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**Design and Manufacturing of Car Doors:
Report on Visits Made to US, European and
Japanese Car Manufacturers in 2007**

Daniel E. Whitney
MIT Engineering Systems Division
Cambridge MA

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東京大学21世紀COE [工学経営]
ものづくり経営研究センター

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Everyone designs and manufactures doors differently and everyone thinks their way is the best.

I. Background

Starting in 2003, a research project was initiated at MIT aimed at understanding how to improve the design process for car doors. This research approached doors as complex systems in their own right and sought to make recommendations on how to improve door design in a systematic way. The results of this work, documented in [Stevens] and [Noor], are discussed in a later section of this report.¹

In 2007 the author, funded by the International Motor Vehicle Program (IMVP), visited Europe and Japan and studied door design and manufacture by several major auto manufacturers. The findings from these visits are also discussed later in this report.

The statement at the top of this page reflects the main finding. It contrasts the author's finding regarding automobile engines, which are largely designed and manufactured in similar ways [Peschard and Whitney]. In the discussion section we speculate on why there seems to be industry convergence in engines but not in doors.²

II. Characteristics of Doors

Doors are highly complex structures that contain just about everything that a car as a whole contains except for power train elements. Customers interact intimately with doors and are aware of them along many dimensions, called attributes by Ford and similar terms by other companies. Doors also comprise both interior and exterior elements, causing them to be links between these two domains of the car. Many of the attributes conflict: for example, better water leakage and wind noise behavior will make it more difficult to close the door; better side intrusion protection will make the door

¹ This research project was sponsored by Ford and pursued with consideration given to complementing organizational changes at Ford.

² A study done by Jay Baron of the Center for Automotive Research in Ann Arbor MI in the late 1990s compared door locator strategies across many car companies and also found no convergence. Also, no locator strategy could be correlated with the best variation in door fit [Baron].

heavier; better leakage around the glass makes it harder to raise the glass, requiring stronger motors, making the door heavier.³

The main door architectures in use today are shown in Figure 1.

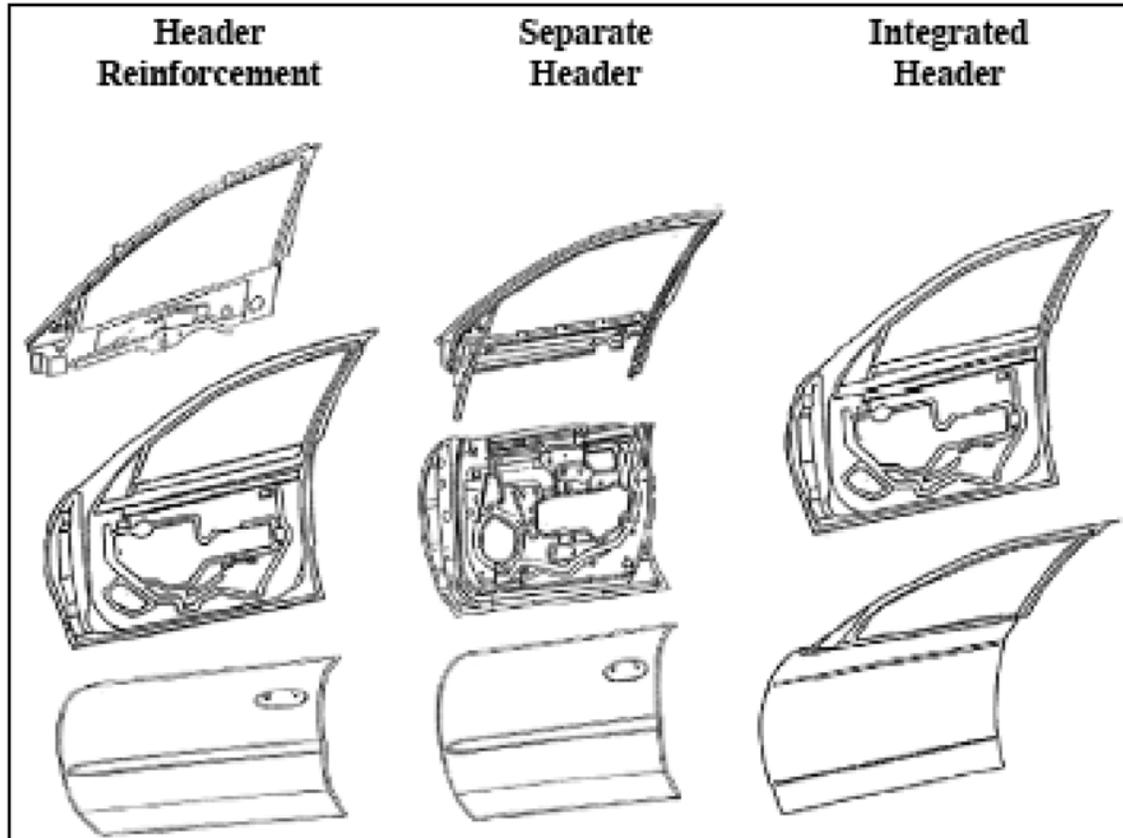


Figure 1. Three Different Door Architectures Used by Companies Visited (courtesy of Jay Baron [Baron])

