Ora RESEARCH
technology business strategy for 21st-century engineering practice

P.O. Box 61334
Raleigh, NC 27661 USA
tel +1 617 875 9598
www.oraresearch.com

Time for Automotive OEMs to Transition from Wind Tunnel Testing to Simulation-Driven Design

By Bruce Jenkins, Principal Analyst, Ora Research

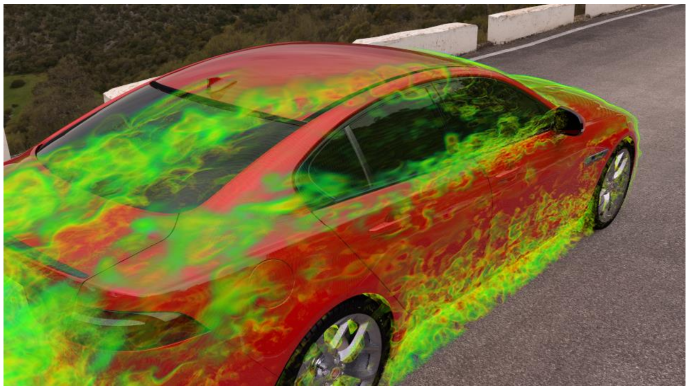
Automotive OEMs have long relied on wind tunnels and physical prototypes to prepare for on-road regulated testing of new vehicles. But a mounting body of evidence suggests the time has come for automakers to put an emphasis from wind tunnel testing of physical prototypes to vehicle development processes based on digital simulation of aerodynamic, thermal and aero-acoustic behavior. More and more automotive engineering executives, wind tunnel experts and simulation technologists agree that:

1. **Wind tunnels do not reflect fully the real world and thus fall short predicting real-world performance.** Simulation-based processes and results are much more repeatable and reproducible than those based on physical prototype testing, and can model real-world driving conditions with higher fidelity than wind tunnels.
2. **Physical prototypes give feedback on performance but do not easily yield the insights needed to make a better design.** Simulation results provide engineers with much greater understanding of the factors controlling and influencing vehicle performance than wind tunnel testing. Simulation provides greater clarity into the aerodynamic forces, acoustic behavior and thermal performance of a vehicle design, as well as how each interacts with and influences the others.
3. **Studio designers and engineers need to collaborate early in the design process** to evaluate and refine the performance of their proposed designs. Simulation can begin much earlier in design than physical testing, when critical decisions must be made, and simulation results visualized as photorealistic renderings can help studio designers gain insights into how to improve their designs to meet performance targets.
4. **Working with wind tunnels and clay models is a very sequential process and not very fluid.** Early in the process when critical decisions are being made, designers are limited by the process of working with cumbersome clay models that cannot be easily changed to quickly explore a wide range of design alternatives. As a result, designers and engineers are limited in what they can learn and test in the wind tunnel. Wind tunnels and physical prototypes cannot occur until later in the process by the very nature

of having to build a prototype—which then falls out of date—whereas simulation can occur much earlier, giving a much better chance at making good tradeoff decisions. In addition, modern optimization methods can be applied more efficiently with simulation-based design.

5. **Wind tunnels, clay models and full physical prototypes are very costly.** Typical automotive OEMs can see more than 500% ROI by transitioning from wind tunnel testing to simulation-driven design.

1. Wind tunnels do not fully reflect the real world and thus fall short predicting real-world performance



Wind tunnels cannot fully reproduce real-world driving conditions. Dr. Ales Alajbegovic, Vice President of Ground Applications at CFD software developer Exa Corporation, points out that the wind tunnel is only an approximation of the on-road conditions, and does not provide good absolute measurements. “For example, for the same car, ten different wind tunnels give ten different drag measurements. Which is right?” he says. “On top of that, incremental changes to the geometry will show different effects in different wind tunnels, sometimes even opposite trends. This is due to the interaction of the wind tunnel geometry with the measurements.”

