SAE Baja: Project Proposal
Suspension and Steering

Benjamin Bastidos, Victor Cabilan, Jeramie Goodwin, William Mitchell, Eli Wexler

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Overview

- Introduction
- Concept Generation & Selection
- Engineering Analysis
  - Structural: Tie Rod, Front A-Arms, Rear Trailing Arms
- Cost Analysis
- Conclusion
Project Introduction

- 2014 SAE Baja Competition
- Customer is SAE International
- Stakeholder is NAU SAE
- Project advisor is Dr. John Tester
Need Statement

- NAU has not won an event at the SAE Baja Competition in many years
- Goal of the suspension team is to design the most durable, and versatile front and rear suspension systems
- Goal of the steering team is to design an efficient steering mechanism that will meet the needs of off-road racing
Design Objectives

- Minimize cost
- Maximize suspension member strength
- Minimize suspension member weight
- Minimize turning radius
Constraints

• AISI 1018 tubing or equivalent strength
• Funding
• Must Follow SAE International Collegiate Design Series, Baja SAE Series Rules
# QFD Matrix: Steering

<table>
<thead>
<tr>
<th>Customer Needs</th>
<th>Customer Weights</th>
<th>Y.S.</th>
<th>Caster Angle</th>
<th>Ackerman Angle</th>
<th>Turning Radius</th>
<th>Cost</th>
<th>Bolt Shear Stress</th>
<th>Unit of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lightweight</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td></td>
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<tr>
<td>2. Maneuverability</td>
<td>10</td>
<td></td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>3. Relatively inexpensive</td>
<td>6</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td>9</td>
<td>3</td>
<td></td>
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<tr>
<td>4. Stable/safe</td>
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<td>9</td>
<td>9</td>
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<tr>
<td>5. Must be durable</td>
<td>8</td>
<td></td>
<td>9</td>
<td></td>
<td>9</td>
<td>3</td>
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<tr>
<td>6. Transportable</td>
<td>8</td>
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<td><strong>171</strong></td>
<td><strong>171</strong></td>
<td><strong>141</strong></td>
<td><strong>156</strong></td>
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<td><strong>17%</strong></td>
<td><strong>17%</strong></td>
<td><strong>14%</strong></td>
<td><strong>15%</strong></td>
<td><strong>5%</strong></td>
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<td>psi</td>
<td>degrees</td>
<td>degrees</td>
<td>ft</td>
<td>$</td>
<td>psi</td>
<td>lb</td>
<td></td>
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## QFD Matrix: Suspension

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<th>Customer Needs</th>
<th>Customer Weights</th>
<th>Ground Clearance</th>
<th>Suspension Travel</th>
<th>Y.S.</th>
<th>Stiffness</th>
<th>Spring Rate</th>
<th>Cost</th>
<th>Weight</th>
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</thead>
<tbody>
<tr>
<td>1. Lightweight</td>
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<td>2. Maneuverability</td>
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<td></td>
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<td>9</td>
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<tr>
<td>3. Relatively inexpensive</td>
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<td>1</td>
<td></td>
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<td>9</td>
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<tr>
<td>4. Must be safe</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>5. Must be durable</td>
<td>8</td>
<td></td>
<td></td>
<td>9</td>
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<td><strong>135</strong></td>
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<td><strong>Relative Weight</strong></td>
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<td><strong>13%</strong></td>
<td><strong>14%</strong></td>
<td><strong>12%</strong></td>
<td><strong>12%</strong></td>
<td><strong>15%</strong></td>
<td><strong>21%</strong></td>
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</tr>
<tr>
<td><strong>Unit of Measure</strong></td>
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<td><strong>in</strong></td>
<td><strong>in</strong></td>
<td><strong>lb</strong></td>
<td><strong>lb/in</strong></td>
<td><strong>$</strong></td>
<td><strong>ft</strong></td>
<td></td>
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Operating Environment

- Cinders OHV Area
- El Paso Gas Pipeline Service Road
- NAU Building 98C
- NAU Parking Lot 64
Concept Generation & Selection

- Steering
  - Rack and Pinion
  - Pitman Arms
- Suspension
  - Double A-Arms
  - Twin I-Beam
  - Semi-Trailing Arm
  - Solid axle
- Tubing Selection
Steering Design 1

• Pitman Arm Steering Assembly
  • Advantages
    o Easily repaired
    o Robust
    o Strictly Mechanical Components
  • Disadvantage
    o “Dead Spot”
      ▪ Response time