III. Ford Study 2003 - 2007

Ford funded a study of door design under the Ford-MIT Research Alliance. The study was co-directed by Dr Janice Klein of the MIT Sloan School of Management and Dr Daniel Whitney of the MIT Engineering Systems Division and Department of Mechanical Engineering. Both management and technical aspects of door design were addressed. The Ford sponsors were Mr Will Boddie, then Vice President of North American Engineering, and Mr Al Ver, then Vice President of Advanced Manufacturing. Mr Boddie sought to improve door design by creating a new job title called Closures System Integrator (CSI) in the Engineering Department and Mr Ver sought similar results by creating a new job title called Manufacturing Systems Integrator (MSI). The goal was to increase focus on door attributes that customers pay attention to, such as wind noise, water leakage, closing effort, and squeaks and rattles, and to coordinate design and

³ This list is typical but valuable detail was provided by Mr Olivier Demouy of PSA.

manufacture of doors to achieve attribute targets with better time to market and lower variability.

Two strands of research were conducted. In [Stevens], the organizational and management issues were addressed. Engineers and managers were interviewed, organizational behaviors and power relationships were described, and methods for improving incentives to accept the CSIs and MSIs and address doors as systems were proposed. Ford is known for excellence in components, but attention to components has often overshadowed the need to compromise among components in order to meet the attribute targets. Power flows to the components in the form of budgets and signoff authority, and at best the CSIs rely on reputation and persuasion to obtain these compromises.

In [Noor], the design process for doors was documented using the Design Structure Matrix (DSM) methodology [Eppinger et al]. The DSM has been actively used at Ford for nearly 10 years and several of the CSIs had learned about it while obtaining advanced engineering degrees at MIT. DSMs are built by interviewing participants in the process. Noor also used a second method for documenting the structure of doors as mechanical assemblies. This method is known as the Datum Flow Chain (DFC) [Whitney]. It allows engineers to define locator schemes for door parts and necessary assembly tooling so that achievement of geometric attributes can be documented in a simple and consistent way.

Previous research on DSMs has shown that they are useful for documenting design processes and showing how components, organizations, and decisions interact. Once these are documented for an as-is situation, they can be learned by everyone involved and the process can be improved by removing redundancies, shortening or eliminating feedback loops and delays, and improving the accuracy and timeliness of information exchanges. Previous research on DFCs has shown that they not only document the engineering design intent but also display different organizational ownership of different parts of the chains. This in turn shows where cooperation and information exchange must be addressed in order to achieve each geometric attribute.

The DSM developed during this study traced the components and decisions related to five important attributes and thus does not comprise the entire door design process. Nevertheless it is large and highly interconnected. These facts show that few decisions can be made independently from others, and management of interfaces in the door and in the organization is essential for success. The DSM was also subjected to a time-based stochastic simulation, which showed that not enough time exists to carefully consider all the decisions that the CSIs and engineers want to address. As a result, the study recommended that Ford do more to standardize components, designs, and design processes, improve Computer-aided Engineering (CAE) methods for predicting door attributes, and improve design-manufacturing communication. All of these changes will shorten design time, increase the likelihood that doors will not need engineering changes after design, and reduce rework loops in the process.

Both studies recommended maintaining the CSI and MSI job positions and strengthening the organizational power of those positions vis-à-vis the power of component design supervisors.

IV. IMVP Visits 2007

MIT and the IMVP funded a series of visits by Daniel Whitney and IMVP colleagues to car makers in Japan and Europe in the Spring and Summer of 2007. Additional information from visits in the US in prior years was added to the more recent visit findings to fill in gaps. No visit to an engineering office or a plant lasting a day or two can permit a thorough analysis; even the four year study at Ford uncovered only a fraction of the activities, decisions, and effort required to design and manufacture car doors. Thus the visits must be viewed as snapshots. Every attempt was made to keep their content consistent so that comparisons would be possible. Each visit focused on how door attributes are managed during design and manufacture. Particular attention in engineering was paid to job descriptions, organization charts, span of control, state of standardization, and design aids such as CAD and CAE. Factory visits covered door buildup from stamped parts, door mounting to unpainted bodies, door final assembly, and door mounting and adjustment during final assembly, with detailed attention paid to locator schemes.

