Applying a Complex System Architecture Evaluation Method to the 2005 Ford GT

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Outline

- Background – Ford GT
- Introduction
- Method Overview
- Method Applied
  - 2005 Ford GT Powertrain
- Conclusions
- Lessons Learned
- Question and Answer

Photo by Orlando Echeverria
Ford GT Background/Heritage

- Ford Centennial – 2003
- 1960’s GT40 Race Car Heritage
  - Beat Ferrari!

1966 Ford GT40 Winning LeMans 1-2-3

Henry Ford’s Original Horseless Driven Carriage
Ford GT Background/Heritage

- 1967 Ford GT40 Mark IV Win at LeMans

Owner Caroll Shelby with the Winning Car

First Champagne Spray...in Racing...Ever
Introduction - System Architecture

- Function
- Related by Concept
- To Form

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Introduction - System Architecture

- Function
- related by Concept
- to Form

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Introduction - Architecture Influence

• System Architecture Dominates Outcome

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Introduction - Industry Challenge

- System Architecture defined mainly by judgment
- **Issues uncovered** in tooled hardware...too late
Introduction - Industry Challenge

- Often compounded by inadequate Goals, Constraints, Boundaries and Context definition
Introduction – Challenge – Softer Side

• Softer Influences
  – Corporate Core Competency
  – Political, Cultural and Strategic Lens
  – Major impact on the Ford GT System Architecture – especially Powertrain
Method – Framework

• Hierarchical synthesis of known tools and methods

Phase 1
- Upstream & Downstream Influences Identification
- Functional Requirements Cascade

Phase 2
- System Architecting Principles Application

Phase 3
- QFD Analysis

Phase 4
- DOE Methods Applied In Parametric Models

QUALITATIVE

QUANTITATIVE

Holistic System Architecting Framework
Method – Phase 1: Upstream Influences

Regulation

Corporate, Marketing Strategy

Beneficiary/Customers

Competitive Environment

Downstream Strategies, Competence

Technology

Need

Goals

Architecture

Function

Form

Concept

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Method – Phase 1: Downstream Influences

Architecture

Form

Concept

Function

Design
Implementation

Operator (training, etc.)
System Operating
Operational cost

Evolution

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Method – Phase 1: Concept Cascade

- Function, Concept, Form and Operations Decomposition

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Method – Phase 2: Architecture Principles

• System Architecture Principles
  – An underlying and long-enduring fundamental that is always or almost always valid

  *Massachusetts Institute of Technology © Ed Crawley 2001*

• Five chosen and developed for application
  1. Minimize Complexity
  2. Form, Function and the Laws of Physics/Nature Union
  3. Balanced Architecture
  4. Synergy
  5. Balanced External Forces
1. Minimize Complexity by Crawley
   - Minimize actual and perceived complexity

\[
\text{Complexity} = N\_\text{things} + N\_\text{thing\_types} + N\_\text{connections} + N\_\text{connection\_types}
\]

Massachusetts Institute of Technology © Ed Crawley 2007

1966 Ford GT40 Frame

2005 Ford GT Frame
2. Form, Function and the Laws of Physics Union
   – By Frank Lloyd Wright with Ahlman Addition
   – Architect form and function as one, in unison with the Laws of Physics

South Pointing Chariot
Compass
3. **Balanced Architecture** by Ahlman

- Architecture is absent of “extremes” and embodies necessary compromise
- 0th Order Judgment Based
  - Balanced by Physics
- Very Context Based

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**Method – Phase 2: Architecture Principles**
Method – Phase 2: Architecture Principles

4. Synergy
   – Where the whole is greater than the sum of the parts
5. Balanced External Forces by Lim, Crawley and Ahlman

- Balance the system goals and constraints against inherent risk in the system architecture
- Includes consideration for
  - Emergent Behavior
  - Corporate Core Competency
  - Political Environment
  - Corporate Strategy
  - Corporate Culture
Method – Phase 3: QFD

- Way beyond 7 +/- 2
Method – Phase 4: Design of Experiments

- Models applied to better understand complex dynamics
### Method – Phase 4: Design of Experiments