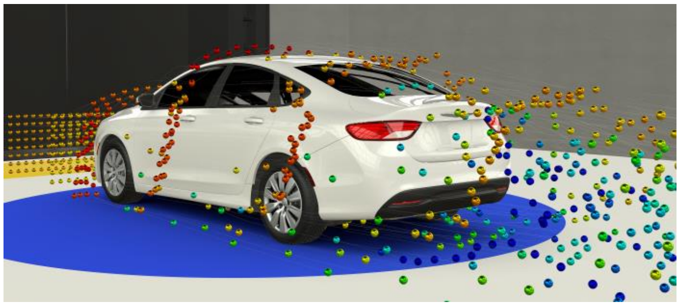
Physical experiments do help to identify issues with designs, Alajbegovic says. “However, using experiments, it is difficult to get the understanding of the underlying physics—what is causing certain behavior.” Why? “The airflow is transparent and cannot be seen. The smoke can provide some quantitative idea about the flow structures; however, quantification of the phenomena is impossible.” Another test-based approach is Particle Image Velocimetry, which can provide both flow structure measurements and flow quantification. “However,” he notes, “it is incredibly difficult to do, making it practically impossible.”

Alajbegovic sums up the problem: “Today there is a discrepancy between the CAD geometry and what is actually measured. Because of that, the OEMs really don’t know the geometry details of the car that is being measured. That is constantly confusing them about what impact certain geometries really have.”

“Wind tunnels are not perfect simulations of the road,” observes a senior automotive engineering executive with experience at Detroit-based OEMs. “Lack of moving ground underneath the vehicle” limits what wind tunnels can reveal in aerodynamic and thermal testing, he notes, resulting in “poor simulation of underbody flows and cooling flows, and compromised under-hood flow.” In addition, wind tunnels are unable to reproduce the multidirectional wind forces that vehicles experience on the road.

A related problem is that wind tunnels are affected by temperature and humidity of the surrounding environment, which can vary from one test to another. Thus the same test regime, repeated on different wind tunnels or the same wind tunnel on different days, may yield different values. By contrast, the parameters in simulation runs can be tightly controlled, ensuring engineers that results will be self-consistent, varying only in accordance with intentional parameter and setup changes.

Beyond wind tunnels, the limitations of physical test-based development processes extend to on-road testing, where "repeatability is compromised due to variability in climatic conditions and traffic/speed variability," the Detroit executive says. What's the solution? "Virtual analysis is needed to examine what the actual road conditions are," according to him, "to simulate movement of the road under the vehicle, movement of tires and wheels, under-hood conditions, and turbulence and yaw conditions." Simulation allows automakers to represent all of these conditions, resulting in a design whose real-world performance is well understood and optimized prior to full-scale prototyping.



Simulation lets engineers measure the performance of a design without influencing the results, whereas the nature of physical testing means that a quantity cannot be measured without influencing the outcome of the test. Wind tunnel experts note that any placement of a sensor on a car's body will impact airflow on the sensors around it, and thus the results of the study on the design. Also, sensors are only able to measure the parameters where they are placed, and limitations on the number of sensors may lead to incorrect conclusions. For example, noise inside a vehicle may reach a peak in a location where there is no probe, and thus go undetected by physical testing. By contrast, simulation makes it easy to examine vehicle behavior and performance in a global manner that is often infeasible or impossible with physical testing.

Wind tunnel test results may be misleading to the consumer. *Car & Driver* magazine conducted wind tunnel tests of the Chevrolet Volt, Mercedes-Benz CLA250, Nissan Leaf SL (2012), Tesla Model S P85 (2012) and Toyota Prius. Reporting the results in its June 2014 issue, the magazine commented: "While manufacturers often tout the slipperiness of their products, comparisons with competitive models are rare. The expert in charge at our clandestine test location explains: 'All wind tunnels strive to accurately quantify the aerodynamics a car will experience in the real world. The vehicle and the tunnel constitute a system with complex interactions. As a result, drag and lift measurements on a particular vehicle can vary from one tunnel to another.' A group of vehicles may rank differently in different tunnels, he says. This is why most manufacturers have so little faith in aero numbers measured outside their own facilities."

