Visit to Toyota July 31, 1991

Background

My host was Mr Y. Kuranaga, head of Development Div 1 of Information Systems Div 1 in the Information Systems Division. The entire operation has 641 people plus at least 330 outside software developers. Its mission is to develop and disseminate software for engineering, business, and factory operations, plus to provide software training. Toyota has agreements with several companies such as Nihon Unisys to support and sell its CAD software to Toyota's vendors.

The engineering computation system consists of 8 large mainframes and 4 supercomputers at headquarters plus other mainframes in the US and at the various plants. Recently a Transputer system was added to do color renderings of car bodies (see below). The administrative computing system also has 7 mainframes.

As at Nissan, computation supports most aspects of vehicle design, including CAD/CAM of body parts, exterior and interior design (interior was not as well developed at Nissan), CAD/CAM of mechanical parts like suspension and power train, structural and aerodynamic analysis, laboratory automation, stamping die manufacture, NC programming, and machining process planning. Toyota last made a clay model as primary design data input between 3 and 5 years ago. A good summary of Toyota's computational design work is in [Ohara].

Toyota makes about 3 times as many cars per year as does Nissan. About 5 new models, plus many minor redesigns, are in the design system at any time. There are about 200 stylists and 800 body engineers. No data are available on how many mechanical, production, and tooling engineers there are. It appears, however, that Toyota has more in-house people per car design project than Nissan has.

Nissan was a little better than Toyota at presenting the full picture and giving the flavor and comprehensiveness of its long range plans. However, I'm sure that Toyota is ahead in many areas technically. The scientific depth of its work in surface representations and data structures for holding and manipulating design data are two of many examples. The effort reminds one of Nippondenso's commitment to manufacturing equipment excellence as part of manufacturing excellence: it is something you cannot achieve by buying things from vendors.

Use of Computers in CAD/CAM/CAE

Toyota has major activities in this area. I was shown demonstrations of body styling CAD, stamping die design, formability analysis of sheet metal parts, CAM of stamping dies, engineering analysis of mechanical parts, process planning of machining, and offline robot programming. I did not see anything comparable to the assembleability analysis that Nissan showed me, however.

Body Styling

The objectives of computerized body styling are stated as

1) making higher quality surfaces
2) reducing the required manpower and leadtime
3) integrating CAD and CAM

Higher quality surfaces are smoother, the different sections of the body blend together better, and the final metal realization fits together better. Reduction of leadtime, interestingly, is stated as an explicit objective, something Nissan would not do. Integration of CAD and CAM is a longstanding goal of every car maker. Toyota appears to be several years ahead of other companies in realizing these goals.

The body styling activity takes the first year of the normal 4 year car design cycle. During this year, three or four complete cycles of styling and evaluation may occur. A cycle consists of making three-view sketches, converting them to 3D models and refining these, and making a 1/5th scale clay model by NC machining from the computer data. At least one full size clay is also made before the end of this year. A cycle typically takes 40 days, an impossible schedule to maintain if clay were used as the stylists' working medium and as the source of input data for computer models.

Body styling by computer dates to 1981, (Exhibit 1, top) with a complete end-to-end system working by 1986 or so. [Higashi et al] Major efforts were made to overcome well-known difficulties with designing and joining surface patches described by earlier theories. Methods of surface generation and curvature evaluation were devised that followed the stylists' methods. Control of surface curvature, its continuity, and its regularity or uniformity were found to be the most important factors. Primitive shadowing and rendering of highlight lines were possible in 1983. In the last year, extremely realistic color renderings have become possible. [Takagi et al]

The color renderings are computed on a parallel computer with 256 Transputer elements. Computation takes into account such factors as color, type of paint, weather conditions, and sun angle at various geographic locations. A new car or view angle can be computed in 30 minutes, a new color for the same view angle in 5 minutes. Among the features available that imitates the stylists' old methods is representation of reflections from several fluorescent tube overhead lights.

(refer to the graphic at http://web.mit.edu/ctpid/www/Whitney/japan.html)
Exhibit 1. Body CAD/CAM Integration at Toyota

The styling and rendering system is now used not only to design exteriors but interiors as well. I was shown photos of rough NC-milled clays of dashboards and center consoles (ash tray, shift lever etc.). The design studio has 65 32" diagonal measure flat screen CRT displays (2000x2000 pixels) for the purpose of designing and modifying these surfaces. They run off a Unisys 2200 mainframe.