The companies visited were A, B, C, D, E, and F. We thank our hosts at these companies.

V. Findings

The findings are summarized in Figure 1. In general, the only common thing in the processes documented is that all the companies remove the doors after the body is painted, assemble components to doors on a separate line, and reassemble the doors to the cars late in the final assembly process. Almost nothing else is common. Each visit looked at a single car's doors in the factory, and in most cases doors for other cars at the visited company are designed and made differently in many respects. Toyota is notable in its efforts to design and make the majority of its doors based on the same standards [Whitney et al]. This is due to Toyota's extensive use of standard components, door architecture, and design and process commonality. Toyota developed its current standards 5 to 10 years ago. We speculate Toyota's policy of designing cars for production anywhere in the world and its practice of making as many as 8 different cars on the same line has also spurred the use of standards. The other companies visited have standardized to lesser degrees, have launched standards practices more recently, or standardize fewer things. Company E has the least opportunity to standardize because it makes cars for other car companies and must follow the procedures that their customers dictate.

In all other matters, designs, design organization, and locator schemes differ widely. Companies A, B, C and E focus on the door itself from an organizational point of view and are the most oriented toward the components in terms of design organization and

responsibility. Companies D and F recognize the system nature of doors more explicitly in the organization of the engineering processes, with D actually having departments and job titles containing the word “architecture” and “architect.” Toyota addresses the need to integrate by empowering the Production Engineering department [Whitney et al]. As noted in Section III of this report, Ford introduced the CSI position with the same intent. Toyota’s focus on production engineering as the integrator is unique in the car industry as far as we know.

Another important difference among the companies visited regards the scope of design authority accorded to the closures design organization. At a minimum, such a group has cognizance over the sheet metal and mechanical items in and on the door. At the maximum, this group (at company F) is responsible for all the closures and the adjacent glass all around the car. Being responsible for, or owning, all the glass as well as the sheet metal and mechanical components allows this group to exert coordinated design cognizance over a number of important attributes.

No one uses the same door architecture although all companies agree that simplicity, low part count, and stiffness are marks of a good architecture. Many say they have studied the others’ architecture and cannot understand why they should switch, being quite satisfied with their own choices.

Most companies showed me multiple cells in the body shop comprising multiple robots that accomplish door buildup. These systems contained between 12 and 18 robots, depending on the complexity of the door design and the degree to which people were used to load or transfer parts and subassemblies.

Finally, each company has adopted different locating schemes. Hinges were observed with one bolt hole, two bolt holes, and two bolt holes plus a locator stud for a total of three holes. Hinges come off doors, hinges come apart, and (in one company visited 7 years ago) hinges come off car bodies. Some doors have hinges with integral checks while others have separate checks. Some companies locate door outer panels to inners on holes while others use hem surfaces. Some use locator holes on doors to index them to car bodies while others measure gaps and position the doors to suit using robots or manual techniques.

Table 1. Summary of Findings

Company / Topic	A	B	C	D	E	F
Type of car at visit	Sedan, mid-market	Sedan, mid-up-market	Sedan, mid-market	Sedan, economy market	SUV	Sedan, mid-up-market
Door architecture (arch) at visit	Stamped inner and outer	Stamped inner and outer, outer occupies lower half only	Roll-frame upper welded to stamped lower after lower inner and outer are hemmed (smallest hemmer seen)	Stamped inner and outer	Stamped inner and outer, outer occupies lower half only	Stamped inner and outer, outer occupies lower half only
Other door arch remarks	One-piece inner	Stamped or roll formed upper reinforcement, one piece inner	Two-gauge inner spot welded during door buildup, threaded hinge reinforcements weld directly to inner	One-piece inner, separate nut plate reinforcement, nuts loose in pockets in this reinforcement	Two-gauge inner laser welded prior to door buildup; hinge studs welded directly to inner	One-piece inner, separate nut plate reinforcement, roll-form frame reinforcement
Is this the standard arch?	No	Emerging as the standard	Yes	No	Yes for this family of vehicles	Emerging
Reason for adopting this arch	No standard arch	Simple, stiff, can't see a reason for using roll-form frame arch	Simple, stiff	No standard arch		Stiffer than roll formed frame arch and much stiffer than stamped plus roll-form upper reinforcement
Other standardized items	?	Hinges, latches	Hinges, latches, door handles, window regulator, static and dynamic seals	Seeking but not achieved yet	No	Hinges, inner and outer handles, latches, window regulator, static and dynamic seals, motors
Date of start of standardization	Still developing	5 years ago for components	5 to 10 years ago	Still developing	Not applicable	10 years ago for components, 5 years ago for door
What CAE exists	Partial DCE*	Partial DCE	Regressions for DCE, blowout, tip	Packaging methodology in CAD, partial DCE	DCE emerging, noise mature	DCE