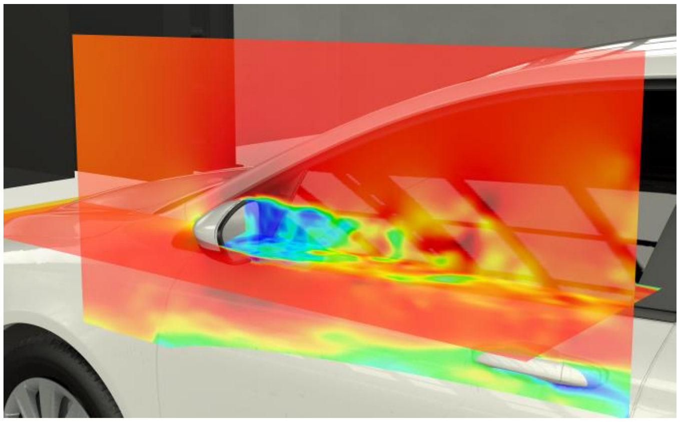
In the same article *Car & Driver* reported on the CLA250: "Mercedes-Benz says this car's drag coefficient of just 0.23 is not only the best in its lineup, but a new low for the entire industry." The magazine then added, "Given the wide range of methods for measuring drag coefficients, comparisons between automakers are often inaccurate." Indeed, *Car & Driver*'s own tests of the CLA250 subsequently measured a drag coefficient of 0.30.

Truck manufacturers have already proved the feasibility of fully virtual testing. Minimizing aerodynamic drag is critical for commercial truck manufacturers. At highway speeds, semi-trucks typically expend more than 50%

of total engine output overcoming drag resistance. However, these vehicles are generally too large to fit in the wind tunnels used by commercial automakers, so physical testing requires renting very costly time in large wind tunnels normally used for aircraft and which are poorly suited to testing bluff body vehicles in the proximity of ground. “Trucks are so large that there is no facility to test them in, and small-scale models don’t fully represent detailed geometry,” notes Kevin Golsch, Exa’s Technical Director of North American Field Operations. These economics have driven truck manufacturers to make substantial use of simulation to identify and minimize drag sources. Indeed, proving the feasibility of moving to development processes based entirely on virtual testing, Golsch notes that “several truck companies—Volvo Trucks, Kenworth and others—use Exa software exclusively and don’t do physical prototypes.”

2. Physical prototypes give feedback on performance but do not easily yield the insights needed to make a better design

Simulation results provide engineers with much greater understanding of the factors controlling and influencing vehicle performance than wind tunnel testing. Simulation provides greater clarity into the aerodynamic forces, acoustic behavior and thermal performance of a vehicle design, as well as how each interacts with and influences the others. For example, an automaker may minimize drag to improve fuel economy, but the ensuing reduction in airflow may cause overheating.



In developing its Model S, Tesla adopted CFD simulation as its principal engineering analysis tool, with wind tunnel testing used primarily for validation. Tesla describes how simulation-driven design provided more information than physical testing, enabling engineers to diagnose and develop solutions to drag problems much faster than physical testing would have done.

“The drag coefficient of early design concepts of the Model S was 0.32,” says Rob Palin, Tesla’s Senior Manager, Aerodynamics. “The major shape changes reduced the drag to 0.27, and the smaller changes provided further improvement to 0.24. These numbers were validated with wind tunnel testing using standard SAE International procedures, and extended using CFD modeling to add in factors that are not traditionally included, due to practical limitations in experimental testing, but do contribute to the on-road drag of the car.”

