

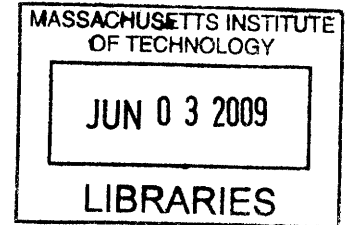
Value Proposition Development of Early Stage Computational Fluid
Dynamics Analysis in Automotive Product Development

by

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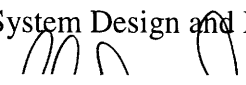
Submitted to the System Design and Management Program
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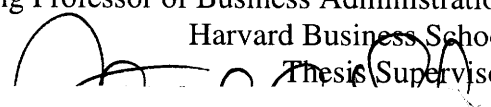
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ABSTRACT

Concurrent engineering initiatives and the closely related principle of front-loading development processes – identifying and solving problems early rather than waiting for traditional development and test processes to uncover them – have been shown to be highly effective in improving product development performance. This often means shifting to new experimentation technologies that can be used much earlier in the development process than traditional technologies, delivering performance assessments much faster. Thus problems within new design ideas are exposed much sooner, allowing for cost-effective problem solving techniques without having to rewind significant parts of the development process. Front-loading accelerates innovation by permitting new ideas to be tested and refined faster than traditional techniques, allowing them to be incorporated into products without the risks often associated with the use of unproven ideas. Traditional methods might still be needed for fine-tuning a design, but new rapid-feedback technologies have demonstrated their value when used within their limitations.

Front-loading has gained acceptance in many vehicle product development organizations, but one field in which it has not yet been introduced for early-stage design assessments and problem solving is air flow analysis. The earliest stages of design for a new vehicle focus largely on the shape and character of the vehicle's surfaces, which in turn have a significant influence on many aspects of the vehicle's performance. Thus the introduction of new experimentation technologies like Computational Fluid Dynamics (CFD) requires a great deal more consideration due to their impact on these critical early stages of product development, but the value of these methods and changes can be demonstrated. The resulting changes required in the development organization to support these methods – including preservation of important creative processes and a pragmatic view of the complexities of process change – are found to be complex but approachable given suitable motivation, realistic mindset and a holistic view.

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1 Introduction

In the last 20 years automotive companies have been forced to make significant changes in their product development processes to shorten development times, reduce non-recurring engineering costs, and improve product performance for new car models. Changes in customer preferences and new regulatory and market pressures have meant that five- and six-year development timelines that had been common into the 1980s are no longer sufficient to ensure a competitive position in the market. Competitive pressures have required constant improvements in product quality without substantial increases in price. In this environment leading companies have reduced their product development timelines to as little as three years, and under continued pressure they are still searching for new ways in which improvements can be made without sacrificing product quality or performance.

Several management practices and new technologies have been key enablers for these improvements. Concurrent engineering initiatives and the closely related principle of “front-loading” the development process (identifying and solving problems early), and the use of Computer-Aided Engineering (CAE) software have all been critical factors without which many of these improvements would not have been possible. Previously, much of automotive product development and testing was done sequentially, meaning significant design problems were not identified until late in the program when they were very costly or impossible to correct. Higher non-recurring engineering costs and missed product performance goals were typically the result. Now, many major sources of cost and schedule risk are identified as early as possible, and design and development teams work in parallel to ensure these risks are addressed early when designs are still flexible and changes can be made without the need to significantly rewind the development process and incur the related costs. Expensive physical prototypes, which had previously been required to identify and assess such problems, are generally not available in these early phases of product development, so CAE tools have been crucial in identifying and resolving many major problems without prototypes. Virtual decking (where component interference problems are identified and solved) and crash worthiness testing through

computer simulation are two examples of major product development areas where CAE tools have enabled solutions much earlier in the development process.

One important aspect of the automotive development process which still has potential to yield significant development performance gains from early-stage problem identification and resolution is that of aerodynamic analysis. The aerodynamic performance of a ground transportation vehicle is often connected directly to traits that govern its engineering and commercial success. Fuel mileage, handling, safety, noise levels, and reliability all depend heavily on the design's interactions with the highly complex flow of air around the vehicle and through its subsystems. Yet today, aerodynamic analyses – including aeroacoustic and thermal management assessments – are typically done late in the automotive design process in relation to other analyses that are also critical to final product performance such as crash simulation. Prevailing automotive development paradigms hold that aerodynamic analyses are performed after much of the styling process has been completed, when it is very expensive or impossible to change designs based on the results of computer simulations and experiments.

Computational Fluid Dynamics (CFD) technologies now exist that could be used early in the design process. As with other simulation technologies, CFD solutions may not provide the same level of fidelity as some traditional evaluation techniques. But when used in the early phases of product development and combined with traditional techniques in later phases, such technologies can provide important information at a time when it can still be considered in important design decisions, thereby improving performance of the product development organization (either by saving time or reducing costs), improving product performance, or both. This thesis evaluates how CFD technologies could be used and looks at major barriers to their adoption. It discusses changes needed in both automotive product development processes and in the capabilities of CFD software to enable use of CFD in the early phases of automotive design, and how these changes can be achieved given the pragmatic considerations of complex large-scale product development systems.

To explore these issues, we first compare and contrast CFD analysis with another tool, crash simulation, which has been incorporated successfully into the early stages of

automotive development. In Chapter 2 we provide a general description of prevailing automotive development processes in place today, to provide background and context for the discussions that follow. In Chapter 3 we discuss the opportunities and value which could be created when these new problem-solving methods, which are often useful much earlier in the process but do not offer 100% of the fidelity of more traditional methods, are employed very early in the product development process.

In Chapter 4 we apply these concepts to aerodynamic performance assessments performed at automotive companies. The systemic nature of air flow problems in automotive design is discussed, and requirements for CFD software for use in the early phases of automotive design are detailed. Based on this information, in Chapter 5 we explore the practical realities of changing the development process to use new problem solving technologies, and approaches to overcoming these obstacles are explored. We end with a brief conclusion summarizing the findings of the thesis.

1.1 Crash Simulation vs. CFD Simulation

Before discussing the details of the automotive development process and air flow analysis, we review the impressive changes that have taken place in the last 20 years with the introduction of crash simulation software into the automotive design process. A number of useful similarities and differences can then be observed between crash simulation and CFD simulation, which provide insights for the discussions that follow.

Crash worthiness is a vital quality attribute of a vehicle. Strict government test regulations, high-profile press reports regarding safety problems, and increasingly public safety information have a strong impact on quality perceptions and vehicle sales, giving car makers little choice but to ensure their products will protect passengers as much as possible in the event of a crash. Until the early 1990s, crash worthiness testing required a large number of expensive physical tests. Crash tests could not be conducted until structural prototypes were available, perhaps half way through the development process. These prototypes were built, instrumented and destroyed in crash tests recorded by high-speed cameras. If any problems were found – and problems are always found with new designs – engineers analyzed the video footage, proposed solutions, and new prototypes had to be built and crashed to test the solutions.

The introduction of crash simulation software in the 1990s significantly reduced the cost of crash worthiness testing for companies that leveraged its capabilities effectively. Some companies now mandate crash simulation of proposed designs before allowing those designs to proceed into detailed engineering, and in some cases simulation has all but replaced physical prototype crashing except for late-stage verification and government-mandated tests. The introduction of this technology has been aided by many factors:

- Crash worthiness is critical to a company's ability to market and sell the vehicle. Selling an unsafe car is not an option, so any major problems must be solved no matter how late it is found or how expensive it is to fix.
- Traditional testing and problem solving methods are very expensive for crash worthiness. Since crash simulation does not require structural prototypes, it can be done much sooner. Since it can be done quickly on large computers, many more tests can be run to test solutions.
- Design changes that result from crash worthiness improvements tend to have a relatively weak effect on the exterior shape of the vehicle since designers already work within packaging and general proportion constraints. Thus crash simulation can be done in parallel with other early design tasks with only minor impact on the behavior of teams involved in those tasks.
- Crash simulation technologies provide insight into failure modes that are not shown in physical tests, since failures occur in areas hidden from video cameras. With this knowledge new design alternatives can be proposed and tested quickly with new simulations.

Taken together, these factors provide a very compelling argument for using crash simulation technologies early in the development process. Cost of implementation is relatively low, and the benefits are significant. CFD analysis shares some of these benefits, but it is different from crash simulation in several important ways:

- Most changes designed to improve air flow around a car have a strong effect on the exterior shape of the car or the design intent. Thus air flow improvements

usually affect work done by the vehicle's designers, making coordination with designers and the associated process changes a key requirement of introducing CFD analysis to the early-stage design process. CFD techniques cannot be done in parallel with other design tasks because the changes that would result from them may well have a significant impact on the behavior of other teams involved in early-stage design tasks.

- Although some aspects of air flow around a vehicle are important to the customer's perception of quality, the connection to the company's ability to market and sell the vehicle is relatively weak. Increasingly strict government regulations and fluctuating energy prices are increasing the importance of aerodynamic performance, but it has not yet reached the same level of awareness as crash worthiness.

This comparison shows an important difference in the requirements associated with introducing these technologies into the early phases of automotive development: because CFD introduces the need for a more significant behavioral (process) change, a much higher threshold must be met in order to justify its use. A compelling case has been made for the use crash simulation due to its high impact and relatively low requirement for behavioral changes, but this threshold has not yet been reached for CFD analysis. The need to overcome such barriers is illustrated by Gourville, who explains that a high-impact product is much easier to deploy if it requires only small behavior changes in the development organization. If significant behavior change is required, a longer-term deployment plan is needed [7]. As shown in Figure 1-1, both Crash Simulation and CFD require a high degree of product change, but only CFD also requires a high degree of behavior change.

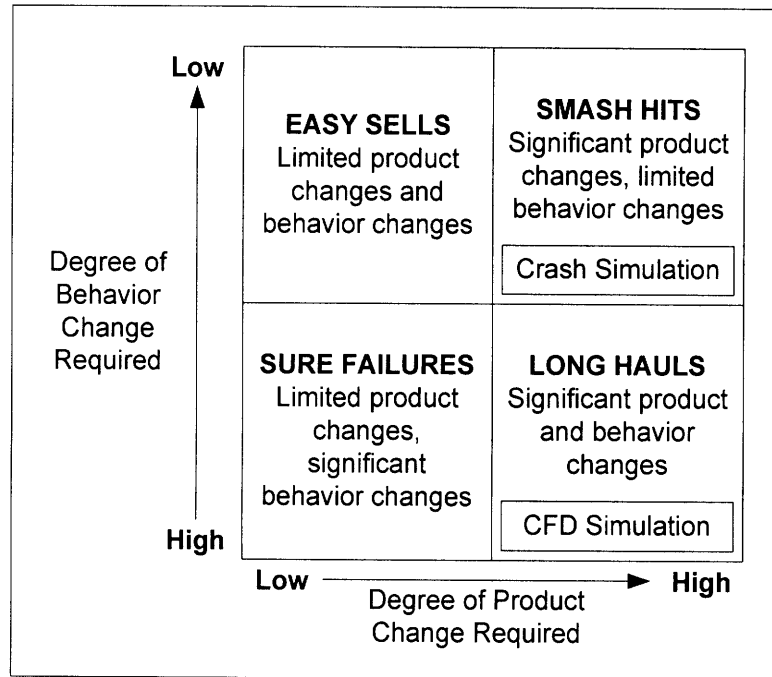


Figure 1-1: Capturing value from innovations
 Adapted from Gourville, "Eager Sellers and Stony Buyers", Harvard Business Review [7].

2 Aerodynamic Analysis in the Automotive Product Development Process

The development of an automobile is a highly complex process. Aside from inherent complexity in the final product due to a large number of diverse subsystems and components, vehicle development is heavily constrained by customer preferences, government regulations, organizational capabilities, competitors' products, maintenance requirements, budgets, and the physical laws of nature. Between the launch of a new vehicle program and the completion of the last car to roll off the assembly line several years later, an enormous number of problems will be solved within these constraints. These problems cover a wide range of fields and expertise: defining targets for product attributes such as fuel efficiency, handling characteristics, seating capacity, and noise levels to position the product favorably in the market; choosing the most appealing designs for all customer-visible features; developing each of the vehicle's systems to deliver their slice of functionality; etc. Many of these problems must also be addressed for each subsystem in a cascade that gets progressively finer in detail until each component of the vehicle has been defined, manufactured, delivered, assembled, and supported throughout its life cycle.