Company / Topic	A	B	C	D	E	F
Ability to predict door closing effort	Depends on prototypes	Good understanding of current design	Excellent understanding of standard design	Some	Some	Based on CAE and familiar design
Basis of door design org and management of attributes	Component-driven, system coordinator for attributes	Component-driven, will appoint an integration manager soon	Function-driven, strict adherence to standard design	“Door architect” coordinates requirements, “door pilot” coordinates components, both watch attributes	Function-driven, expert experience	Door design manager balances attributes, plus competence centers for sub-functions and components
What’s in door design responsibility scope	Door sheet metal and mechanicals	Door sheet metal and mechanicals	Door sheet metal and mechanicals	Door sheet metal, mechanicals, and door glass	Door sheet metal and mechanicals	Entire car glass perimeter, door sheet metal, mechanicals
General description of door mounting	Door inner has hinges located to inner panel master locators. Mounting fixture holds door on outer panel hole locators and indexes to body locators	Robot holds door, laser measures gaps and dist to seal, 2 nd robot tightens all bolts and nuts	Small fixture indexes to body locators and mounts hinges to body; doors attach via net holes on hinges and shoulder bolts	Door inner with hinges indexes via master locators to fixture installed in door opening that indexes to body locators	Door has hinges located to outer panel hems. Fixture indexes to body locators, holds door on outer panel hems. In-out set by shims in 0.5mm increments based on 2x/day CMM check of seal gap. Operators adjust F/A door position to achieve gaps.	Fixture mounts front and rear hinges to body at once, indexing on body locators at hinge mount area fwd and striker area aft. Hinges have locator cones that mate to door locators. Lower cone is loose and is tightened to set in-out.
Locators used during door buildup	Master locators on door inner, holes on door outer	Hinge plates located to inner via threaded holes that are not used as locators; master locators on inner, hem surfaces on outer used during hemming	Upper hinge plate located to hinge reinforcement via threaded hole; lower hinge plate indexed via threaded hole to inner panel master locators; holes on inner and outer used during hemming	Nuts loose in pockets in reinforcement; reinforcement located to inner master locators	Holes on door inner, studs on hinge plates, outer located on hem edges for hemming	Threaded hole and small clear hole in hinge plates, locators on hinge reinforcement, locator holes on inner panel, locator holes on outer panel used for hemming

Company / Topic	A	B	C	D	E	F
Locators used for hinges	Hinges located U/D and I/O from inner, location held with epoxy washer	Hinges have open holes on both flaps	Hinges mounted to car body using fixture that holds hinges by net pierced hole in door side flap	Studs on reinforcement used to place hinge locator studs in loose nuts; hinges index to these studs	Outer hem surfaces used to locate hinges on door	Cones on hinges go into large hole on hinge plates
Locators used for door mounting	Door outer locators and body locators, epoxy washer set during paint curing	Laser measurement of gaps and flushness, then bolts are tightened	Door bolted to hinge flap via shoulder bolt through net pierced hole	Door inner masters mate to fixture indexed to body	Outer hem surfaces for U/D and F/A, and shims for I/O	Hinges mount to body; fixture indexed to body uses cone on upper hinge to locate it to fixture, rotates door about X and sets lower cone
Are screw threads (internal or external) used in location?	No (all bolts go through open holes except one bolt goes through net hole in epoxy washer)	No (all bolts go through open holes)	Yes	Yes	No (all bolts go through open holes)	Yes
Door-off method	Hinge comes off door, epoxy washer holds door location on door side hinge flap	Bolt comes out of hinge	Shoulder bolt comes out of door side flap	Door side flap comes off locator studs on door	Bolt comes out of hinge	Hinge comes off door, uses cone for relocating
Robotics used for door buildup	No except for sealant at inner-outer joint	Yes	No except for sealant at inner-outer joint	Yes	Yes	Yes
Robotics used for door mounting	No	Yes: one holds and maneuvers door, other tightens bolts	No	No	No	No
Other aspects of door mounting	One door at a time	One door at a time	One door's hinges at a time	One door at a time	One door at a time	Front and rear hinges simultaneously by one fixture