- **Design Parameter (Factors)**

<table>
<thead>
<tr>
<th>Factor Level Setting</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor Name</td>
<td>Low (-1)</td>
</tr>
<tr>
<td>Overall Weight (lb)</td>
<td>3100</td>
</tr>
<tr>
<td>CG Height (in)</td>
<td>17</td>
</tr>
<tr>
<td>Weight Distribution (%)</td>
<td>43</td>
</tr>
<tr>
<td>Overall Yaw Interia (ft-lb-s^2)</td>
<td>1800</td>
</tr>
<tr>
<td>Overall Pitch Inertia (ft-lb-s^2)</td>
<td>1700</td>
</tr>
<tr>
<td>Overall Roll Inertia (ft-lb-s^2)</td>
<td>900</td>
</tr>
</tbody>
</table>
Method – Phase 4: Design of Experiments

- Against Output Variables (Responses)
  - Balance, cornering speed, straight line speed
**Method – Phase 4: Design of Experiments**

- **Utilizing Specific Designed Run Matrix**

<table>
<thead>
<tr>
<th>Run</th>
<th>Factor A</th>
<th>Factor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Where -1 = low setting, 0 = nominal setting and 1 = high setting for a factor
Method – Phase 4: Design of Experiments

- Quick Turn-Around Analysis with Resultant Response Surface Equations
- True Sensitivities
Method Applied– Goals Background

- Initial 2005 Ford GT Goals
  - Program Mantra - “Looks Good, Goes Fast, Handles Great”
  - Program Benchmarks – 2003 Ferrari 360 Modena and Dodge Viper
  - 1960’s GT40 Race Car Heritage – Beat Ferrari! Dominated LeMans
  - Functional Attribute Targets
  - Ford Centennial – 2003 - 1 year after program start

2003 Ferrari 360 Modena

1966 Lemans Ford GT40 Win 1-2-3
Method Applied – Phase 1: Goals

- High Level “Vision” but Lacked Prioritized System Goals
  - Big gap between high level and detailed functional requirements

Created the System Goal Statement (Mission)

- Intent
  - Provide the undisputed performance leader in the two seat, tier three supercar segment (under $200K) to customers from 2005 – 2008

- Process
  - by creating the best balance of attribute performance, image, quality and refinement in a Ford Motor Company vehicle

- Metric
  - provides XXX SVA and symbolizes our engineering excellence
Method Applied—Phase 1: Live/Die Goals

1. Overall Vehicle Dynamic Performance
2. Handling Performance
3. Straight-Line Acceleration Performance
4. Aesthetic Appeal – Maintain the GT40 Concept Integrity
5. Braking Performance
6. Steering Performance
7. Craftsmanship
8. Exhaust Tone/Note
9. Drivability
10. Shift Quality
11. Primary Ride Quality
12. Seating Package
Method Applied – Phase 1: Constraints

1. Federal Regulations
2. Timing
   – The Ford Centennial
3. Quality/Reliability
   – Corporate Requirements
4. Functional Attributes
   – Corporate Requirements
5. Assembly
   – Meet production schedule
6. Technology Strategy
   – Use only industry proven technologies
7. Maintainability
   – Serviced at Ford Dealerships with current Service Tools
Method Applied—Phase 1: Constraints

- Timing - toughest constraint by far

Ford S6, P6
Standard Timeline

1.8 x GT Timeline

Left Side of “Vee” - Architecture & Design
Definition - 6 x GT Timeline

Ford GT Timeline

Budget ~ Lincoln LS Refreshening
¼ Engineers to Standard Ford
No time for Iteration
We had to be Very Predictive

3 Production Level Cars Delivered for Centennial
Full Production Starts
Method Applied – Phase 1: Concept Map

Ford GT steering & handling functional requirements concept map example

**Goal**
- SS Lat Acc > 0.99 G's
- 600' Slalom Speed > 71 mph
- Yaw Phase Lag Frequency
- Response < 80 ms
- Steering Torque vs Lat Acc = Linear

**High level Concept**
- "Supercar"

**Operator**
- Driver

**Event Timing**
- Steering Wheel Input
- Corner Entry
- Mid Corner - SS Corner Exit

**Vehicle Concept**
- Chassis
- Powertrain
- Body
- Electrical
- HVAC

**Function**
- Creating Cornering Dynamics
- Controlling Cornering Dynamics
- Housing Driver/Passenger

**1st Level Decomposition**

**Function**
- Creating Tire CP
- Forces/Moments
- Controlling Tire CP
- Forces/Moments

**Chassis Concept**
- Frame/Structure
- Suspension
- Steering
- Brakes
- Wheels/Tires
- Dynamic Control System

**2nd Level Decomposition**

**Chassis Form**

**Design Parameters**
- Mass - Sprung, Unsprung (lbm)
- CGx, CGy, CGz (in)
- Ixx, Iyy, Izz - Sprung, Unsprung (in^4 lb)
- Track - front, rear (in)
- Wheelbase (in)
- Aerodynamics - Drag and Lift (lbf), CofP (%)