This chapter presents a brief generalization of the automotive product development process as it relates to aerodynamic analysis, along with a number of typical problems that arise throughout the process. This description is distilled from several sources, including Thomke [19, 21], Thomke and Fujimoto [22], and interviews with a number of current and former employees from four auto development companies. Note that although the major elements outlined in this description are present in each company's development process, the specific execution of the process can be quite different.

These differences include, for example:

- the amount of overlap between phases
- the level of involvement of key stakeholders in earlier phases of the process
- the level of flexibility in revising the details established in a phase once that phase has been completed

These differences are highlighted, especially where they have a significant impact on communication and problem-solving processes.

2.1 A Brief Overview of Air Flow/Design Interaction

There are three key categories of air flow interactions with a car's design:

- aerodynamics
- aeroacoustics
- thermal management

Although these categories share some common attributes, each of them has different drivers, requires different levels of expertise to address, and is generally handled by a different part of the development organization. They are described separately here to examine their differing roles and influences, and to serve as a basis for the discussions that follow. Note that some types of air flow assessments, such as “internal” flows seen in ducting systems, are not included in these categories. These other areas involve still different drivers and areas of expertise, and are managed by different development teams within the organization. We focus on the three categories above since they are sufficient to inform our discussion within the context of early-stage automotive development.

Aerodynamics

When most people think about air flow around a moving object, aerodynamics is what they are thinking of. An object displaces air as it moves, and in the process complex patterns of air movement are created. The interactions of the object with the air, the resulting motion of air, and the forces imposed by the air on the object all fall under the umbrella of aerodynamics.

The shape of a vehicle defines its aerodynamic qualities. Thus decisions that establish that shape, which generally take place in the earliest phases of automotive design, have a direct impact on all of the performance attributes affected by aerodynamics. A partial list of these performance attributes includes:

- The vehicle's drag, which has a strong influence on its fuel efficiency and acceleration performance. Drag is a direct result of how aerodynamic forces are distributed on a vehicle's forward- and backward-facing surfaces.
- The vehicle's lift, which has a strong influence on its handling and stability, especially at high speeds.
- Soiling: the tendency of water, mud, and snow to accumulate on windows, air intakes, or other areas where such foreign materials can result in quality or maintenance problems.

A number of driving conditions must also be considered, in particular driving speeds ranging from idle to the vehicle's maximum speed and wind conditions ranging from quiescent to strong side winds.

Targets relating to some of these performance attributes are assigned at the beginning of the vehicle program. In particular, a target for fuel efficiency is established early, often as part of a company's requirement to meet government-mandated fleet targets. Handling characteristics are typically a cornerstone attribute for the car's target market. Meeting these targets is a complex process that relies heavily on the vehicle's aerodynamics and subsystems, including its power train, suspension, and chassis.

Aerodynamics also has a direct relationship to many other key engineering activities. For example forces acting on the hood, doors and body panels determine how these components must be designed and attached to limit deformation. One interview subject relayed a story where late in the design of a car, testers found that when driving at high speeds, forces acting on the door caused the door to deform so much that it separated from seals designed to isolate the cabin from outside air flow and noise. The resulting "red alert," as he put it, resulted in design changes which, although they were minor, were still costly due to the late stage in which they had to be implemented and the increase in materials costs of every vehicle built over its production lifetime.

Aeroacoustics

Aeroacoustics is a specialized area of Noise, Vibration and Harshness (NVH), a department responsible for ensuring that a vehicle's occupants do not experience

excessive amounts of noise or vibration while in a car. Undesirable noise and vibration are generally perceived by occupants as signs of poor vehicle quality, and excessive wind noise is one of the most frequent consumer complaints in the highly influential J.D. Power and Associates initial quality survey [9]. Special attention is normally given to noise and vibration experienced by the car's owner, who is usually assumed to be the driver but who in some cases may also be in the rear seat, as in some high-end models.

The “acoustic package” of a car is established early in its development and provides a general description of the auditory experience of a car's occupants. In many cases this means providing an environment that is as quiet as possible, although for some vehicles – in particular high-performance vehicles marketed to driving enthusiasts – special attention is given to tuning the sound of the engine and exhaust system to appeal to those drivers. Sound and noise from many sources must be accounted for in developing the car's acoustic package, including the engine, exhaust, ambient noise (e.g., traffic), tires, fans, and noise generated by the rush of air over the car. Broadly speaking, aeroacoustics deals with identifying noise sources caused by the flow of air over the vehicle, and propagation of sound – whatever the source – through air and into the passenger compartment. Sound generated by the movement of air over a car is normally subdivided into two types, since the basic physical phenomena and problem-solving expertise can be quite different:

- “Wind noise” generally refers to sound created by any rapidly-oscillating flow patterns caused by interaction of the air with the moving vehicle's surface. Due to the complexities of turbulent air flow, such oscillating flow patterns can be created in many ways even by simple shapes. For shapes with complex curvature, small gaps between surfaces (as between the door and front fender), and appendages like side mirrors, these oscillatory flow patterns are nearly impossible to entirely avoid.
- “Buffeting” is primarily related to open windows and sunroofs. Here, oscillations in air flow patterns interact with an opening of the passenger cabin. At certain frequencies these oscillations will resonate within the cabin, creating a loud and sometimes painful noise. This mechanism is identical to Helmholtz resonance,

which is often heard when blowing on the top of an empty bottle. An example of such a problem on a real vehicle is described later in Section 4.1.1.

Once noise sources have been identified, assessing the impact of that noise source on an occupant's ear requires assessing the propagation of sound through air and vehicle structures. Then, depending on the actual sound experienced by the driver and the vehicle's targets, measures might be taken to moderate the noise heard by the driver. These measures might include modifying the shape of the vehicle's surfaces to reduce noise generation or adding expensive parts – commonly special door seals and laminated window glass – to reduce transmission of noise into the cabin.

Because of the complexity involved with the physics of turbulent air flow and the propagation of sound, aeroacoustics typically requires a very high level of training and expertise. Currently, such work is done primarily by specialized experts who have Ph.D.'s in related fields.

Thermal Management

The design and engineering of a vehicle includes a number of critical thermal management issues that must be addressed:

- Heat generated by the engine must be dissipated. Coolant is streamed through the engine to absorb heat, then run through a radiator where the heat is dissipated into air that is also passing through the radiator.
- Hot combustion products from the engine must be channeled through the exhaust system. This system, consisting of a series of tubes and emission control devices, ejects those gases through the exhaust pipe, and has components which commonly reach several hundred degrees Celsius.
- The environmental controls require distribution of warm and cold air into the passenger cabin. These controls generally use heat from the engine for warm air, and cool air is provided by an air conditioner, including a heat-releasing condenser, typically placed in front of the radiator.
- Air that enters the engine compartment through the grille or other openings typically runs through the condenser, radiator, and other heat exchangers (oil

coolers, etc.). It might then pass over hot engine and exhaust components, absorbing more heat. As this hot air propagates, it will in turn heat any other components it comes into contact with, including plastics, electronics, fuel lines, fluid reservoirs, etc. Such components must either be designed to withstand such temperatures or be kept cool, perhaps by isolating them from the hot air.

- A vehicle's brakes typically use friction to slow a vehicle, which convert all of the car's kinetic energy into thermal energy. Most of this thermal energy is absorbed by brake disks, which must then be cooled quickly to insure proper operation in demanding environments.

Finally, all of these factors must be considered for each combination of engine and vehicle configuration, which may number in the tens, over an extremely challenging range of driving conditions:

- Ambient temperatures ranging from very cold (e.g., polar latitudes during winter) to very hot (equatorial latitudes during summer)
- Driving speeds ranging from idle to the car's maximum speed (e.g., on the Autobahn in Germany)
- Driving loads ranging from long, steep declines (challenging for heat dissipation from brakes) to long, steep inclines while pulling a trailer (challenging for heat dissipation from engine and exhaust)

In nearly all of these situations, all of this heat must be dispersed into air in such a way that the heated air does not itself cause problems. Although there are exceptions (thermal radiation can play a significant role in cooling very hot exhaust and brake components), proper management of air flow through the engine compartment and around other components is critical to ensuring a vehicle's robustness and safety.

Thermal management has one critical factor that distinguishes it from aerodynamics and aeroacoustics: failure to account for it thoroughly in the development of a vehicle is a major source of risk for development cost, warranty cost, and safety. While aerodynamics and aeroacoustics targets are relatively "soft," missing thermal management targets,

which may involved overheating and component or system failure, frequently requires costly late-stage design changes, maintenance costs, and recalls.

2.2 Development Process Overview

In general, the phases of the product development process common to most auto manufacturers are Product Selection, Concept Development, Engineering, and Production, as shown in Figure 2-1. Within and between these phases, the details of a product are refined. This refinement continues at some level through to the end of the product's production. Even after a vehicle has been in production for some time, changes might be made in the manufacturing facility in an effort to reduce costs and improve quality. As we will see, some of these changes can effectively override important design decisions made earlier in vehicle development and have a significant impact on product performance.

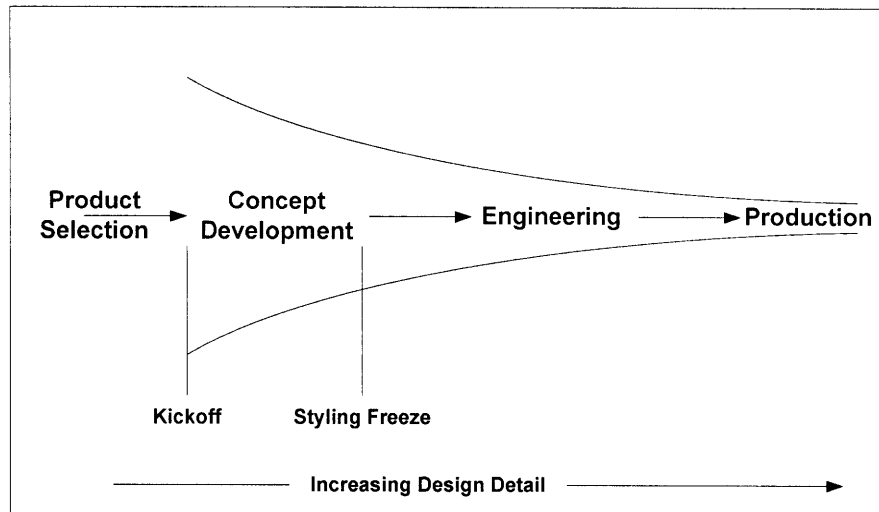


Figure 2-1: Generalized Product Development Process

For our purposes we will focus on development phases in which important design decisions are made. The Product Selection phase is primarily a marketing activity and involves review of corporate strategy and selection of a target market for a new vehicle. It is not discussed here as it is outside the scope of this study and it defines the constraints within which the remaining product development process functions.

Although the phases are described separately below, in practice there will generally be some amount of overlap, especially in companies that have implemented concurrent engineering initiatives. The degree of actual overlap between these phases has a significant impact on performance of the teams involved, which we shall discuss in later sections.

2.2.1 Concept Development

In Concept Development corporate strategy and goals are translated into a specific product concept or concepts to be developed in later phases. Starting from a high-level view of the target market and product goals, a design studio prepares 10-20 concepts for a vehicle that are expected to satisfy those goals. The range of concepts is deliberately planned to provide a wide variation of styles. Some will be incremental improvements on existing models while others focus on entirely new shapes and ideas. Over time a competitive process is used to refine the initial set of concepts and narrow the design options to a few popular “themes.” After another round of assessments and refinements, a winning theme is then selected, minor changes are made, and the surface is “frozen.” This process is illustrated in Figure 2-2.

A notable exception to this process of narrowing design ideas down to a single “winning” concept is Toyota, which has been described as deferring final styling decisions until as late as the 2nd full-vehicle prototype [16], long after the concept development phase has ended in other companies. This characteristic is also present in other phases: in general there is a great deal more overlap and interaction between phases at Toyota relative to its competitors.