Company / Topic	A	B	C	D	E	F
General layout of door manufacturing*	Stamping far remote from buildup, buildup remote from mounting	Stamping near-remote from buildup, buildup near mounting	Stamping near-remote from buildup, buildup right at mounting	Stamping near-remote from buildup, buildup near mounting	Stamping near buildup, buildup remote from mounting	Stamping near-remote from buildup, buildup near mounting
Degree of door adjustment at final	Considerable hammering and bending by hand or tools	A little hammering plus hitting striker	A little hammering plus hitting striker	A little hammering plus hitting striker	A little hammering plus hitting striker	None
Other aspects of door adjustment			Crews doing door mounting and final adjustment swap jobs at mid-day		Crews doing door mounting and final adjustment swap jobs each week	
Door passes thumb test**	No	Yes	Yes	Yes (Tested on previous model)	Yes	No, but large integral check closes the door

Notes: DCE = door closing effort. U/D = up/down. F/A = fore/aft. I/O = in/out. CMM = coordinate measuring machine. CAD = computer-aided design. CAE = computer-aided engineering. *General Layout: Far remote= more than 100m, remote = more than 10 km, near-remote = more than 100m, near = less than 100m, right at = less than 10m. **Thumb test: the front door is closed to the point where the latch gently rests on the striker. Other doors and windows are closed. The tester pushes sharply on the door with the thumb, which is placed on the door at the rear hem near the window belt. If the door closes, it is said to pass the thumb test. In the 1990s the author found that doors in this position had to be pushed with the foot to close them.

VI. Discussion

Automobiles are complex products. Their design and manufacture require that they be decomposed into manageable subunits, but there is no unique best decomposition. The components at the bottom of the decomposition, at least with current technology, seem distinct and easy to separate. Examples include wheels, exhaust pipes, power steering racks, shock absorbers, windshields, and headlights. But if we go up the decomposition we find ambiguity about which subsystems these apparently separate components belong to. Does glass belong to body? What about its effect on heat load and thus passenger comfort systems? Do exhaust pipes belong to chassis (for packaging and vibration) or to power train (for their role in emissions control)? Who should own the glass in doors?

Researchers have noted these difficulties. Both [MacDuffie] and [Fourcade] discuss the ambiguities over what “module” means and present via interviews and detailed case studies the problems that occur in engineering design and supply chain management when module boundaries are set inappropriately. [Fine and Whitney] identify this as a generic problem in make-buy decisions. Even though the parts are similar and assemble to each other in similar ways, the question of who owns them during design cannot be answered unambiguously. Hence we see different organizational assignments in different companies. Doors are a particularly acute example.

The situation with doors is complicated by the fact that their attributes conflict. Moreover, even though the closures designers own (that is, are responsible for) the attributes, some of the design decisions that affect the attributes are controlled by organizations that are outside the scope of closures design organizations, even those that own all the glass. This means that closures designers lack the necessary freedom to make their design choices in a simple independent way. Instead, their decisions interact with each other, not to mention that they interact with decisions made by others.

The result, not surprisingly, is that different companies have organized door design differently. Even those (companies C, D, and F) that recognize the system nature of doors most clearly, have chosen different routes. The only common thread is a move toward standardization, but even here there are differences, with Toyota being the most comprehensive (parts, architectures, and processes) as well as the most rigid. Standardization freezes the complex decisions in a place where everyone understands the outcomes. But such freezing can keep designs from evolving in useful or innovative ways.

Other companies, including A, B, and F, hope to manage the complexity by means of CAE. Neither standardization nor CAE solve the problem of ownership but each eases the discussion and decision processes by presenting the organization with well-documented or well-understood choices.

Not only are many organizational structures used but many door designs are used as well. All of them work to varying degrees but each represents a different endpoint in an over-constrained design space where no design can meet all the requirements ideally.

Less common than standardization is a move to emphasize the system nature of doors explicitly in the organization. Again, different companies have done this in different ways or to different degrees. Toyota retains a functional organization but ensures that middle and senior managers are fluent in system thinking and understand how things inter-relate [Sobek]. D has renamed its major engineering organizations and job titles to emphasize architecture and interactions. F assigns a manager to a car's closures who is responsible to the chief vehicle engineer for all door attributes. The other companies visited have moved less decisively along this route but appear to recognize the value of doing so.

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