The method of converting stylists' sketches to 3D model data demonstrates a widely-felt problem, namely that 3D modelers are too hard to use. Toyota employs specially trained computer technicians who convert the sketches into a first model which the stylist and the technician correct together. The technician interprets the shading in the sketch to obtain an impression of the intended shape, then produces that shape in a surface model. The stylist can view the realistic renderings, an orthographic line drawing, or a cross-section. Curves can be modified in ways very similar to those available in Macintosh drawing programs, the most familiar being adjustment of endpoint tangent vector lengths and orientations.

These technicians are obviously rather special people since they must have both an artistic sense and computer skills. They must also provide an important part of the human interface between the stylists and the computer.

Die Face Design and Formability Analysis

Dies cannot be the same shape as the desired final metal part due to the springback of the sheet metal and friction between it and the die face. It used to take about three weeks to design a simple die but now with the computer system it takes only one week. The functions supported include direct data transfer from the styling database, addition of shape details for the final part (lightening holes, folds from front to back, locations for fasteners) and details to permit forming (flanges where the die grips the perimeter of the piece), plus formability analyses. These analyses permit the die designer to predict possible forming problems and redesign the stamping process (or occasionally ask the stylist to change the part) to avoid them.

This system is well-described in [Takahashi et al, 1985] and is credited with shortening die design time by 50%, die manufacturing by 30%, and die tryout by 30%. A major point made by this paper is that the program does not use

Finite Element Method (FEM) for stress and formability analyses. Instead, rather basic analyses are used. These include local elongation ratio, speed of deformation in local regions, shape change of grid lines, and other functions that can be computed either from geometry alone or from basic stress analysis. The goal was not a perfect system but one that would help designers find good solutions using methods they could understand and interact with.

Exhibits 2 and 3 contain a nice example. Here the use of the mean section length ratio is shown. Along a particular feature line, different segments are defined (sections) and their length before and after forming is calculated. The maximum ratio before and after and the rate of change of this ratio along the feature line are cross plotted. Data of this type for ten past designs were collected and correlated with the die tryout time for each. Excessive tryout times (over 900 hours) lie above the diagonal line, providing designers with rapid feedback on potential problems months in advance. Another feature of this type of analysis is that the designers can put in their own experience, giving them a feeling of ownership and confidence in the program and allowing data to be accumulated for future use or training of new designers.

Exhibit 2. Use of the Mean Section Length Ratio
(refer to the graphic at http://web.mit.edu/ctpid/www/Whitney/japan.html)