Clay models are the first prototypes created in the development process and play an important role in the design selection process. As noted in 2002 by Chris Bangle, Head of Worldwide Design at BMW, “Every car you see out there was sculpted by hand. ... [Machines] reproduce it, but the originals are all done by hand.”[3] Although more digital design tools are used now than in 2002, the main elements of the process remain similar. In the earliest stages of product development most design proposals and discussions focus on sketches, drawings and paintings created by designers. Many of these are eliminated early and are never evaluated for their engineering, performance, or manufacturing

viability. Small-scale clay models are created for several promising concepts to provide a tangible basis for collecting feedback, after which several more concepts are eliminated.

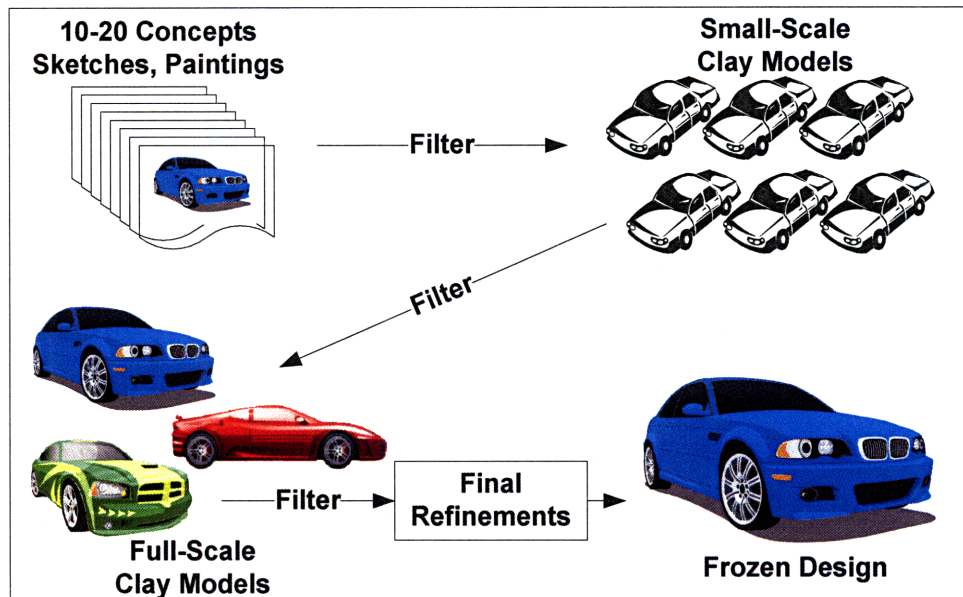


Figure 2-2: Concept Development Selection Process

After another round of refinements full-scale clay models are created for the surviving candidates and painted so realistically that “an inexperienced observer could not tell a finished 1:1 clay model from a real car.”[21] These are used as the basis for a final series of refinements before a winning concept is chosen. At this point the surface is “frozen.” Construction of a full-scale clay model may cost up to US\$200,000 and typically takes a month to build. Several such models are generally required during this phase. If the model is to be used for aerodynamic testing in a wind tunnel, the addition of realistic underhood geometry may increase costs to \$500,000.

Concept Development is focused primarily on the aesthetic or emotional appeal of the design, reflecting a belief that the auto industry is in some important ways a fashion industry with complex performance attributes. Designers and senior management are most interested in the appeal of the car to the target market. Engineering information is used in the evaluation process of proposed concepts to the extent to which it is available, but the availability of engineering information varies widely among auto makers and areas of expertise. For example some auto makers now require results from crash

simulations to be available as part of the concept selection process, before the surface of the vehicle can be frozen. Since crash worthiness is now a highly regulated and visible feature of the final product, establishing the safety of a design early is critical to avoid rewinding the development process and making changes to improve passenger protection. This is a key example of “front-loading” the development effort, which we will explore in more detail in Chapter 3. Other types of engineering information, including the interaction of proposed designs with the air flow around the vehicle and through its subsystems, are not as readily available in this phase.

2.2.2 Engineering

In the Engineering phase goals and the chosen concept for a vehicle are evaluated and developed into a completed product design. This phase is often split into “Advanced Engineering,” which works more closely with designers and focuses on system-level design issues, and “Product Engineering,” which focuses on component-level design.

Freezing a design means that the customer-visible surfaces of the car may no longer be changed, initially because those surfaces are the result of a lengthy design process that is costly to rewind, and later because other resource and tooling commitments proceed assuming those surfaces are not changing. These surfaces are produced by stamping presses that cost tens to hundreds of millions of dollars and two or three years to build. They can handle small changes, but changes more than a few millimeters require the process to be restarted, incurring new costs for rush orders to make up for lost time. Thus once the surface of a design is frozen, any problems found in the Engineering phase must generally be solved without changing the customer-visible surfaces of the car, though the extent to which this rule applies varies between companies. In the words of one interview subject, “Once the surface is frozen, it takes an act of God to change it.” Others commented that changes are very difficult after the surface freeze, but that divine intervention is not always necessary. Such high barriers for altering parts of the design once it has been frozen further constrain an already challenging problem to be solved by engineers, and can add significant cost as problems must often be solved by adding parts that might otherwise not have been necessary.

A common example of a part that must be added or modified to resolve problems found in the Engineering phase of development is laminated glass. This expensive variation of the glass in a vehicle's doors reduces the transmission of wind noise into the passenger compartment. Complex interactions between the shape of a vehicle and air flowing over that shape often result in vortices that generate noise. This noise can penetrate the cabin through windows, door seals and other seams unless measures are taken to reduce or eliminate it. Since wind noise is one of the most frequent consumer complaints in quality surveys, car makers look closely at the tradeoff between added cost and reduced noise. Reducing this noise may mean making small changes in the shape of exterior surfaces, or adding laminated glass and special-purpose seals to a door to attenuate the noise. Such problems are rarely understood well enough to influence a design before it is frozen, so adding parts or sacrificing cabin noise targets are often the only options available to engineers. Even minor changes are disallowed, as illustrated by one former Noise, Vibration and Harshness engineering manager, who described a situation where making a two millimeter change in the radius of the A-pillar (the structural member between the windshield and the front door) was needed to reduce noise levels in the cabin by two decibels. The change was rejected because it was already too late: too much work had already been done to change the design, and tooling commitments had already been made.

Structural prototypes are built during the Engineering phase. These functional prototypes represent the actual structure of the evolving design, as opposed to early clay prototypes which can be used only for assessing the exterior surface shape. At a cost that can exceed \$1 million for a prototype, these models are an important step in the verification and testing of the design. Prototypes are typically built in at least two stages, with later stages reflecting a more mature state of the design. In most companies all prototypes must be destroyed soon after mass production of the vehicle has begun. Thus any costs not recovered by exposing problems through testing on a prototype before production begins are not recoverable.

2.2.3 Production

In Production the necessary tools, supply networks, assembly procedures, and other factors required to mass-produce the final design are completed. Actual production of the vehicle begins, and generally continues with only minor changes for three to five years, depending on the model. The transition from Engineering to Production is a stressful part of the development process during which many problems are identified, investigated, and corrected. Final prototypes are built and undergo extensive testing, in the course of which many of these problems are found. Changing existing parts of the design is nearly impossible at this stage due to the very high associated costs of changing tooling and related parts, so most problems must be addressed by adding parts to the final assembly.

As mentioned previously, changes to a vehicle's design do not end after it has transitioned to production. New solutions to problems relating to part and assembly costs are constantly being investigated, sometimes with unintended consequences on performance. An interview subject who until 2008 was a vehicle NVH manager at a major auto company described a typical example where a door seal was modified long after a vehicle production run had begun. The modification was motivated by cost reductions, since it required a simpler process during assembly. It was tested at the plant, but testing focused primarily on the effort required to close the door, an important measure of the seal's design and an easily measured quantity at the plant. The impact of the design change was not evaluated for its impact on wind noise transmission into the cabin. It was not until customer complaints increased that a problem with the change was found and its source identified.

2.3 Prototypes

Although CAE tools have reduced or eliminated the reliance on prototype testing for some things, prototypes remain important for identifying, understanding and solving issues that arise in the design and engineering of vehicles. With respect to air flow in particular, prototype testing is important for aerodynamics and is critical for aeroacoustics and thermal management.

There are generally two types of prototypes used during the development process: clay prototypes made during concept development and the early phases of engineering,

and structural prototypes made during the engineering phase. (Figure 2-3) Clay prototypes can be used for limited aerodynamics testing, but since they do not yet have many important subsystems the fidelity of these tests is not high. They generally cannot be used for aeroacoustics or thermal management testing due to missing subsystems and dependence on physical properties of the materials used in a production vehicle.

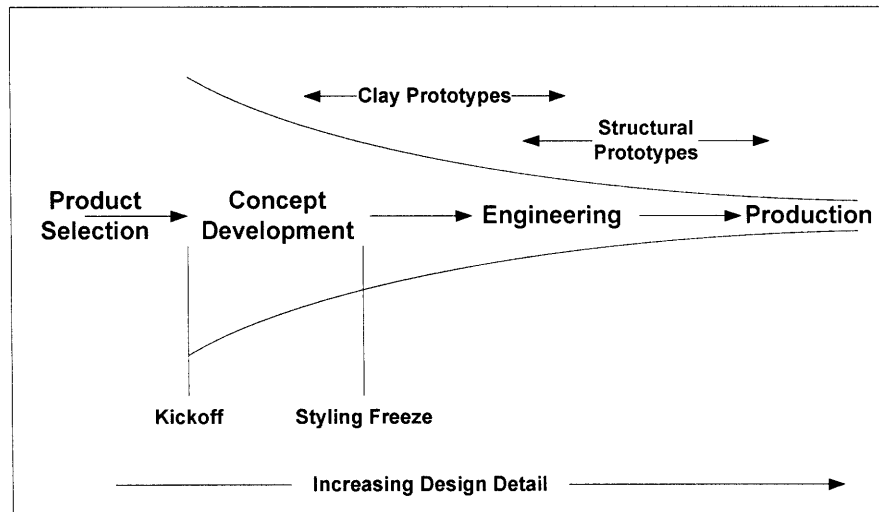


Figure 2-3: Prototype availability

Structural prototypes, as mentioned previously, are built by hand to reflect the “current” state of the vehicle’s design at the time they are built. They are frequently used for a variety of air flow experiments. In some cases design information might not be available for some subsystems, so a certain amount of improvisation – most commonly substituting components from an earlier model of the vehicle – takes place.

Prototype testing is not always a reliable or predictive problem-solving experience. The fidelity with which prototypes represent actual production vehicles is often questioned due to several factors:

- They are hand-built. The process of assembling a vehicle by hand differs significantly from the process used in a factory. In particular, if two parts must be positioned relative to one another with a very small margin for error in order to prevent a problem, a hand-built prototype will likely reflect this attention while production vehicles may not.

- When information is not yet available for a component, substitute components might be used, or the component may be excluded entirely.
- The design is evolving even as the prototype is being built. As a result, by the time the prototype is completed some of its value as a basis for experiments has been lost.
- Details of a design might not be reflected in the prototype, or subtle changes will be made for purposes of building or testing the model that are not believed to affect performance, when in reality they may have a significant impact. Since such changes are often not documented, their effect is not understood until much later, when higher-fidelity prototypes or preproduction vehicles are tested.

Because of these factors engineers know that the prototype is not a production vehicle and may not consider problems observed with the prototype to be “real.” Two interview subjects involved with wind noise described situations in which a problem was observed with a prototype, but since “the prototype is not representative,” and since a highly intricate physical mechanism dependent on fine details of the car’s construction was required to cause the problem, the observer did not feel it would be an issue in production vehicles with their associated subtle changes. In both cases the observation was wrong. One of these interview subjects said this was not an isolated incident and quoted a senior manager as saying “nothing happens only once,” meaning if a problem is found and not solved, it will return. Conversely, experienced engineers know that some problems truly are specific to the prototype and will not be found in production, and fixing all of them is also an expensive and time consuming process.

The issue of engineering confidence in the fidelity of a prototype has profound implications for the engineering design process, especially for a highly complicated physical phenomenon like air flow that does not lend itself to intuitive insight. Since the genesis of many such problems requires subtle interactions between many components, they are difficult to measure and more difficult to unravel into root causes, especially with conventional experimental measurement tools. Similar to crash analysis, where simulation technologies provide the ability to look deep inside a problem that video

recordings of prototype crashes might not show, CFD technologies expose information which makes such analyses and a higher level of understanding possible.