There is no way to look at multidisciplinary aerodynamic, thermal and acoustic issues with the wind tunnel. This limitation leads to conflicts later in the design process which can drive poor design compromises, delays and cost overruns. In vehicle aerodynamics engineering, the most important metrics are drag coefficient and frontal area, according to Exa’s Golsch. But meeting the vehicle’s thermal management requirements is a task that is to some extent in conflict with aerodynamics requirements.

Thermal engineers are seeking “all the cooling they can get to meet design requirements, but meeting cooling requirements generally result in 10% of the car’s total drag,” Golsch explains. “The aerodynamicist has to figure out how to most efficiently get the air to the cooling package.” A third objective, aeroacoustics engineering to minimize interior noise experienced by the driver and passengers, is still done mostly through physical prototype testing conducted late in the development process, according to Golsch.

Digital simulation allows all these disciplines to be investigated not only individually but simultaneously, as they influence and interact with one another. This makes it possible to “design problems they could not with physical testing,” says Exa’s Alajbegovic. Engineers from different disciplines “can solve problems jointly, as opposed to aerodynamics and thermal requiring separate tests.”

In this way, digital simulation supports multidisciplinary optimization of vehicle designs in ways not possible with physical testing. Simulation can examine many variables simultaneously, balancing the tradeoffs between aerodynamic, thermal and acoustics performance, which are often in opposition to one another. Thermal management is frequently in conflict with aerodynamics, as the goal of aerodynamics is to reduce drag as much as possible while thermal management requires airflow inside the vehicle body to cool the engine. Simulation-based optimization helps the development team determine how to most efficiently get air to the systems under the hood that require cooling, while impacting aerodynamics to the smallest degree possible. Simulation also helps engineers understand the cause and effect of each force impacting the vehicle, and to solve multidisciplinary problems concurrently, overcoming the challenge of, for example, correcting an aerodynamic problem in a way that negatively impacts thermal or acoustic performance.

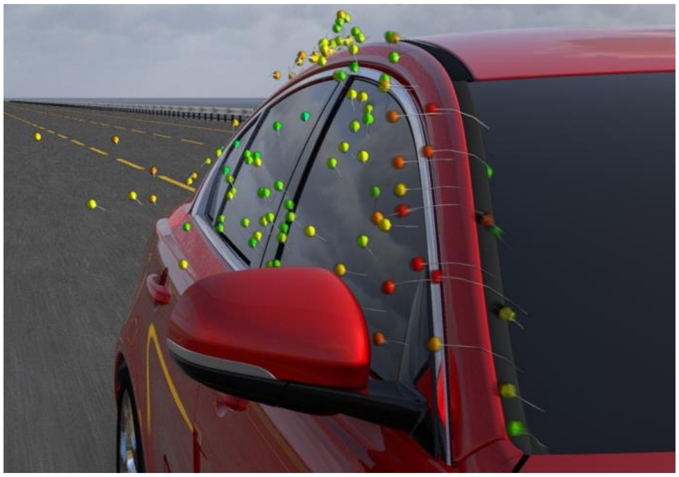
3. Studio designers and engineers need to collaborate early in the design process to evaluate the performance of their proposed designs

Design of a new vehicle begins with vehicle layout and packaging and the design studio which develops the vehicle’s shape and styling. This styling design is then transmitted to the aerodynamics, thermal and acoustic engineering teams, which must translate the styling design into an engineering design that meets all the various functional criteria. The vehicle design and development process typically includes multiple iterations of the design back and forth between the design studio and the engineering teams in order to achieve the engineers’ functional criterial while maintaining the design studio’s styling objectives.

In the absence of digital simulation, design changes required by the engineering sectors are communicated back to the design studio using engineering drawings and/or verbal or written guidance. But when design changes are communicated in this manner, the design studio is often unable to fully grasp the reasons why the changes are needed; as a result, they will often resist changes that they perceive as “compromising” their design from a styling perspective. For example, in physical testing, smoke wands may be used to help visualize the airflow field around a vehicle model, and images of the smoke flow will be used in communicating with the design studio. But this technique only shows airflow direction; it does not reveal details such as velocity or temperature. By contrast, simulation reveals those details, which can be key to helping the design studio understand why engineering needs the design studio to change its design.