**Operation Concept**
- Driver/Vehicle Cornering Concept

**Event Timing**
- Front Tire Slip Angle
- Front Tire Lat Force
- Vehicle Yaw
- Rear Tire Slip Angle
- Rear Tire Lat Force
- Lateral Weight Transfer
- Vehicle Roll Angle

**Design Parameters**
- Tire 3 Axis Force and Moment Properties
- Steering Wheel Torque vs Lateral Acceleration
- Steering Wheel Torque vs Yaw Gain
- Damping - Sprung/unsprung Mass
  - 3 Axis Translation/Rotation (lbf-s/in)
- Suspension Compliance - Unsprung Mass
  - 3 Axis Translation/Rotation (lbf/in or lbf/deg)
- Suspension Kinematics - Unsprung Mass
  - 3 Axis Translation/Rotation (in/in or deg/deg)
- Suspension Friction (lbf)
Method – Phase 2: Architecture Principles

1. Minimize Complexity
   – Actual and perceived
Method – Phase 2: Architecture Principles

2. Form, Function and the Laws of Physics Union

- Weight
  - S/C
  - Accessories
  - Cooling
- CG height and weight distribution
- Polar Moments of Inertia
- Torque

![Engine Image]

![Graph Image]
3. Balanced Architecture
   – Architecture is absent of “extremes” and embodies necessary compromise
Method – Phase 2: Architecture Principles

4. Synergy
   – Where the whole is greater than the sum of the parts
1. Overall Vehicle Dynamic Performance
2. Handling Performance
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8. Exhaust Tone/Note
9. Drivability
5. Balanced External Forces

- Balance the system goals and constraints against inherent risk in the system architecture
- Includes consideration for
  - Emergent Behavior
  - Corporate Core Competency/Culture
  - Political Environment
  - Corporate Strategy

Many Super Charged Engines

V10 – Advanced Powertrain
Method Applied – Phase 3: QFD
## Method Applied – Phase 3: QFD Example

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Weighting</th>
<th>Engine/Induction</th>
<th>Architecture</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Federal Regulations- Emissions only</td>
<td>10</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>2- Timing- J123, Production</td>
<td>10</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3- SVA impact- Fixed Cost</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>4- SVA impact- Variable Cost</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>5- Quality/Reliability</td>
<td>10</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6- Mfg/assembly</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>7- Maintainability: No specialty Tools</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live or Die Goals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8- Overall Vehicle</td>
<td>10</td>
<td>3</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Dynamic/Track Performance</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>9- Handling Performance</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>10- Straightline Acceleration Performance</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>11- Aesthetic Appeal- Maintain GT Concept Integrity</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>12- Braking Performance</td>
<td>8</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>13- Steering Performance</td>
<td>8</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>14- Craftsmanship</td>
<td>8</td>
<td>3</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>15- Exhaust Tone/Note</td>
<td>7</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>16- Drivability</td>
<td>7</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>17- Shift Quality</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18- Primary Ride Performance</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>19- Seating Package</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>
Notes for Background on the QFD shown during the webinar, especially based on questions after showing the QFD result versus the chosen GT powertrain architecture.

- It was completed by chassis/vehicle dynamics engineers with aid by power train engineers. So it embodies a vehicle dynamics focused perspective. A QFD of this nature should be completed by multiple stakeholders since it does involve significant judgment.
- Corporate powertrain engineers noted Concept 4, the Aluminum 5.8L, pushrod actuated OHV, normally aspirated engine was not likely feasible for Ford due to migration away from this type of architecture.
- Program constraints, core competency and politics hurt Concept 3 a lot, the V-10, from the start as a legitimate concept to consider, but it was worth having in the analysis.
- The power of the QFD is shown in which many of us, including powertrain experts, intuitively believed the twin turbo version would “win” this comparison. It was last.
- As noted, program timing constraints heavily dominated some of the system architecture decisions. Evaluations shown in this framework show there were considerable opportunities to improve the architecture decision, but in the end viewed as infeasible.
  - Could such a special vehicle been even better with respect to its goals? Likely. But the results within extreme constraints, where “churning” was not an option, may point to some significant lessons regarding constraints and their impact on system results.
### Method Applied – Phase 3: QFD