A final complication with prototypes is that they often appear too late to enable cost-effective solutions to the problems that they expose. For structural prototypes in particular, many key design attributes might already have reached a level of maturity that changing them is too costly. This was emphasized by the head of vehicle integration at a major American auto maker who noted, “There’s nothing worse than looking at a lousy prototype and knowing that there’s not a thing I can do about it.”

2.4 Summary

The successful development of a vehicle requires establishing an aesthetically appealing design for its shape and developing, among many other things, a number of systems that involve complicated interactions with the air flowing around the vehicle and its components. The development process that has evolved for most car makers can be broadly considered as consisting of three overlapping phases: Concept Development, Engineering and Production. Through these phases the requirements of aesthetic appeal and product performance are reconciled with each other, normally by establishing general physical appearance during Concept Development, then identifying and solving problems relating to air flow in the Engineering phase, often through prototype testing.

This process appears to leave a lot of value creation potential on the table. By deferring many key problem solving processes until long after many problems are introduced, solving these problems becomes much more expensive than it might otherwise be. In Chapter 3 we explore ways in which front-loading the development process can accelerate innovation and product development by using new experimental technologies to identify and solve problems much earlier than is often possible with traditional technologies. We then return in Chapter 4 to see how application of these methods to air flow analysis might be applied in the automotive product development process.

3 Value of Front-Loading Problem-Solving

Product development is primarily a problem-solving process. While developing a vehicle, problems must be solved that require a wide range of talents from marketing, art and design, many fields of engineering, and so on. The information required to solve these problems is rarely available from the outset, and many of the problems are uncovered only as the development process unfolds.

In *Experimentation Matters*, Stefan Thomke shows that the ways in which an organization goes about solving such complex problems through experimentation can strongly affect the performance of the development organization [21]. He highlights a number of factors that contribute to improved Research and Development (R&D) performance, in particular by focusing on the positive impact experimentation has on learning in the development organization.

Within and between development phases, product details are refined. In many cases this creates a paradox: early refinements are done with less information about downstream development requirements and product performance consequences, but they often have far-reaching implications for both. This well-documented phenomenon [21,25] emphasizes the value of early information and is a primary motivation for many systems and concurrent engineering initiatives. In this chapter, which draws heavily on work from Thomke[21] and Terwiesch, Loch, DeMeyer [11], we explore the nature of these effects and begin to examine how they affect aerodynamics analysis in the automotive product development process.

3.1 Experimentation and Knowledge Creation

Experiments are designed to fill gaps in knowledge. If a problem is posed for which solutions are not readily available, an experimental program is typically planned to understand the principles at work and ultimately provide a solution. Consider for example the problem of determining the look of a new vehicle. What should the vehicle look like and what attributes should it have to be visually appealing to the target market, conformant to government regulations, within the organizational capabilities to cost-effectively develop and manufacture, etc.? It simply is not possible to provide a useful

answer to this question. Too many parameters are in play, some tangible and many intangible. In this case, a large-scale experimental program involving designers and other experts steeped in the traditions of artistic expression and car design must be conducted to explore the available options and choose a design. This is the primary purpose of the Concept Development phase described in Section 2.2.1.

Experiments are useful only if they provide results in a timely and cost effective manner. If experimental results cannot be obtained quickly enough, the development organization has three key options:

- It can defer decisions until necessary experiments can be conducted and evaluated.
- It can make decisions based on whatever information is available, and schedule verification tests – another kind of experiment – for a later date.
- It can alter experimentation techniques to provide faster feedback.

The first two options have important cost and risk ramifications. Deferring decisions is often not an option, since existing experimental technologies may take weeks or months to complete and decisions may be required within hours or days during critical stages of development. Making decisions based on incomplete information implies that the risk of a poor decision is not eliminated. Studies show that in automotive development the cost of correcting a problem increases by a factor as high as ten for each development phase downstream of where the problem is introduced [18]. (Figure 3-1)

When risks associated with design decisions are recognized early these costs can be managed through parallelization in the design process, assuming the costs of keeping multiple design options open are not too high [16]. If those costs are too high, new experimentation technologies capable of providing earlier and faster feedback, if they are available, appear to be a natural choice for informing early-stage design decisions. But introducing such technologies often has its own challenges. In automotive development, traditional methods are typically based on physical tests of prototypes and as such are assumed to provide only highly accurate test information (an assumption we will revisit

later). New rapid-feedback technologies generally take the form of software that implements mathematical models of the physical effects being investigated.

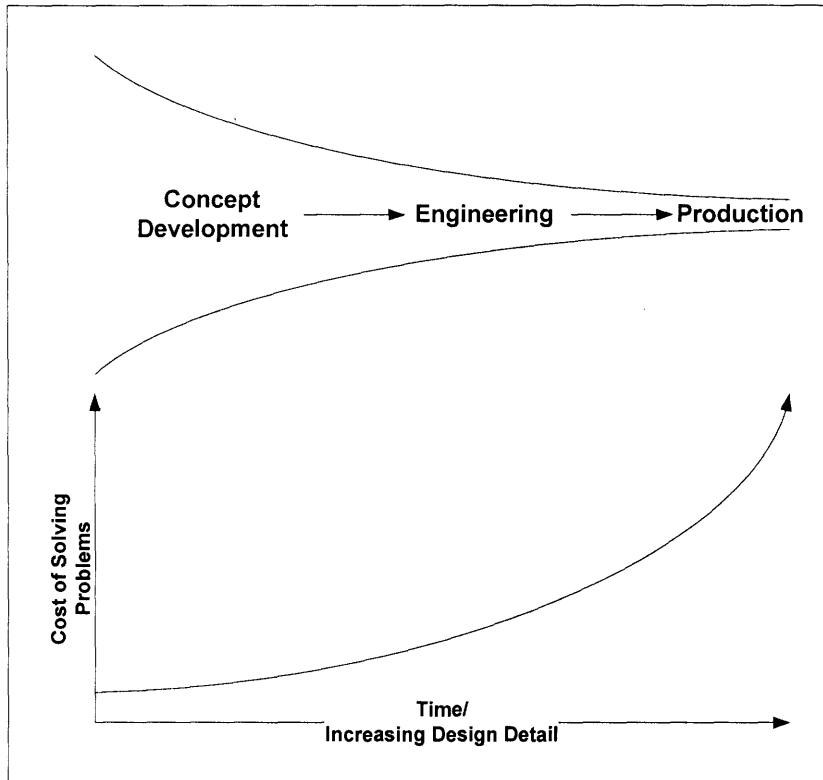


Figure 3-1: Value of early information

These software packages require information that is generally available much earlier in the development process, before costs associated with prototype production have been incurred. The accuracy of a solution and the time required for the computer simulation to run are both dependent on the model used in the software and the resources (both human and computer) dedicated to the problem. But even in the best of situations, the new method might achieve 80% (for example) of the accuracy of established methods, making wholesale replacement of established methods impossible and reinforcing arguments that only the established methods are sufficiently reliable for product development purposes. It should be noted that “80% accuracy” can mean several different things:

- It provides numerical solutions that are within 80% of the actual values.
- It provides precisely correct solutions for 80% of the parameters being evaluated

- For 80% of the simulations run it provides precisely correct values for all of the parameters being evaluated.

Usually it will be a combination of these, though this will depend on the technology.

Regardless, in the worst cases, organizations have found that adopting new technologies with the goal of reducing costs have found that costs actually increase, since decision makers do not trust the results of the new techniques and require that the older, more expensive techniques be used to verify results of the new techniques. Not only are costs not reduced by using the new method in place of the old method, perversely more costs are incurred with the old method to verify the new method's results.

Looking more closely, we find that the belief in the need for traditional verification of tests run with new technologies is often flawed. While the new technology may have lower fidelity in comparison to existing methods, the increased rate at which the new methods provide information makes them very useful in informing decisions that cannot wait for feedback from slower and more costly established methods. Eventually as the development process progresses, the rate and cost at which the new methods deliver useful information will no longer exceed that of the established method. At this point, the older method is more cost effective and a switch is in order. By combining appropriately both the old and new methods as complements to each other, the entire process is optimized. (Figure 3-2)

An interesting example of this mechanism in action can be seen by returning to the example of crash simulation technologies. Twenty years ago, nearly all crash experiments were done with prototypes and preproduction vehicles which had to be custom-built during vehicle development and then destroyed in the test. Although models and test dummies were heavily instrumented, a limited amount of information about actual failure modes could be recovered from these tests, even from reviewing high-speed video recordings.

In the 1990s, computer simulations began to be used much more frequently as software models improved and processor speeds increased. In addition to allowing for rapid test iterations without prototypes, failure modes could be easily analyzed using simple analysis techniques by "replaying" the simulated crash as slowly as needed.

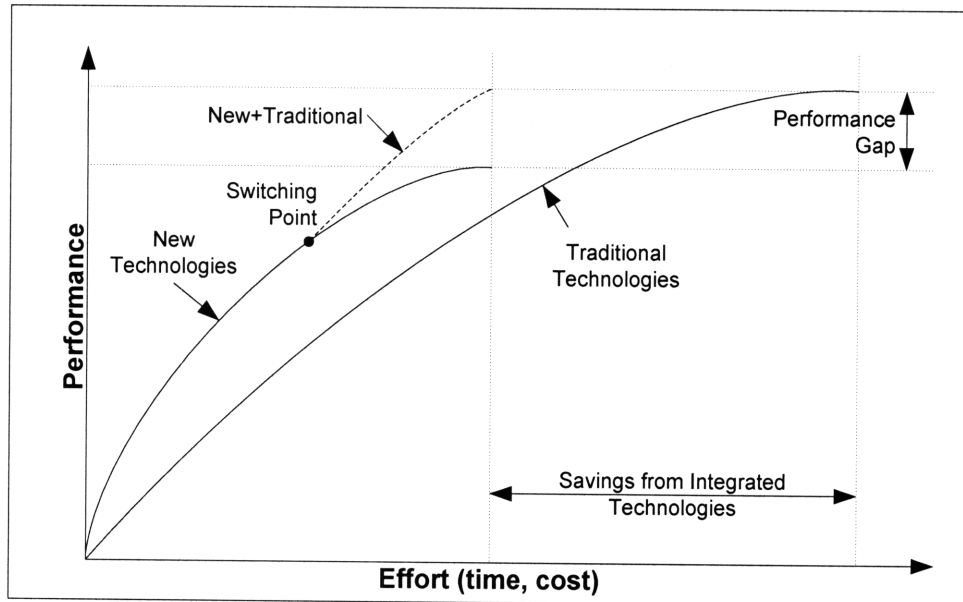


Figure 3-2: Combining old and new technologies to leverage both
Adapted from Stefan Thomke, *Experimentation Matters*, Ch. 5.

Today, according to one interview subject, crash simulations have improved to the point that their results are assumed to be correct. Only a few tests are now performed on actual vehicles, and “surprises” – failure modes not observed in simulation – are very rare, even on models that earn a “five-star” safety rating. This is in contrast to using older methods, which for one four-star car model required 120 crash tests of physical prototypes and production vehicles whose cost ranged from €450,000 at the beginning of development to €5,000 for production vehicles. While crashing a certain number of preproduction and production vehicles may always be required to fulfill regulatory testing requirements, the most expensive tests which involve early-stage prototypes and the associated longer iteration times have effectively been eliminated by the more progressive front-loaders in the industry.