"Use of simulation software helps with communication with the design studio," says Exa's Golsch. "They are not aerodynamics experts." With digital simulation, he says, engineering "can show them an image or movie of what's actually happening, and thus why you need to change a surface. This helps them understand through visualizations." By depicting air velocities and temperatures as color plots, simulation can serve as a rich communication tool between engineering and the design studio to visualize exactly what forces the vehicle will experience, and how this will affect its on-road performance.

Unlike physical test results, simulation results are readily integrated to photorealistic rendering software, providing a lifelike image of the vehicle with overlaid simulation results that greatly facilitate non-specialists in understanding the nature of the fluid flow and its impact on vehicle performance. Simulation results can likewise be viewed in 3D stereo with the proper graphics hardware and glasses, making the data that much more impactful. This can help designers to truly understand the impact of their design decisions and work closely with engineering teams to make the best tradeoffs.



Simulation-driven design takes place early in the design process when critical decisions must be made. Digital simulation allows real-world operating conditions to be modeled and analyzed early in the design process, when physical prototypes are unavailable or not sufficiently mature to be revealing, and powerful insights are derived to improve the design.

"Wind noise is an example," says an aerodynamics engineering executive at one automaker. Without simulation, "you do not know the performance until you have the full-vehicle prototype. In one project, the first time we tested a drivable car, we were shocked by the terrible result." The problem was wind noise related to the front fascia, the wheel and the tire. Without simulation, this problem could not be predicted until a full-vehicle prototype was available. "Changes at that late stage were difficult," the executive reports. "It cost a lot to change parts and tooling" to remedy the issue.

By providing a greater understanding of the performance of all aspects of an automobile design in realistic driving conditions, simulation decreases the need for late-stage design changes which can delay the schedule of a vehicle development program and add significant costs in the manufacturing process. For example, when wind noise is discovered during full-vehicle acoustic testing late in the design process, it is too late to redesign the shape of the vehicle body to correct this noise. Instead, engineers must find other ways to mitigate this noise, such as coated glass, in order to meet customer expectations and sell vehicles. The use of coated glass will solve the problem, but may cost $10 per unit, which results in millions of dollars in unanticipated costs during manufacturing, as well as a delay due to the change in components.

4. Working with wind tunnels and clay models is a very sequential process and not very fluid

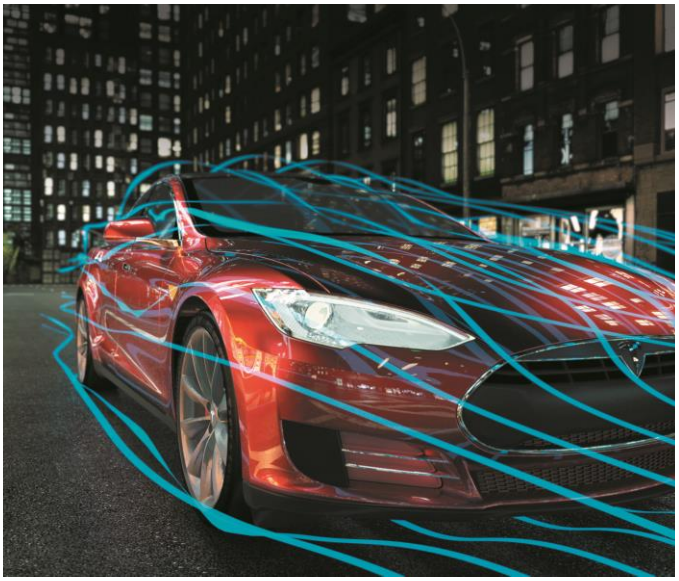
Physical tests have long lead times, thus identifying many issues too late in the design process, due to constrained availability of prototypes, test resources or both, whereas simulations are not constrained by these limitations. For example, “the cooling module is one of the longest lead-time items,” says Exa’s Golsch. “By the time a prototype of the cooling module is available, it’s sometimes too late to make changes—it would be way too expensive.” By comparison, a digital simulation model of the cooling system is available far sooner.