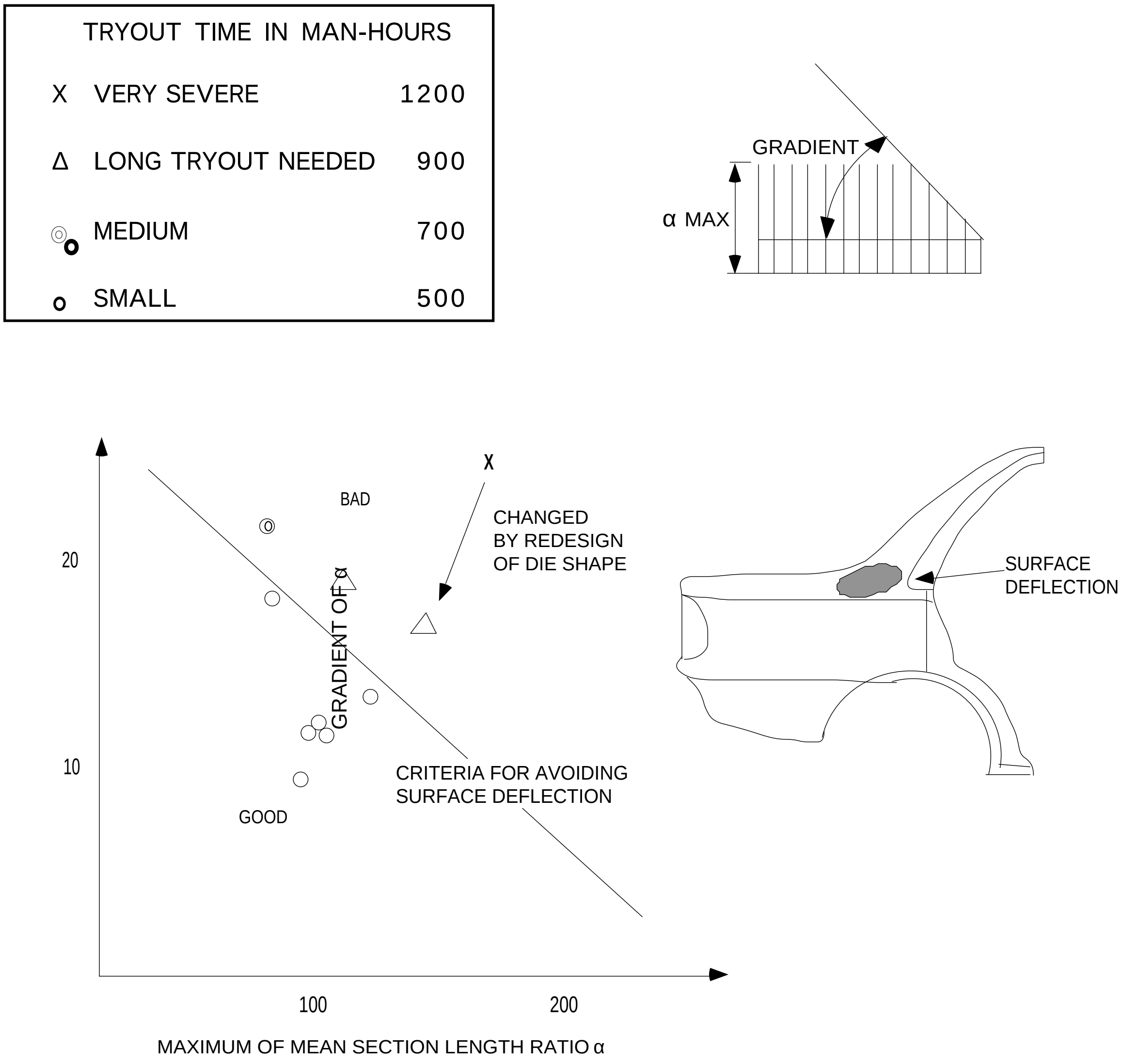

Exhibit 3. Criteria of Surface Deflection in Quarter Panels by the Mean Section Length Ratio. The pillar base of a quarter panel for a notch-back style car is in the shape of a saddle, which results in nonuniform forming. Therefore, surface deflection tends to occur at this portion. It is vital to check on the mean section length ratio as well as the spreading behavior of the punch contact area to avoid the surface deflection. The figure shows processed data of the formability evaluation according to mean section length ratio in 10 kinds of quarter panels of recent models. Maximum values of this raio are plotted against gradient of this ratio and a line is drawn to separate the good designs from the bad ones according to the die tryout time.

It is said that in some US car companies, methods like this cannot be used effectively because the stylists will not modify their designs. In one company, the stylists report to the chairman of the board whereas the engineers report to the president. In another company, a similar integrated body engineering system is being pursued but is delayed because many of the component analyses are approximate. Toyota obviously decided not to wait until perfect analyses were available, and went ahead to tackle the problems of integrating the existing tools into one system. This decision has put Toyota on a higher plateau, since integration is a new learning opportunity.

Process Planning for Machining "Box-type" Metal Parts

This system helps designers to choose the necessary machines and tools for making complex parts. An example is a complex aluminum cylinder head with pockets and holes for cam shafts, valves, valve springs, and so on. It is assumed that the part will be made on an existing set of NC machines with a continuous parts conveyor. Parts can circulate on this conveyor and visit any machine in any sequence. Thus transportation capability does not limit process planning.

The part is divided up into regions in two ways: by type of feature (hole, flat) and direction of machining (front, back, perpendicular, oblique). I believe that the software finds the features itself, but I am not sure about this. The machining system is divided into zones containing machines capable of dealing with one or more feature types and directions.

The software makes two types of calculations: finding the right zone for a group of features, and planning the cutting conditions for each feature. When several zones are capable of making a feature set, the designer chooses one. He does this apparently without any consideration of workload in the zone from other parts. Each hole feature is classified by a group technology technique using such characteristics as number of steps, tolerance on diameter, need for threads and chamfers, and so on. From these characteristics, the cutting time is estimated and compared with the cycle time capability of the zone. The designer can alter the plan to correct cutting time imbalances among machines or he can try a different zone. The system then calculates the details of the plan such as cutter path and tool number.

The process plan for the valve cover took 5 days vs a month before the system was used.