3.2 Influence of Rapid Feedback on Ability to Innovate

An equally important effect of rapid experimentation technologies is the potential it creates to test and evaluate ideas that previously would not otherwise have been possible because of the time involved and the expense incurred. When forced to work with incomplete information, decision makers might choose a conservative path that offers little risk or a more innovative path that may require additional costs and delays as

problems with the new ideas are found and solved downstream. By providing a means of obtaining feedback early, many more new ideas can be proposed, evaluated and refined without significantly increasing risk in downstream development efforts. (Figure 3-3)

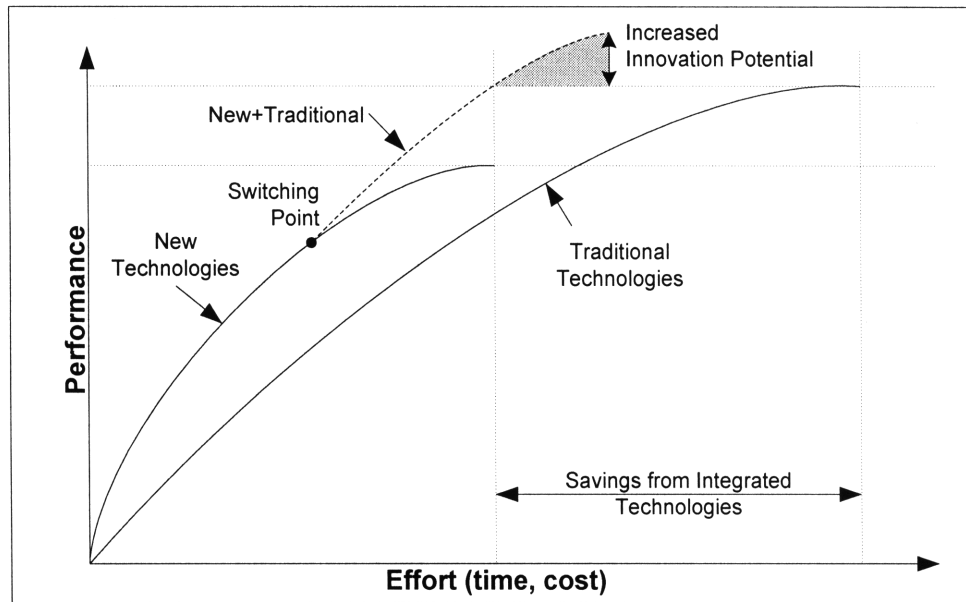


Figure 3-3: Early feedback enables innovation
Adapted from Stefan Thomke, *Experimentation Matters*, Ch. 5.

This effect on an organization's ability to innovate when using front-loaded development processes that include CFD analysis was prominent in the efforts of Team New Zealand's entry into the 1995 America's Cup yacht races [8]. Faced with much larger opponents but constrained to a budget of \$20 million by its limited resources, Team New Zealand chose to build and test two yachts, as other teams did. But through a continuous program of rapid feedback experimentation, led by experienced yacht designers that involved physical models, the two competition yachts, as well as an estimated 5,000 to 10,000 CFD simulations, many changes were made to the two yachts, including over 50 changes made to the keel alone. New Zealand easily won the right to compete in the finals without even having to compete in the final qualification heats. They won the final best of nine series 5-0, an unprecedented margin of victory.

To make the most of rapid feedback and test new ideas, an organization must be capable of performing and processing experiments quickly without becoming overloaded.

This requires careful planning and a balance of both people and computer resources. The addition of the technology itself is not enough. Without sufficient expertise and computer power to use that technology effectively, it still cannot provide needed information on a timely basis. Team New Zealand, for example, had a closely integrated team with computer resources very close to their design and test facilities, iterating the design right on the dockside. This team met nearly continuously to review results from both CFD and physical tests, select new ideas to investigate, and kick off new simulations to be reviewed several hours later.

Assessments of how much expertise and computing power is appropriate for a given technology may not be straightforward. In several interviews conducted, stress was placed on the need to simplify software interfaces to the point at which design and engineering generalists, who are readily available in development organizations, can quickly adapt to and use the new technologies. Critically, solutions that require highly specialized skills – which typically means engineers with Ph.D.'s in specific fields of study – hamper efforts as people with those skills become a scarce resource. Two interview subjects highlighted this effect in stories about initiatives to replace an established experimentation technique with another technique that superficially appeared to be cheaper. In both cases the initiatives failed because it had been determined that adopting the new product required hiring a stable of highly specialized experts.

Computing power must also be carefully planned to insure that it does not become a scarce resource. If new technologies are to be used to improve overall development performance, it must be possible to quickly design, run, and analyze the results of an experiment. Established queueing theory shows that once a scarce resource reaches approximately 70% to 80% utilization, the time spent waiting for that resource increases significantly and non-linearly. In this case, if the resources required to run simulation experiments – such as computing capacity or availability of experts required to perform highly specialized experiments – are planned to match expected capacity for those resources, waiting times will be very high and the ability to provide rapid feedback is lost [20]. (Figure 3-4) Thus planning and budgets must reflect a need for a certain amount of additional capacity relative to the average planned capacity in order to realize the full benefits of introducing a rapid-feedback technology.

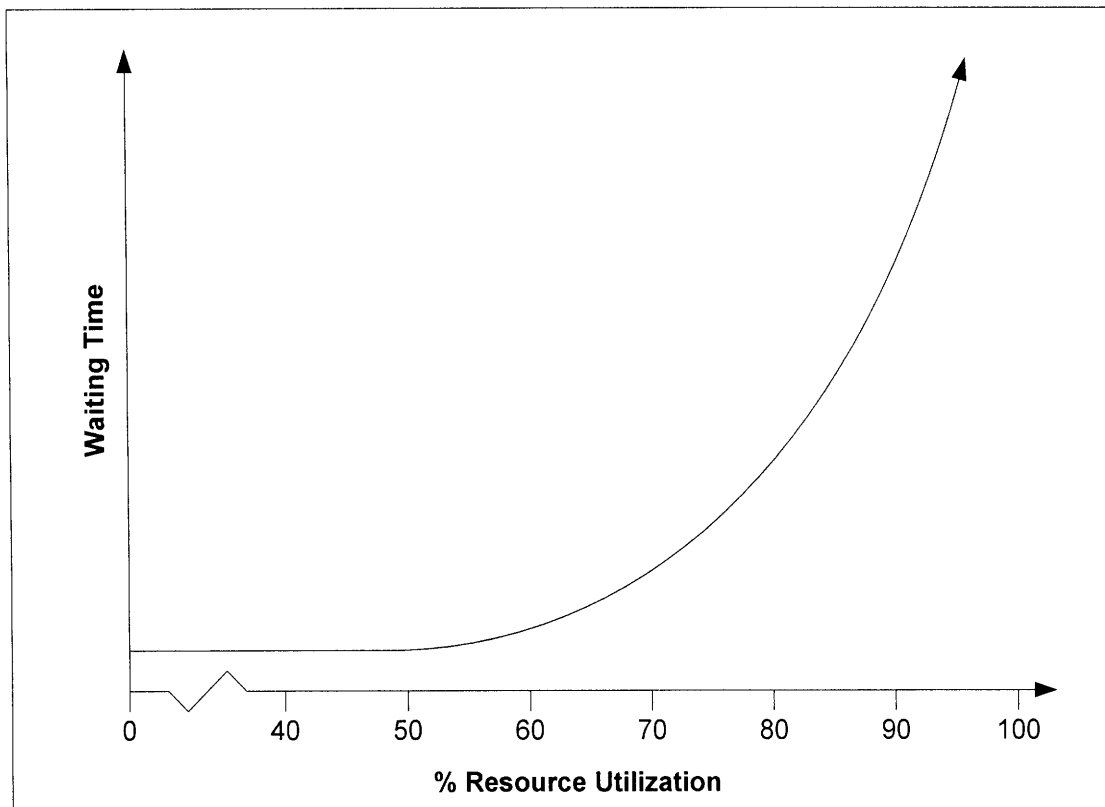


Figure 3-4: Waiting time for a resource increases dramatically at high utilizations.
Adapted from Stefan Thomke, "Enlightened Experimentation" [20]

3.3 Summary

Rapid-feedback experimentation technologies offer a great deal of promise for improving product development performance. When used correctly they enable a problem-solving paradigm that identifies and fixes problems early, eliminating the need to spend a great deal more money fixing problems when they are found much later in the development process, or sacrificing on product goals because they cannot be fixed without rewinding too much of the development process.

If accompanied by the right type of organizational changes, rapid feedback testing also enables new innovation capabilities. The ability to test new ideas quickly provides a powerful vehicle by which innovations can be proven without incurring the risks and costs associated with running a limited number of tests early or deferring assessments to a later phase of product development. But to take full advantage of this promise development organizations must adapt to integrate experimentation capabilities into the

early phases of product development. They must be able to quickly define, run, analyze and process the results of experiments, and begin new experiments as needed.

These kinds of organizational changes are very difficult, especially for long established and very large companies. Team New Zealand was able to organize this way from the beginning, but for an existing organization to change in this way is a much more difficult transition. In Chapter 5 we investigate the practical realities associated with making these kinds of changes. First we will take a look at the implications of rapid feedback testing for air flow analysis in automotive product development, then consider these implications in our discussions on organizational change.

4 Application to Automotive Aerodynamics Analysis

Compared to many types of engineering information that are used in the development of a car, aerodynamics and its many influences introduce a number of special complications. The complexity inherent in the physics of turbulent fluid flow makes all but the most crude of predictions inaccessible to human intuition for real problems, and nearly all fluid flows of interest in the automotive development process are turbulent. Yet the way in which air flows around a car and through its subsystems has a significant impact on the performance of the final product: fuel efficiency, noise levels, safety, handling, and reliability all have traits that depend directly on successfully managing air flow. Thus one of the most important levers available for reaching product goals – alteration of the car’s outer surface – is removed once the design is frozen and that surface can no longer be changed.

In this chapter we review some the ways in which air flow is unique relative to other engineering information, and what this means for the need to assess its behavior early in the development process. We build on the information in Chapters 2 and 3, then review the advantages associated with incorporating air flow simulation technologies into the early phases of automotive product development and discuss changes needed in software implementations of these technologies to enable this use.

4.1 Systemic Nature of Air Flow as an Engineering Problem

The flow of air around a complex shape has a number of characteristics that complicate its management as an engineering problem. Chief among these problems are its resistance to intuitive reasoning for most “real” problems, and its tendency to produce non-local effects: an interaction with one part of a vehicle often has a significant influence at a distance on air flow interactions with other seemingly unrelated parts of the vehicle. Air flow *creates* highly unpredictable relationships between vehicle components that would not otherwise be related, and these relationships in turn can have a major impact on the performance of the vehicle as a whole. Thus changes to the design could also either create or destroy these interactions (which may either be beneficial or detrimental) in a way that is equally unpredictable by intuition.

The impact of these variable relationships can be demonstrated with a variable-based Design Structure Matrix (DSM), as shown in Figure 4-1. A DSM is a useful tool for developing an understanding of relationships between the components of a system, and is often used during product development to ensure that dependencies are accounted for properly as the system and its components are being designed. In this simple example, there are 20 components or design parameters that might each represent a design attribute – the shape of the hood, radius of the A-pillar, size and shape of the grille, etc. An “X” indicates that the variable in that row has a strong dependence on the variable identified in the column. A dot indicates a weak dependence. Once the DSM has been created, these dependencies are analyzed to optimize development plans across all components.