- **Reasoning Matrix – Reasoning for Each Score**

<table>
<thead>
<tr>
<th>Row-Column</th>
<th>QFD Scoring Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Turbo charger's negative impact on catalytic converter light-off as it absorbs heat.</td>
</tr>
<tr>
<td>1-4</td>
<td>Pushrod historic emissions performance and OEM-A's departure from development of this architecture.</td>
</tr>
<tr>
<td>2-2</td>
<td>Core competency is not as strong with regard to turbo charged systems; therefore, increased design/development time is predicted with respect to option 1.</td>
</tr>
<tr>
<td>2-3</td>
<td>Noted V10 challenges including crank and cooling; therefore, a considerable increase in design/development time is predicted with respect to option 1.</td>
</tr>
<tr>
<td>2-4</td>
<td>Emissions challenges and OEM-A's departure from development of this architecture; therefore, a considerable increase in design/development time is predicted with respect to option 1.</td>
</tr>
</tbody>
</table>
## Method Applied – Phase 4: DOE

### Handling DOE Factors

<table>
<thead>
<tr>
<th>Handling Factor Level Setting</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor Name</td>
<td>Low (-1)</td>
</tr>
<tr>
<td>Overall Weight (lb)</td>
<td>-5%</td>
</tr>
<tr>
<td>CG Height (in)</td>
<td>17</td>
</tr>
<tr>
<td>Weight Distribution (%)</td>
<td>40</td>
</tr>
<tr>
<td>Front Camber (deg)</td>
<td>-0.25</td>
</tr>
<tr>
<td>Rear Camber (deg)</td>
<td>-0.25</td>
</tr>
<tr>
<td>Front Tire Peak Cornering Grip Scaling</td>
<td>-5%</td>
</tr>
<tr>
<td>Rear Tire Peak Cornering Grip Scaling</td>
<td>-5%</td>
</tr>
<tr>
<td>Front Tire Peak Brake/Drive Grip Scaling</td>
<td>-5%</td>
</tr>
<tr>
<td>Rear Tire Peak Brake/Drive Grip Scaling</td>
<td>-10%</td>
</tr>
<tr>
<td>Front Tire Cornering Stiffness Scaling</td>
<td>-15%</td>
</tr>
<tr>
<td>Rear Tire Cornering Stiffness Scaling</td>
<td>-5%</td>
</tr>
<tr>
<td>Overall Yaw Moment of Inertia (lb-ft-s^2)</td>
<td>-5%</td>
</tr>
</tbody>
</table>
Method Applied – Phase 4: DOE

200 Foot Constant Radius Event - Peak Cornering Speed Factor Sensitivities

Peak Cornering Speed (mph)

-0.2 0 0.2 0.4 0.6 0.8 1 1.2

- tire-Plat  rTire-Plong \%  rTire-CS * 
  Wt  CG-h  Fw/2  Tire-Plat * 
  rTire-Plong  rTire-CS  Wt * CG-h

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Conclusions and Lessons – Method

- Clearly defined and prioritized Goals and Constraints are fundamental
- Crawley’s Upstream and Downstream Influences encompass the major elements
- The addition of Design Parameters to the Functional Requirements Concept Maps are Important
- Rigorous process and methods still maintain significant white space for judgment and creativity
- The holistic framework and rigorous hierarchy – increasing fidelity functioned well – right tool at right step
- The process showed significant areas of opportunity for improvement on the Ford GT architecture. As often the case, constraints (timing, resource and mandates) along with the “softer side” influences can dominate architecture decisions.
Lessons Learned - Method

• Recommend more explicit definition of architecture boundaries and context – Skateboard Example

- What is the whole product system?
- What is the use context in which it fits?

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Conclusions – Ford GT

• In the end, the Ford GT Team created a car that met and exceeded its Goals within unmatched constraints
• The 2005 - 2006 Ford GT dominated its competitors in performance for almost 5 years
• Over 30 international magazine covers
• Already appreciating in value
The 3 Centennial Cars