Acoustic testing has similar constraints. “Acoustic testing can only be done in certain wind tunnels, which are expensive,” Golsch says. “Wind tunnel operators often brag about how many data points they can collect in a day—they can do 24 runs in a typical shift, whereas it usually takes a CFD analyst two weeks to collect that many points. Of course, this time depends on the available computational resources. Some OEMs increased their computational resources to the point where they reduced this time to a day or even less. However, physical tests take weeks prior to the test for setup, then weeks afterward to analyze and examine what worked and what didn’t, and make changes accordingly. Whereas CFD takes those extra weeks and makes more progress through subsequent runs. Because of this, by using digital simulation you can cut development time in half, as well as reduce the number of people needed.” Golsch observes that automakers such as Tesla and others founded comparatively recently are especially reaping these benefits from simulation because they do not have the legacy constraints of personnel, existing wind tunnel facilities and the like that older companies do, and thus can use analysis more heavily and effectively.

Traditionally, with physical testing, some variables are not (or cannot be) tested without a full-scale prototype, which means some issues will be identified too late to make changes. For example, noise testing is not introduced until late in the process, at which point it may be too costly to modify the design to meet noise targets. In many cases, the solution to noise and cooling issues will require changes in tooling and the use of more expensive components in the production vehicle. In addition, such changes can result in millions of dollars in additional investment to modify the production line.

Single iterations of simulation and physical testing require similar amounts of time, but a large portion of the time required for physical testing is to set up the equipment and examine the results. Simulation, however, makes more progress during this time by executing subsequent runs to further refine the design process, necessitating a smaller number of iterations, and thus less time, to find the optimal design.

Digital simulation results in improved design quality. Simulations are developed based on imported CAD models, whose geometry can be manipulated more expediently and accurately than foam or clay models, much less sheet-metal prototypes. Digital morphing tools are available during the design process to create many individual designs with small differences between them, which can all be run through the simulation software to find the best possible solution. Additionally, various components of multiple models can be combined to form a single, improved model that can be tested using simulation software. For example, the front half of one vehicle can be combined with the back half of another vehicle, then simulated as a single item. Many iterations of CAE models can be created in a short time, then tested successively to determine the optimal selection of variables. By contrast, carrying out the same degree of iteration and design manipulation with physical prototypes would require significantly greater time and money.



Digital simulation facilitates always evaluating the most up-to-date model revision. "A big problem is keeping the prototype up to date with the current design of the vehicle," according to the Detroit automotive executive. "Parts are many times not up to date, invalidating the test results or causing tests to be delayed and repeated." Why is this? "It takes about four weeks to build a prototype and ship it to a wind tunnel," he explains. "But during this time, the design may already have been changed three times, meaning the model for validation is out of date. This is a big problem, especially in the early stages of design. With physical prototyping, the iteration rate is slow, and the models are not very representative of the current design." Because digital simulations can be run on the CAD model as it is developed, tests can always be run on the most up-to-date version of the design.

5. Wind tunnels, clay models and full physical prototypes are very costly

Wind tunnel testing of styling models and complete vehicle physical prototypes incurs very large costs. To begin, there is the cost of the wind tunnel itself. A full-scale aerodynamics wind tunnel constructed in 2002 cost one U.S. automaker $37.5 million, according to the Detroit automotive executive, and a scale-model wind tunnel built at the same site, for testing 3/10 or 4/10 scale models, cost $3.5 million. Meanwhile a thermal testing facility can cost $5 million. Then there are the costs of running the tests; each test in an aero-acoustic wind tunnel can cost $200 to more than $600, he says.