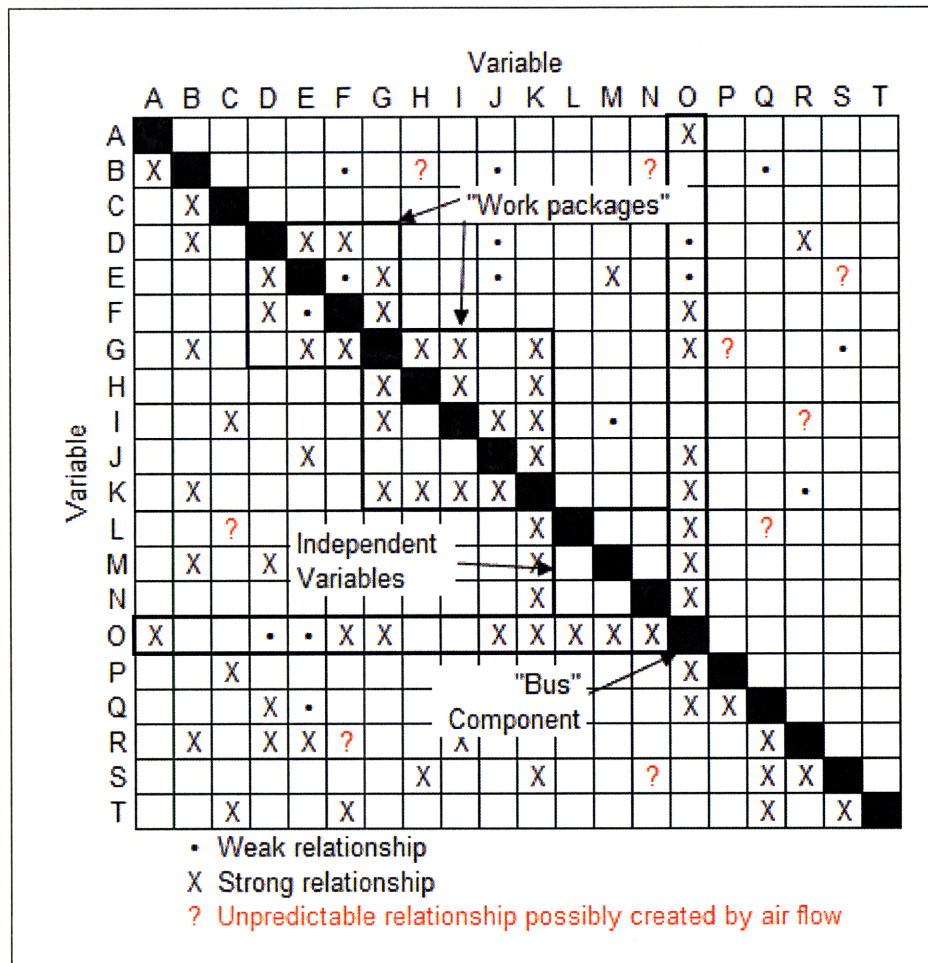


Figure 4-1: Air flow may create unpredictable component dependencies

In the presence of air flow, however, this process may fail to recognize important dependencies between components, shown with question marks. Without this information development plans proceed assuming these relationships do not exist, potentially resulting in new problems that may not be discovered until testing is well under way. To illustrate this complexity and explore its consequences for automotive product development we will look at a concrete example in detail and then discuss the primary drivers for improving air flow characteristics for a vehicle.

4.1.1 Example: A-Pillar Vortex Noise

We start with an example that was relayed to me several years ago by a senior aerodynamicist at a major auto company. The subject of the example is the interaction between a prominent air flow feature on most vehicles – the so-called A-pillar vortex – and an open driver’s side window. The A-pillar is the first of three structural members that connect the main body of a vehicle to its roof. The A-pillar is between the windshield and the front door, the B-pillar is between the front and rear doors, and the C-pillar is between the rear door and the rear windshield. (Figure 4-2)

As a car moves down the road at normal driving speeds, air that approaches the side of the front windshield is deflected up and to the side. A number of factors affect the result of this deflection, but a prominent result is the creation of a vortex – a tube of spinning air – that usually starts at the bottom of the A-pillar and gradually moves higher as it propagates down the side of the car. If you have ever noticed a roughly horizontal line of water on the outside of your window while driving in the rain, this is a result of the A-pillar vortex holding water up as gravity pulls it down on the glass. Through a number of mechanisms not directly relevant to this discussion, this vortex is often a significant source of noise for the occupants of a vehicle. In this example, if the driver’s side window was left open while driving at moderate speeds, this vortex interacted with the open space of the window and the B-pillar (at the back of the open window) to create a very loud noise within the cabin. This is an example of the buffeting phenomenon described in Section 2.1. If any other windows or the sunroof were also open, this noise did not occur.

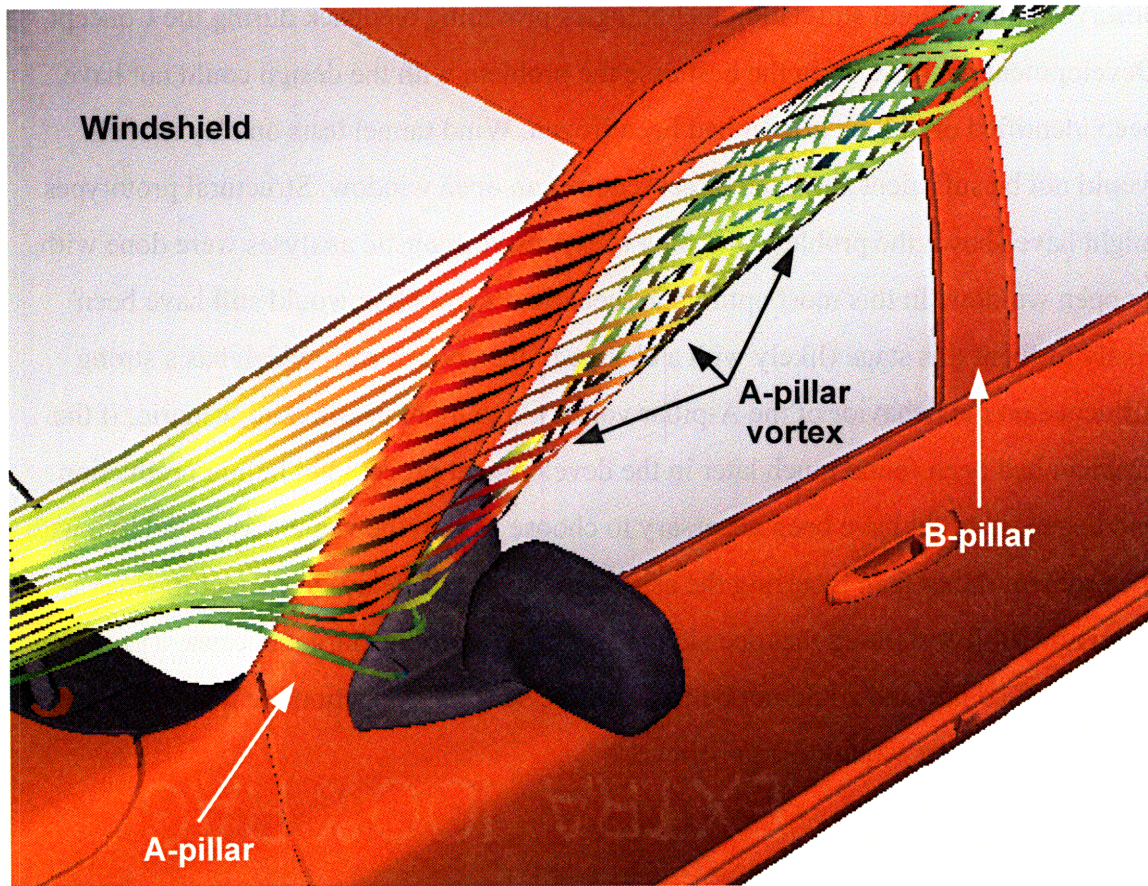


Figure 4-2: A-pillar vortex illustration
Image courtesy of Exa Corporation

The problem was not found during development and testing of the vehicle. It soon became a common complaint among buyers of the vehicle, creating a minor crisis for the aerodynamics team. After reproducing the problem on the road, engineers found that by simply placing two fingers one centimeter through the open window just in front of the B-pillar, the problem went away. This solution is not practical for production vehicles, but the point is that a small change far away from the origin of the A-pillar vortex corrected the problem. Both the problem and the result of those two fingers were not effects that lend themselves to intuitive problem solving. An experienced aerodynamicist would certainly be aware that the vortex would be present and *might* cause problems, but he could not know about many of the other complex air flow issues that might occur.

Imagine now how the development process for this vehicle likely progressed. The problem was fundamental to the shape of the car, and required an open window to

observe. Thus without simulation technologies providing feedback during the Concept Development phase, even in the best case the problem with the design could not have been identified until long after it had been frozen. Wind tunnel tests on clay models would not be sufficient since the effect requires an open window. Structural prototypes might have shown the problem, but only if expensive acoustic analyses were done with an open window. In this most optimistic scenario, the problem would still have been costly to fix at this stage (likely with a change to the door mirror, which has a strong influence on the behavior of the A-pillar vortex). In a more pessimistic scenario, if the problem had been found much later in the development process but before production had begun, it might have been necessary to choose to ship the vehicle as-is and live with the problem rather than incurring the associated costs and delays to correct it. One interview subject stressed that decisions to sacrifice a product target because a problem was identified late and could not be fixed before start of production are not as uncommon as many customers would like to believe.

4.1.2 Aerodynamics

The influence that a design's shape has on the vehicle's aerodynamics may be the easiest to understand intuitively. What is often not well understood is the sensitivity of aerodynamic performance to even seemingly small changes in shape. Even for very simple shapes, a minor change in the shape of a vehicle component has the potential to dramatically change the resulting air flow, which in turn would result in a major change to the aerodynamic performance of the shape [1]. These complexities are compounded when working on actual vehicle shapes with complex curvature and hundreds of distinct components, many of which are developed by separate teams.

Testing on clay and structural prototypes still plays a prominent role in identifying and solving problems with vehicle shapes. As we saw in Chapters 2 and 3, this limits the product development process in several ways:

- Prototypes are often not representative of the actual design in consideration. This can lead to false conclusions or loss of confidence in the test results.
- Reliance on prototype testing early in the process makes testing of new ideas much more expensive, since they must first be built into prototypes. Thus many

ideas may be discarded due to perceived risk without being evaluated for their potential for beneficial impacts on product performance.

- Prototype construction is typically a long, expensive process. Waiting until prototypes are available to perform tests delays problem identification and resolution.

A new experimentation technology like CFD capable of delivering quick feedback to design ideas would address each of these issues. It represents the actual shape under consideration and is capable of performing tests much earlier and faster than prototype testing, accelerating tests for innovative new ideas and enabling early problem solving.

4.1.3 Aeroacoustics

Aeroacoustics shares all of the advantages described above for aerodynamics. However, the practical realities of aeroacoustics analysis actually provide a more compelling case for identifying and solving potential problems early in the development process. Problems in aeroacoustics can be very sensitive to minor changes in the shape of a vehicle. But because of this sensitivity, reliable physical testing is often not possible even with initial structural prototypes, which may have slightly simplified geometry, missing door seals, and substituted components that heavily influence the noise heard in the passenger cabin. Since meaningful testing might not be possible until the second generation of structural prototypes is built, any problems that might be found are much more difficult to address.

Another factor in physical testing techniques which is especially difficult for aeroacoustics is the decomposition of the noise heard by occupants into constituent sources. Reducing noise requires an understanding of its origins, and traditional experimentation methods offer little insight into these origins. CFD technologies offer the potential to identify these sources and inform noise mitigation decisions with information not available from existing techniques.

4.1.4 Thermal management

Thermal management is also tied closely to aerodynamics. In particular, the shape of the vehicle's front structure and the nature of air flow around the car affects the amount

of air that will pass through the cooling package (radiator, condenser, other heat exchangers and fan) and over the rest of the engine. But as with aeroacoustics, thermal management poses a number of challenges for product developers.

While the exterior surfaces of a vehicle are relatively simple to define, most thermal management problems deal with much more complicated shapes and more complex component interactions. The engine and dozens of its associated components, fans, and the surrounding structures add up to a chaotic air flow environment that can be very challenging to study experimentally. Brake cooling and other thermal management problems deal with similar factors. When combined with concerns about prototype fidelity and the importance of thermal management in controlling development costs, warranty risks and safety issues, early-stage problem solving with CFD offers the potential for dramatic improvements in product development performance.

4.2 Requirements for CFD Software

For any technology to be viable in front-loading automotive product development, a number of important requirements must be satisfied in actual product development settings. To emphasize a point made in several interviews, it is not enough to fulfill these requirements in idealized settings and then assume that they will be satisfied when integrated into real product development environments where change is constant and flexibility is essential. Here we look at the primary requirements for any such technology, with a special emphasis on CFD Software.

4.2.1 Accuracy

First and foremost, the technology's results must be useful as a predictive tool in evaluating the relevant attributes of performance for a design when employed by capable users. In Section 3.1 we saw that when the technology's limits are known, operating within those limits assists the development team in evaluating their ideas and understanding problems at a time when identifying and fixing those problems is relatively inexpensive.

With respect to CFD, accuracy requirements depend largely on the specific area in which problem identification is needed. For all areas it should provide a means to

compare multiple design variations for their relative effects on key performance attributes:

- Aerodynamics: drag and lift; air flow patterns
- Aeroacoustics: wind noise sources; noise propagation characteristics; noise levels heard by occupants
- Thermal Management: distribution of temperature in air after heating from engine, radiator, exhaust, brakes, etc.; surface temperatures on parts heated by air

As we have seen, in some cases CFD simulation can be used to advance a design to a certain stage, at which point traditional physical testing systems should take over. An example of this was described in an interview where the optimal angle of a spoiler at the rear of a car needed to be established. While CFD had been useful in the development process, it was found that performing a parametric study on the spoiler in a wind tunnel could be done much faster, since the only result needed was the force acting on the spoiler for each angle. Rather than run a series of simulations, a short wind tunnel test program was performed instead.

