for manufacturing. "Beyond that new manufacturing techniques like additive manufacturing can completely skip the CAD model to create components," he says, "We need to prepare for that by creating models that are suited to CAE right away to allow CAE to add significantly more value in the design industry."

What role does and can artificial intelligence play?

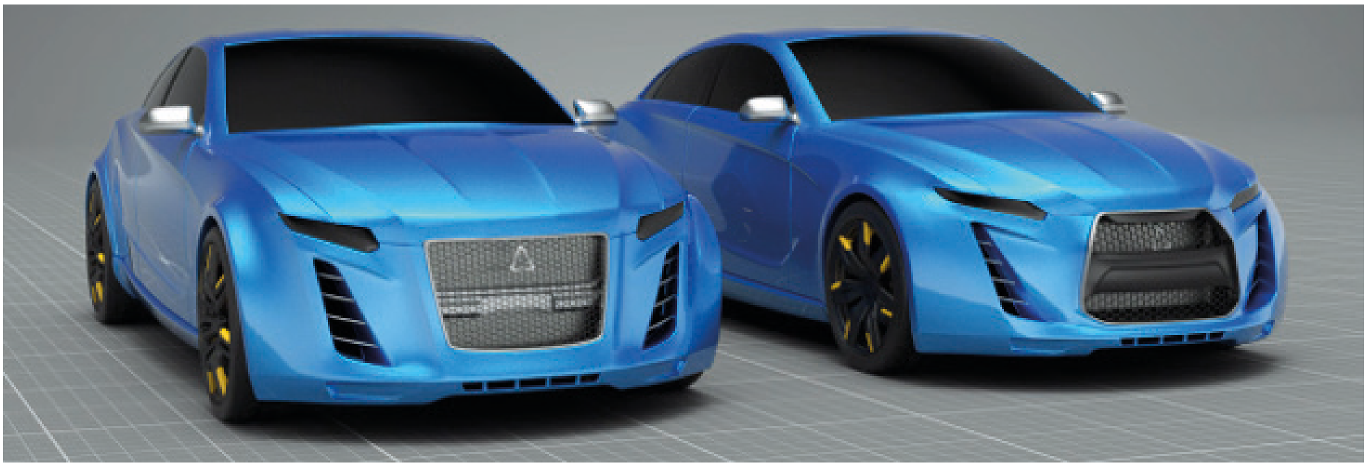
"The latest hype around AI is over-extended compared to what it can deliver," says Stewart, emphasizing that it is still extremely valuable to the design process, "however, it is not going to replace the important human aspect of innovation." Stewart says that AI was called pattern recognition when he was an undergraduate, and that he considers it a more accurate description of the initial forays into deep learning and neural nets, etc. "The algorithms were 'trained' by being fed a lot of data from past experiences in which they identified various relationships and behaviour patterns. These behaviour models could then be used to predict expected behaviours, or searched to identify optimum behaviours."

> "We need to prepare for that by creating models that are suited to CAE right away to allow CAE to add significantly more value in the design industry.

He comments, "In that project at Ford where a DoE was used to study the effects of three shape parameters on the windscreen using 30 vehicle design-combination simulations to understand the sensitivity of those shape parameters and how to arrange them to optimize drag, you could say there were two core problems with our initial approach, namely the cost, and the scope of the design space or selection of shape parameters."

Explaining, he says, "Consider cost: 30 simulations to understand three shape parameters is far too expensive. An experienced aerodynamicist could probably achieve a similar answer by trial and error using around a quarter of the simulations, maybe fewer. Then consider that a typical production upper-body aero-design task actually involves from 10 to as many as 25 or 30 parameters for which a DoE would require hundreds of simulations. However, this problem is solvable: at EXA my group did research into AI including adaptive sampling and progressive shape parameter selection which allowed accurate response models to be built at ratios closer to three simulations per design parameter."

Regarding the scope of the design space, however, Stewart contends that it is not solvable with AI. Citing the windscreen design-space problem again, he asks, "What if there were a fourth parameter that was even more effective at improving drag than the three that had been selected? Or a fifth? There is nothing in the machine learning approach that will detect whether effective parameters are missing in the learning, let alone identify them. This is because AI builds its understanding of the universe based on what it's been taught; it fundamentally lacks the ability to create," he states, "It can propose combinations of



Understanding specific flow behaviors at the earliest stages of concept ideation allows the designer to evolve their entire design language coherently in few hours before it is set in stone. Three concept evolutions produced the vehicle on the right with drag reduced by 15%. Notice how the character lines from the hood have all shifted inward one feature on the fascia to accommodate a rounder fender while maintaining an aggressive look. A significant improvement over simply bending the collective surface.

parameters that have never been tried before, and thus appear to be 'creating' something new, but it cannot propose a new dimension of exploration."

He hurries to clarify however that he sees AI as "a powerful tool for performing a task that is extremely difficult for humans, namely modelling and predicting the complex integrated behaviour of multiple shape parameters without a preconceived notion of good and bad combinations. A project with dozens of individual parameters can be like solving a 25-dimensional Rubik's cube: every time you change the value of one parameter, the behaviour of all the others changes."

Stewart describes his favourite part of each production project which he came to call it the "Aha!" moment: "At some point the response model would uncover a combination of design parameters that the experts 'knew' by intuition beforehand was not worth exploring because their experience suggested it would not work. Unencumbered by this bias and with the logical ability to pursue a myriad of potentially viable combinations of the design parameters, the process would almost always uncover a successful combination of parameter settings that caused us to re-think our understanding of the physical behaviour."

He says that this phenomenon of experience bias is even more true when the timeframe for finding a solution is tight and inflexible: "People tend to become more conservative and follow what they already know when they're under time pressure," he says. "Between this bias and the engineers' tendency to stop when they reach the target improvement, I feel like we routinely left 10-20% or more of the performance potential behind when we didn't use analytics."

Returning to the perceived threat of AI to many jobs, Stewart reiterates that creativity and innovation - and not intuition - are our differentiators over advanced AI. "With our creativity, humans can change the structure of a problem or change the problem altogether. Take Formula One design for example. While AI can help refine body shapes, it won't propose re-purposing the front-end foils to also provide an air curtain over the front wheels or adding small tabs around the vehicle to generate vortices and improve intake performance, underbody down force, or even disrupt the air for a following competitor.

Those come from a human who saw that the team was solving the wrong problem and could get better overall performance by changing the objective of the problem or the scope of the solution." He says that this is where his understanding of the roles of designer, engineer, and technology have changed yet again: "The engineer must identify the fundamental design objective and work with the designer to create a set of shape parameters (a design space) they believe will have a strong influence on that objective with the goal of building the most active design space with the greatest potential to improve performance. This will offer the most flexibility for crafting an aesthetic solution that meets all the design criteria."

> "[AI is] a powerful tool for performing a task that is extremely difficult for humans, that is modelling and predicting the integrated behaviour of multiple shape parameters and without a preconceived notion of what will and what won't work.

"That relegates AI to the role of exploring and learning about a given design space, analysing the unique value of individual parameters and the potential of their most effective combinations. Once engineers understand, without their knowledge bias, which shape combinations work best, they can re-examine the physics to determine why. Armed with this improved understanding, they can then either change the design space to increase its potential or even change the problem altogether," he continues.

"Combined with the improved modelling processes I described earlier, this further clarifies the relationship between engineer and designer. When engineers can explain to designers how shapes create flow structures and which flow structures are most beneficial, the designers, who are naturally creative spatial thinkers, can use this understanding to create a design language and a shape that will also satisfy the aerodynamic needs," he concludes.