Added to these are the costs of fabricating physical models and prototypes. A typical clay scale model for testing in a wind tunnel costs on order of $75,000, he reports, while an aero-acoustic "buck," or partial vehicle prototype, can cost $300,000 and can require multiple expensive modifications to keep them up to date with the vehicle design. Complete vehicle prototypes cost even more—from $500,000 to $1 million each, according to Exa's Alajbegovic. A typical automotive OEM "burns through 20 to 200 cars with on-road testing before ever selling a car," according to Dr. Ed Tate, Exa's Director of System Modeling and Controls, "a good chunk of them dedicated to thermal effects."

The cost savings from supplanting physical testing with digital simulation are clear. First are the tens of millions to hundreds of millions of dollars saved in not having to construct and maintain wind tunnels. Then come the savings in not having to fabricate thousands of clay models, as many as 200 early-series validation "bucks," and two to three full-vehicle prototypes, says Alajbegovic.

Transition from wind tunnel testing to simulation offers typical automotive OEMs more than 500% ROI, according to new research[1] from Tufts University's Gordon Institute for engineering management. ROI of simulation-driven design was analyzed for three different cases:

Most Conservative	146%	(1.5X)
Most Likely	531%	(5.3X)
Most Inclusive	1209%	(12.1X)

Most Conservative—Automotive engineering organizations in this category already use simulation software extensively. They are not heavily invested in physical test infrastructure and do not use physical prototypes or tests in any instance where this is not mandatory. Thus, for these companies, ROI available from increasing the use of simulation and eliminating the few remaining prototypes and tests is comparatively low—even though an almost 150% ROI remains noteworthy and worthwhile.

Most Likely—The ROI calculation for this category is based on typical or average industry costs for prototyping, testing and simulation. While significant variation exists across the major automakers, this ROI measure approximates the industry average.

Most Inclusive—These automakers will see the greatest benefit from moving to simulation-driven design. They can avoid the investment costs for a new wind tunnel and its upkeep, they can use simulation software for design optimization to reduce part costs in high-volume models, and they can avoid costly late-stage changes that are likely in the absence of a robust simulation-based development process.

The ROI model evaluated the cost-benefit of deploying simulation software for aerodynamics, thermal management and aeroacoustics to replace the related physical prototypes and test procedures conventionally used for vehicle design, development, optimization and validation. The gain from investment is the cost of prototypes and tests that will no longer be incurred together with the additional gains or losses of using the simulation. The ROI formula used in the study was:

$$\text{ROI} = \frac{(\text{Cost of prototypes and tests} + \text{Additional gains or losses} - \text{Cost of simulation})}{\text{Cost of simulation}}$$

Cost of prototypes and tests consists of:

- *Cost of prototypes*—Cost of all the required prototypes built for aerodynamics, thermal and acoustics tests in the design and development process that will no longer be incurred upon transition to a fully digital design process.
- *Cost of tests*—Cost of all the required tests for aerodynamics/thermal/acoustics in the D&D process that will no longer be incurred upon transition to a fully digital design process. These tests can be either done in-house or outsourced.
- *Test facility investments*—Investments in in-house aerodynamics/thermal/acoustics test facilities, plus the costs to maintain and upgrade them.

For "Additional gains or losses" and "Cost of simulation" components, see Appendix at end of paper.

---

[1] Aly K., Costa A., Garreffi M., Yu H.; advisor Liggero S. 2015. *ROI Analysis of Simulation-Driven Design*. Medford, MA: Tufts Gordon Institute.

Conclusion

Transitioning the automobile design process from physical prototyping and wind tunnel testing to a simulation-driven approach will yield compelling competitive gains. While this is not something that can be accomplished in one giant leap, nonetheless automakers need to begin developing and implementing a plan to transition from test-dominated development to simulation-led design across the next five years. For example, according to Mark Stanton, Vehicle Engineering Director at Jaguar Land Rover, "We have an objective to achieve 100% of all our requirements robustly validated through virtual capability by the year 2020."