4.2.2 Rapid Turnaround Time

The ability to run and analyze experiments on a time scale that is useful to developers is critical for any technology to be useful in front-loading the development process. It must be usable much earlier in the process than traditional technologies and it must be fast enough to evaluate proposed solutions more quickly, thus enabling product developers to receive feedback on a proposed design before it changes significantly and thereby realize the technology's benefits. During Concept Development, several interview subjects noted, designs evolve continually based on whatever information is available. If results from CFD assessments are available before the next major round of modifications to the design, they might be considered. There is no value in receiving results of these assessments after several more changes have been made to the model.

This begs the question, how quickly must the experiment run in order to be useful during the early stages of design? If we accept the statement that the results of an experiment have no value if they are not available before the design is modified, then the

answer naturally depends on the rate at which the design is evolving. This rate varies over time. In the first meetings after a project is kicked off, designs (such as they are at this stage) undergo radical “changes” every few minutes. In this scenario anything less than real-time feedback, as one might get by interactively working with experienced designers and engineers, is not useful. In the final meetings of Concept Development, the general concept has been selected and only minor, carefully-vetted changes are being proposed and evaluated before the design is frozen. These final design changes take place at a much slower rate, and tend to be more limited in their impact on the look of the vehicle. Here, more time is available to perform experiments on change proposals before the next change is made, but by this time most key design decisions have already been made: problems found and solved here will already be much more expensive or impossible to address. Thus the question of how fast experiments must be able to run to provide timely feedback depends on where you are in the development process.

The turnaround time for an experiment can be decomposed into three components:

- **Setup:** the amount of time required to prepare the experiment. In the context of CFD analysis, this includes the amount of time to transfer geometric information from wherever it is stored – assumed here to be another CAE system – and define the conditions in which the experiment is to be conducted. As with many experimental techniques this process is likely to take longer the first time the experiment is run. Incremental changes are generally much faster.
- **Run:** the amount of time required to run the experiment. For CAE simulation techniques, this is the amount time required for the simulation to run. This time can usually be reduced by running the simulation on many computers simultaneously.
- **Analyze:** the amount of time required to analyze the results of the experiment and choose next steps.

In an interview a former head of design for one of the “Big Three” auto makers in the U.S. stated that although real-time feedback would be ideal, delivering simulation results overnight would be sufficient to enable a daily analyze-set-run test cycle for early problem identification and solution during Concept Development. Slower results would

typically not be useful as designs change too much over, say, a two-day window. “Overnight” refers only to the time required to run the simulation. Thus to be most useful in such an environment, the setup and analysis times would need to be short enough – perhaps an hour or less – to not interfere with this daily cycle.

4.2.3 Simplified Interfaces and Standard Practices

As mentioned in Section 3.2, the accessibility of a technology to a large pool of product developers is important in front-loading scenarios in order to eliminate bottlenecks introduced by involvement of rare and highly specialized people. This sentiment was echoed in several interviews. If extreme specialization is needed to use the technology, it is not suitable for providing feedback in a constantly evolving, dynamic development process.

A requirement closely related to both simplified interfaces and accuracy is the need for standard or “best” practices in order to provide accurate results. Two interview subjects highlighted this as an important factor in the success of crash simulation and a current concern with CFD simulation in general. In particular, if the quality of the results varies among equally experienced and knowledgeable practitioners, the technology’s value in providing robust feedback will be suspect. Templates, “push button” solutions and consistency in problem-solving techniques across the development process were all cited in interviews as crucial for integration of CFD into earlier stages of product development.

4.2.4 Robust Integration into Comprehensive CAE Environment

The importance of a fully digital process was emphasized in an interview with the former chief of design at an American auto maker who had been a champion of digital vehicle development technologies. He said that changing the development process to use CFD technologies early in the development process “means you have to move to a total digital process so you can work with the whole system.” Relying on physical models and clay, he noted, means that by the time you scan the shape into CAD, run a simulation and analyze results, the clay model will have changed so much that the results of the test will be useless.

Aside from the need to move to a digital process, the transition of geometric information between the CAD/CAS and CFD software systems must be fast and efficient to enable the daily analyze-setup-run cycle referred to earlier in Section 4.2.2. This need for a very short setup time when starting from raw CAD data has traditionally been a challenge for CFD software, which often requires time-intensive manual simplifications to the CAD data before it can be used. The need for such simplifications appears to disqualify packages that require them from use in these daily experimentation cycles.

4.3 Summary

The complexity of air flow introduces a number of complications into the automotive design process, largely because design changes can have unpredictable consequences that are only exposed through experimentation. Air flow creates dependencies between components and design changes that might otherwise be unrelated.

The reliance on prototypes for performing these experiments makes problem-solving difficult, but newer CFD technologies offer promise in front-loading the development process and reducing the dependence on prototypes. To fill this promise, CFD codes must fulfill requirements of accuracy, easy of use, speed of solution, and smooth integration with other CAE packages used for defining and storing the vehicle's evolving design.

5 Practical Realities of Process Change

Most managers will agree readily that solving problems early is better than solving them later. The specific mechanisms of how and why front-loading the development processes improves product development performance, both in cost and time to market, might not be thoroughly understood, but it is relatively straightforward for managers to understand that earlier is better. So if technologies are available for solving problems early in the development process, why would they not be adopted? In this chapter we explore this question, look at how it has been addressed in successful transitions, and what might be necessary to motivate a similar transition for the inclusion of air flow information in the early product development phases of an automotive company.

The most significant factor affecting the adoption of major changes in the product development process is organizational culture, which we define here to be the unstated behavioral norms operating within an organization and governing its actual behavior. This sentiment is prominent in the literature [10,15,21,25,26] and was expressed strongly by several interview subjects, all of whom have spent more than a decade in the automotive industry. As one put it, “culture eats process every time.”

A useful illustration of this cultural difference was described in an interview of a former staff member at a European auto maker. This company had two design studios that fed into the same engineering organization. The two studios, which were responsible for different brands within the same parent company, had very different relationships with the engineering division. One brand had a reputation for cars with aerodynamic shapes and its designers were more focused on aerodynamic performance. They actively engaged the engineering organization seeking feedback and improvements. Designers in the other studio, who did not have this focus on aerodynamic performance, were described as being “very tough – almost kings. Their designs are art that should not be changed.” Unfortunately, information is not readily available to establish the impact of this difference on downstream product development performance. But the difference between these two design studios working with the same engineering organization highlights the range of resistance one might find when attempting to front-load the design process to include engineering evaluations of early designs.

Sections 5.1 to 5.4 look at a number of issues relating to organizational culture as extracted from the literature and interviews. We begin by recognizing the primacy of the creative process in the concept development phase of automotive design. The critical product of this phase is an aesthetically appealing design, which would not be possible without this creative process. We then seek to identify and understand the hidden behavior norms that are present, and build a rational argument for implementing process change without stifling the creative process. Section 5.5 discusses high-level considerations for instituting major process change, and Section 5.6 reviews factors that have been found to be important in successfully implementing such changes.

5.1 Perception of Impact on Creative Process

The aesthetic appeal of a vehicle is among its most important qualities for commercial success. It plays a significant role in differentiating a car from competing products by attracting potential buyers to favor one vehicle over another. For most buyers the car's external appearance is the first thing they see. The adage "you never get a second chance to make a first impression" was made more specific in one interview, which stressed that buyers may never know about a car's excellent performance if it does not first provide the right degree of visual appeal. A beautiful car, on the other hand, will at least get a second look. Thus it becomes critical to have both visual appeal and good performance, since well-performing cars will fare better in a second look than poorly performing ones. But the car must get that second look.

Because of the importance of visual appeal, emphasis is placed on the development of a car's look during the early phases of product development. This in turn requires a great deal of creativity and expertise. The current paradigm involving highly trained designers and modelers has evolved to express this creativity primarily through clay models, whose physical presence allows for visual evaluations of proposals that many believe are more realistic than computer-generated visualizations. Thus shifting to a primarily digital vehicle development process, previously raised in Section 4.2.4 as a key factor in enabling early-stage air flow assessments of new designs, threatens to disrupt the key mechanisms by which new designs are evolved and assessed. Computer Aided

Styling (CAS) solutions have been gaining moderate traction in some companies due to the front-loading effects they promote [21], but the focus is still primarily on clay models.

The addition of air flow assessment technologies in this process poses a further significant new challenge. Adding evaluation criteria based on engineering performance, it is often argued, constrains the flexibility of designers in ways which limit creativity and may foster “cookie cutter-style cars” [24], or otherwise detract from what is fundamentally a creative process through the use of engineering (generally read as “non-creative”) metrics. It is felt that groundbreaking design ideas should be explored for a time without consideration of their engineering implications in order to foster the creative process and yield popular, attractive designs for next-generation vehicles.

Interestingly, most of the comments about constraining design flexibility are in response to questions specific to the use of CFD technologies in evaluating designs. But the specific use of CFD should in fact be irrelevant: the constraint is applied by incorporating awareness of air flow characteristics into a design, regardless of the technique used to create that awareness.

As with any complex design process, addition of new evaluation criteria that were not previously available should indeed provide better information by which design decisions are made. This is one of the key benefits of front-loading. To the extent that this new information results in decisions that would otherwise have been made differently, it does add new constraints to the process. But factual information supporting the belief that such constraints yield unappealing styles is not readily available, and an understanding of the design process does not appear to support it. Nearly everyone involved in the process – even engineering managers and staff – appear to agree with the critical importance of a design’s aesthetic appeal, so it seems unlikely that it would be subordinated by engineering performance information during early-stage design evaluations even if perfect real-time information were available. Thus the question becomes, would the addition of air flow information, with its attendant front-loading effects, to the design selection process change design decisions to such an extent that creative new design ideas would be suppressed?

This seems unlikely for precisely the same reason that air flow analysis is so difficult, as described in Chapter 4: it is typically impossible to predict the effect of a particular design feature on air flow without testing it, and the same design feature might yield very different results depending on other aspects of the design. Without a formal evaluation of design ideas, it is difficult to support arguments of suppressing a design alteration.

5.2 Organizational Interfaces

A vehicle's shape plays an important role in its ability to meet engineering performance goals. But there is often a sharp division between designers and engineering staff who are ultimately working to develop the same product, and these divisions can create barriers to problem solving [2,21]. Some of these divisions result from the practical limitations of current experimental methods. If meaningful performance information can be acquired only from testing on structural prototypes that are not available until long after Concept Development has completed, involving engineers in early-stage design is difficult to justify. Often, however, these separations are artificial.

For example, a prominent factor explaining negative reactions designers often have to early-stage engineering performance assessments was raised in several interviews: engineering assessments of designs are often interpreted as judgments of the design rather than simply being additional information to be used in a larger, more informed assessment framework. Dialogues between designers and engineers are described as infrequent and difficult at best, with designers feeling that the results of their creative efforts are being challenged by dispassionate assessments incapable of recognizing the real value of artistic appeal and engineers feeling that designers are aloof and too willing to push problematic designs off on engineers to solve the problems.

Both views may have an element of truth, but they also appear to reflect a lack of trust and empathy often corrected naturally by closer collaboration and a focus on solving problems at the system level rather than deferring decisions [2]. This was supported in an interview with a former chief of design, who related a story about a small vehicle development team that included members from many different disciplines: design, engineering, marketing, and production. In this team, design and engineering staff who

previously had not gotten along well were able to coordinate efficiently on a new design. This effect is a key goal of concurrent engineering initiatives.