Robot Offline Programming

I was shown a color 3D wireframe simulation of robots spray painting car bodies and parts. Both stationary parts and continuously moving cars were shown. The problem is to program the robot to move the spray gun over the car's surface. In the past this has been done on the factory floor by human teachers who physically grasp the end of the robot and move it while a tape recorder records the moves for later playback. The number of robots now has grown to the point where there are not enough teachers.

This problem was anticipated some years ago and for the last 1.5 years the system I was shown has been in use. It is similar to commercial software available in the US from at least two companies. The programmer moves the robot's tip with the mouse or by indicating target points on the car body and indicating offset distances from the targets to the tip. After a path pattern has been programmed, it can be duplicated and stepped along the surface so that it is "sprayed" completely. The robot's motions can then be simulated and two checks made: range of motion in each joint, and interference between robot and car. The required motion time can also be calculated. Exhibit 4 shows the computer screen during programming of spraying the underside of an open car hood. The line of sight is from the outside of the transparent hood to the tip of the robot behind the hood. A simple path connecting target points at the edges of the hood is shown.

(refer to the graphic at http://web.mit.edu/ctpid/www/Whitney/japan.html)
Exhibit 4. The Computer Screen During Programming of Spraying The Underside of An Open Car Hood.

Curiously, even though the car body is represented by the CAD shape data from the styling system, and die faces can be machined by NC programs that are written directly from those data, the paint robot cannot be similarly programmed. The demonstrator, a Toyota programmer, said he will implement this obvious capability soon.

Another curious fact is that there is no feedback to the programmer concerning whether the robot path's velocity profile and distance from tip to part will provide a good paint finish. Possibly the software picks an appropriate profile once the target points are given.

CAD and CAE in Engine Design and Body Engineering

Typical applications are FEM studies of various types. These date from 1975 and have grown steadily until there are now 60 engineers developing or supporting such software. SDRC's solid modeler is the front end of many of these studies, but Toyota has its own pre/post-processor called CADETT. (Everyone I visit says it takes too long to prepare data for FEM analyses. Even those that have "automatic" meshers say so.) Two Cray's and two Fujitsu vector processors support this work. NASTRAN, MARC, PAMCRASH, ABAQUS and ADAMS are used along with a home-grown solid modeler called SURFES.

Engine component analyses include stress in pistons and connecting rods, temperature distributions, vibration in pipes and oilpans, and residual stress in machined aluminum engine blocks. Simulations using in-house software include piston slap, torsional vibration, oil film thickness, volumetric efficiency, and valve train dynamics. Piston temperature distribution calculations required a fuel consumption model as well as effects of coolant and lube oil on heat dissipation.

In a video I saw very accurate roll-over simulations, side by side with actual cars doing the same thing, plus behavior of active suspensions and skid control systems, engine block-transmission case torsional vibrations, and acoustics of a car interior.

All of the demos I saw were either on video or in the software development and training facility so I could not tell how extensively they are used. However, it is obvious that most of these capabilities are in daily use and many have been for 3 to 5 years or more.

Future Needs and Plans

As mentioned above, I did not get a comprehensive view here like I got at Nissan. The needs expressed here are probably a fraction of what is on their minds these days. These include

1) Better integration of databases. Right now many programs are in islands, requiring painful data conversion. This is especially true of FEM, where Toyota hopes some AI methods might be used to speed up meshing.
2) New ways to design so that the percentage of automation of final assembly can be increased. Currently it is around 5% and they would like to see 20% or 30%. (VW estimates that it has had 25% since 1984.) One approach is to use more modules or preassembled units rather than single parts. Nissan brought up the same issue.
3) Expert systems to help designers lay out the human factors of car interior design. These include where pedals should be located, what is a good view angle or range to dashboard items or out the window, and how much force is needed to move handles, wheels, and buttons.
4) Artificial reality to aid interior design.

Concluding Remarks

Toyota emphasized several points that I also heard at other companies. First, CAD planning activities and implementation departments are a permanent feature of operations. These departments are staffed at least in part by former engineers. They are very conscious of the needs of users when they design new CAD tools: try to recreate the designer's previous working environment and methods, and provide tools that the designers can understand and therefore trust. These ingredients are essential in getting the tools accepted and used regularly.

References

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[Takahashi et al 1] Takahashi, A., Okamoto, I., Hiramatsu, T., and Yamada, N., "Evaluation Methods of Press Forming Severity in CAD Applications," Computer Modeling of Sheet Metal Processes, 1985 (the best citation I have)

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