The business justification is well documented. First, the cost-benefit of digital simulation compared with wind tunnel testing is overmastering. New research proves that typical automotive OEMs can see more than 500% ROI by making this transition, while those OEMs that are most heavily invested in wind tunnels at present can see ROI as high as 1200%.

Beyond cost savings, digital simulation boosts automakers' competitiveness by improving design quality. Physical prototypes give feedback on how a design will perform, but simulation reveals the reasons why a design performs the way it does, and thus what changes will lead to a better design. Because of this inherent advantage over wind tunnel methods, digital simulation brings much more feedback about the design performance into each stage of vehicle development, improving the ability of engineers and studio designers to innovate in balancing design aesthetics with aerodynamics, as well as mastering the tradeoffs among aerodynamic, thermal and aero-acoustic performance targets.

This impact begins early in the design process, when models for physical testing are not yet available but critical design decisions must be made. Simulation models can be created and evaluated at the beginning of design, then easily updated and re-evaluated to keep pace with the rapidly moving design and development process. The result of better design decisions early is superior vehicle performance, fewer costly late-stage changes in designs and production processes, and minimized warranty expenses, liability exposure and product lifecycle costs.

Appendix: ROI components "Additional gains or losses" and "Cost of simulation"

Additional gains or losses consist of:

- *Design optimization*—With advanced simulation software, products can be optimized to reduce cost and improve performance. There have been many successful cases such as using aeroacoustics simulation to reach a low noise level without the laminated glasses originally required for this.
- *Late-stage changes*—These arise from issues with the design that are discovered during testing and must be corrected after the design is completed or nearing completion. Compared with simulation, the iteration cycle of building a prototype and sending it for testing is much longer; thus, late-stage changes are more likely to occur with physical testing. To preserve program schedule, late-stage changes usually come with high retooling costs and/or an increase in the cost of production parts.
- *Test deviation*—Factors such as manufacturing deviation, transportation damage, test repeatability and reproducibility all influence test outcomes. As a result, the actual number of prototypes built to verify product design is typically more than necessary.

- *Warranty costs (unquantifiable)*—If a problem is not found through testing, it may eventually lead to quality or safety problems after consumers have purchased the automobile. This leads to warranty problems resulting in repair or recall.
- *Styling feasibility (unquantifiable)*—Simulation at the early stage enables the designers to create styling themes more flexibly, compromising between the designs necessary to meet aero, thermal, and acoustic parameters with those that the styling team considers most attractive, and these designs will be more likely to attract customers.
- *Performance and perceived quality (unquantifiable)*—Better aerodynamic, thermal and acoustic performance will lead to increased customer satisfaction and will potentially attract more customers.
- *Effectiveness and efficiency in communication (unquantifiable)*—Clear, straightforward visualization of the simulation results can reduce misunderstanding and aid in communication across different functional teams. It can also reduce rework and design cycles.

Cost of simulation consists of:

- *Cost of licensing*—Cost based on the use of simulation software for aerodynamic/thermal/acoustics, measured in CPU hours.
- *Cost of computing power*—The accompanying costs for implementing the software, including the investment in IT infrastructure necessary to run the software.
- *Cost of training*—Training courses to teach engineers the tools needed to run the simulation software, and also to familiarize users with new features and software updates.

Ora Research investigates new technologies that improve innovation, quality and performance and reduce schedule, cost and risk in the engineering of manufactured products and built assets. We seek to identify technologies and attendant work processes that are yielding high return for initial adopters and are on the cusp of first-wave mainstream acceptance.

We aim to inform and guide professionals with fresh information about these technologies and their successful adoption and application. We offer research and advisory services to help engineering organizations evaluate, select and justify new technology investments, and to help technology providers qualify and quantify new market opportunities and validate demand drivers. Our goal is to foster insight and action to strengthen the industries we serve. www.oraresearch.com