Another more subtle effect is found, however, when introducing new technologies which require a high degree of expertise to leverage. If a new technology is sufficiently complex, specialists are often required to make good use of it. The unexpected side-effect of such an interface is a forced separation between information and the people who need it. Thomke provides an illustration of this effect in the use of CAD/CAE technologies, where firms in the U.S. had up to 2.3 CAD specialists per engineer, compared to 0.3 in Japan [21]. The Japanese firms were using much less sophisticated CAD technologies, but their engineers were able to make much better use of these simpler technologies without specialists. As a result they were able to experiment more and solve problems more efficiently than their American counterparts. This requirement for simple interfaces to new experimentation technologies further supports the findings in Section 4.2.3, which found that accessibility of CFD technologies without also requiring high degrees of specialization in its practitioners was an important requirement for their adoption in the early phases of automotive development.

5.3 Evaluation and Incentives

A key element of process change resistance was highlighted in several interviews, including one who put it plainly: “Look, designers know that at the end of the day the product has to perform. But they are *graded* on the visual appeal of the design.” He went on to say that although each engineering team tends to believe that their particular area of expertise is most important – after all, this is how the engineers are graded – the designer must look at the complete vehicle and be responsible for attracting initial attention from buyers.

Thus incentives to coordinate and solve system-level problems early are often not aligned for design and engineering staff working on the same product. This tends to be especially true in the early stages of development, when coordination between teams often means exchanging information which may not be precise due to rapidly changing designs. Terwiesch, Loch and De Meyer explore this effect in some detail with important findings [18] that teams are often reluctant to share early information for two reasons: the

information does not yet meet the team's precision requirements for sharing it; and those that share information earliest must often spend the most time making changes to the design to accommodate changes requested by those that see the information. Thus by waiting longer to share information about proposed designs, the logic goes, teams can satisfy their ingrained preference to provide only accurate information – and not expose the fact that their early information has flaws – by incorporating as much information as possible from prior stages of the design process.

An incentive mechanism that plays a large role in front-loading initiatives is reflected in this illustration. Emphasis is often placed on providing accurate information in one's own area, and not on coordinating with the larger organization to converge on final robust designs earlier at the expense of providing less accurate information and having to rework portions of the design. This larger coordination effort is effectively an experimental process, where information is provided on a best-available basis even though it is incomplete. This exposes evolving details in the information, and thereby the conflicts within those details can as a result be addressed much earlier and more cost-effectively than would be possible if all parties waited for the availability of as-perfect-as-possible information. A key conclusion of this study is to ensure each team's incentives are aligned with the broader goals of organizational learning, problem solving and product development performance. Incentives and evaluations must be based on contributions to learning and front-loading and not on providing incomplete or inaccurate information early.

5.4 Adaptation to Digital Visualization

As we have seen, the automotive concept development process is highly focused on visual information, and physical artifacts – drawings, paintings, and clay models – figure prominently in how this information is communicated between designers and decision makers. They provide a natural, intuitive mechanism by which designs are created, reviewed, refined, filtered and communicated [2,19]. Their creation draws on long traditions of artistic expression that have played a central role for designers charged with creating new styles for upcoming vehicles [21].

Virtual design techniques require a significant transition in tools, activities, processes, and technologies. While some auto makers are transitioning to such tools for some vehicles [4,6,12,17], interviews reveal that clay prototypes are still used heavily in the concept development process. The virtual tools do not currently provide the kind of real-time, visually realistic, and tactile feedback required to properly convey the many cues of a design with the same fidelity as a realistically-painted clay model. In this way Computer Aided Styling software is similar in nature to other front-loading technologies that may not provide 100% of the fidelity of existing problem-solving techniques, but are still useful in identifying and solving some problems early. The use of CAS software at BMW for front-loading is discussed by Thomke [19].

5.5 Process Change

Even without the larger cultural issues discussed above, large-scale process change is very difficult. Studies show many complex interactions in process change, and important dynamic aspects of implementing change in the constant pressure to remain productive during the transition period must be managed to ensure success. This section draws on work from Repenning and others [13,14,15] to explore the nature of process changes – and how such initiatives succeed or fail – through system dynamics models.

The models developed by Repenning, et al. account for a number of factors often not considered when discussing process change. In particular, they account for the fact that process change is a fundamentally dynamic process. One does not throw a switch one day and begin using the new process:

- Workers often resist new policies, and resources must be assigned to ensure the new process is sound, educate workers and management about its benefits, and build the capabilities required in the new process. This takes time and resources, which are then unavailable for working on projects.
- Typically, projects are already under way using the old process. Even if the new process is to be used only on new projects, the same resources must typically be allocated among both old and new projects. But the increased efficiency or performance of the new process is most often the result of front-loading, which implies more front-end work for new projects, and thus more resources. Old

projects must still get finished without the benefit of the front-loaded development. If more resources are required for the new process, how are old projects to be completed on time? This “worse before better” dynamic – productivity initially suffers, then improves as old tasks are completed and the benefits of the new process are realized – is often misunderstood by managers.

- Early indications of the new process often give managers a premature sense of failure. The result is often firefighting: increasing pressure to complete tasks that are behind schedule due to higher initial resource requirements of the new process are completed as quickly as possible, even if some steps of the process (new or old) must be skipped. Such rushed tasks often force rework – either in themselves or other tasks – which in turn require additional resources to address.
- Eventual gains in productivity also give managers a premature sense of success. If gains are not partially reinvested in new capabilities developed by the process improvements, the capabilities degrade over time. Eventually work load increases again, workers begin taking shortcuts, rework increases, and soon firefighting is in full swing.

Due to these effects and others, a thorough understanding of the product development ecosystem and its dynamics is critical to provide a credible framework within which the process can be permanently and efficiently improved. Resources to support the changes and build associated capabilities within the development organization must be allocated, and the actual process of implementing the change must be carefully managed. This is explored in more detail in the next section, where success factors in process change are detailed.

5.6 Success Factors

Success in implementing process change requires overcoming a number of high barriers. Cultural factors and human nature, new capabilities introduced by new processes, and the dynamic evolution of any process that involves the complexities of human interaction must all be considered and addressed to enact meaningful long-term changes. There are three factors that have been found to be most important in ensuring this success:

- A compelling case
- Committed leadership
- Management awareness of the dynamics of process change

5.6.1 A Compelling Case

Clearly, a legitimate sense of importance and urgency is required to institute a major change to a company's vital product development process. As the former chief of design quoted earlier noted, "you have to have one hell of a compelling argument for making this kind of change."

Automotive design is a high-stakes commercial enterprise run by intelligent, creative, and ambitious people. Any proposal for a significant change to that process must be able to withstand their scrutiny and demonstrate its value. As noted in Chapter 1, this value was easy to recognize for crash simulation due to the relatively minor changes required in the concept development process. But for air flow analysis and CFD, the associated effect on the design process is more significant. When and how this argument will be sufficiently compelling is unclear, but there are already some indications that it is taking shape. Competitive pressures are high in the automotive industry and some auto makers are already shifting to no-prototype development models, though the use of CFD in front-loading the development process and improving innovation before designs are frozen is not taking place. Also, as this is being written a global economic crisis has been unfolding for more than six months, which has pushed some high-profile automakers to the brink of bankruptcy. The role this crisis is having in motivating a fundamental shift in product development to reduce costs through process improvements remains to be seen, but any such shift seems likely to benefit arguments that favor rapid-feedback digital design technologies.

Once early adopters demonstrate success in improving development performance through the use of early-stage air flow analysis, the compelling case will be much easier to make to other manufacturers. Since process change at this scale may take a significant amount of time to fully deploy, however, early adopters might expect an initial buffer

period in which they will enjoy first-mover advantages, while lagging competitors adapt to the new competitive necessity of improved development performance.

5.6.2 Committed Leadership

Company leadership must have confidence in major process changes, and once they have this confidence they must be committed to seeing those changes implemented in order to realize the long-term gains. Aside from believing in the compelling arguments for making the change, they must understand the complexities of process change and how it needs to be managed [15].

This may sometimes mean forcing issues, either by requiring a new technology to prove its value or by requiring the use of a technology whose value has already been proven [21,23]. Chris Bangle, for example, describes having to force CAS advocates to prove its value: “Gentlemen, either this puppy pays within three months, or forget it, I’m going to sell the whole thing down the river. [19]” This ultimatum resulted in the eventual adoption of the technology by modelers, who work with designers in defining the actual 3-D surfaces envisioned by designers. Thomke also describes an example relating to new drug discovery technologies. Here, managers at Eli Lilly had to restrict chemists’ access to traditional, expensive screening capabilities until after they had used a newer, relatively inexpensive but lower-fidelity technique [21].

5.6.3 Management Awareness of the Dynamics of Process Change

Finally, management needs to understand the dynamic aspects of large-scale process change, ensure a realistic transition plan is in effect, and be ready to make changes as necessary to support old and new projects during the transition. A more complete set of recommendations can be found in Repenning, et al. [14], and Thomke [21].

- Assign resources to process improvement, and ensure that these resources do not revert to project work. If additional resources are not available, do not invest in new tools and processes.
- Be aware of “tipping point” behaviors. Initial productivity will usually decrease once new process implementation has begun. Only after projects begun under the old process are complete will actual productivity improve.

- Align incentives to promote early problem identification and solution. Sharing information early is valuable even though it is incomplete. Reward early problem identification practices rather than provision of accurate, but late, information.

6 Conclusion

The use of new experimentation technologies like CFD for air flow analysis in the early stages of automotive design offers significant promise in boosting development organization performance, but the changes required to implement these new technologies are not simple and the environmental attributes needed for change are not all yet in place. The highly complex nature of the end products and capital-intensive nature of the automotive industry result in high stakes for process change. Both the rewards and risks can be significant. But the value of front-loading the development process has been demonstrated. Crash simulation and virtual decking have both significantly shortened development times by front-loading the automotive development process, and CFD has been demonstrated to significantly improve development performance in other fields.

One of the most significant complications in introducing CFD to early-stage automotive design is the intrinsic conflict created by introducing engineering performance feedback into a concept development process that has traditionally been focused primarily on creativity. Changes required by other new experimentation technologies like crash simulation have been relatively independent of the aesthetic qualities of a car, so they have been more readily accepted. This is not the case with air flow performance information, which has a close connection to aesthetic qualities and suggests new constraints within which the concept development process would need to evolve.

Making such a change requires sufficient motivation and careful consideration of how the creative process can be preserved in the presence of a major shift in approach and emphasis on software-based tools while also ensuring that the benefits of front-loading are realized. Strong motivation is required in order to overcome relatively high resistance to process change. Pressure will likely continue building from new competitive and economic factors until organizations begin adopting CFD. Unrolling such a process would be done gradually, first with a pilot program before a broader implementation. This is itself a type of front-loading: first run the experiment, learn from it, and modify the approach based on this knowledge before continuing. We will see how it evolves from there, and how long it takes to reach this point.

Future Work

A number of questions and issues were raised while conducting the research for this thesis that are either not addressed or only briefly touched upon here. So in the fine tradition of identifying future work topics rather than trying to write more fully about them in a thesis, here are some of those issues and initial thoughts.

- Two interview subjects expressed concern about the possible long-term loss of deep aerodynamics expertise if companies were to widely adopt CFD in place of traditional experimentation techniques. The thinking here is that if the process is made too simple, experts will no longer have to develop their own deep internal understanding of the subject, and thus will not be as valuable in providing the type of real-time feedback that even the fastest computer solutions cannot deliver. This concern is ironic given the concerns expressed by others about requiring too much expertise in the process, but seems interesting regardless. One might argue – and some have claimed – that CFD actually boosts such expertise, since it makes plain many complex phenomena that are difficult to observe and understand physically, resulting in fewer false conclusions and better cause-and-effect understanding.
- A broader spectrum of interview subjects would likely allow for a more general treatment of some subjects discussed in this thesis. All interviews were with current and former employees of U.S. and European auto makers. Asian auto makers in general and Japanese auto makers in particular are known for using development processes that differ from their Western counterparts, so a deeper comparison of these practices would likely provide new insights.
- Significant organizational process change in the presence of cultural, managerial and technical factors described in this thesis could be expanded into an entire thesis by itself.
- In *Experimentation Matters*, Stefan Thomke includes some front-loading mechanisms that are not addressed here. These include project- to-project learning as a means of not repeatedly encountering the same problems (the ultimate example of early problem solving) and shifting experimentation

capabilities to users of a product rather than retaining exclusive control over those capabilities. Although not directly germane to this thesis, these concepts might play an important role for the network of organizations (auto companies and suppliers, CFD companies, etc.) considering implementing the kind of process change discussed here.

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