Figure 2: Pitman Arm
Source: Car Bibles
Steering Design 2

- Rack and Pinion
- Advantages
  - Smooth gear Meshing
  - Simple mechanical design
- Disadvantage
  - Not as durable than pitman arm style

Figure 3: Rack/Pinion
Source: Car Bibles
Suspension Design 1 (Front & Rear)

- Independent Suspension
- Advantages
  - Lightest weight
  - Good range of travel
- Disadvantages
  - Not as strong as other considered designs

Figure 4: A Arm
Source: CarBibles
Suspension Design 2 (Front)

• Equal I Beams
• Advantages
  o Allows for maximum travel
  o Best articulation
• Disadvantage
  o Susceptible to bumpsteer
  o Radical camber & caster change

Figure 5: I-Beams
Source: HM Racing Design
Suspension Design 3 (Rear)

- Trailing Arm
- Advantages
  - Lots of travel
  - Truly independent
  - Strong
  - Simple
- Disadvantages
  - Camber is static
  - Handling suffers at limit

Figure 6: Trailing Arm
Source: SAEBaja.net
Suspension Design 4 (Rear)

- Live Axle/Solid Rear Axle
- Advantages
  - Tough
  - Simple design
  - Good articulation
  - Reliable
- Disadvantage
  - Large unsprung weight
  - Wheels are not independent

Figure 7: Solid Axle
Source: Motor Trend
### Table 3: Front Suspension Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>A Arm</th>
<th>Equal I Beam</th>
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<tr>
<td>Simplicity (0.20)</td>
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<tr>
<td>Reliability (0.30)</td>
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<tr>
<td>Weight (0.30)</td>
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<td>2</td>
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<tr>
<td>Cost (0.20)</td>
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<td>3</td>
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<tr>
<td><strong>Totals</strong></td>
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<td><strong>3.2</strong></td>
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## Table 4: Rear Suspension Decision Matrix

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<th>Requirements</th>
<th>A Arm</th>
<th>Solid Axle</th>
<th>Trailing Arms</th>
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</thead>
<tbody>
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<td>Simplicity (0.20)</td>
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<td>4</td>
<td>4</td>
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<tr>
<td>Reliability (0.30)</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Weight (0.30)</td>
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<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Cost (0.20)</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>3.5</strong></td>
<td><strong>3.3</strong></td>
<td><strong>3.7</strong></td>
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</table>
Table 5: Steering Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Rack &amp; Pinion</th>
<th>Pitman Arm</th>
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</thead>
<tbody>
<tr>
<td>Simplicity (0.20)</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Reliability (0.30)</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Weight (0.30)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Cost (0.20)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>4.2</strong></td>
<td><strong>3.8</strong></td>
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Tubing Selection

- **SAE Specification:**
  - AISI 1018 Steel
  - 1” Diameter
  - 0.120” Wall Thickness

- **Other Sizes Allowed**
  - Equivalent Bending Strength
  - Equivalent Bending Stiffness
  - 0.062” Minimum Wall Thickness
AISI 4130 Steel

• Equivalent Strength With Smaller Diameter Than AISI 1018 Steel
• Heavily Used In The SAE Mini Baja Competition And Other Racing Applications
• Welding of AISI 4130 Steel Can Be Performed By All Commercial Methods
• Motivated by choice of frame team to use the same material
Front Geometry

Figure 8: Front Suspension Geometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
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<tbody>
<tr>
<td>Upper control arm (UCA)</td>
<td>12.125 in 26.1 deg</td>
</tr>
<tr>
<td>Lower control arm (LCA)</td>
<td>14.5 in 28.5 deg</td>
</tr>
<tr>
<td>KP / spindle offset</td>
<td>4 in</td>
</tr>
<tr>
<td>KP / hub offset</td>
<td>2.25 in</td>
</tr>
<tr>
<td>St. arm / KP offset</td>
<td>-0.5 in</td>
</tr>
<tr>
<td>Rice height</td>
<td>12 in</td>
</tr>
<tr>
<td>Chassis width top</td>
<td>20 in</td>
</tr>
<tr>
<td>Chassis width bottom</td>
<td>20.125 in</td>
</tr>
<tr>
<td>Chassis height vertically</td>
<td>6.25 in</td>
</tr>
<tr>
<td>Dist. between UCA and LCA</td>
<td>6.25 in</td>
</tr>
<tr>
<td>Track width</td>
<td>48.125 in</td>
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<tr>
<td>Roll center</td>
<td>0 in 13.875 in</td>
</tr>
<tr>
<td>Steering rack width</td>
<td>13.75 in</td>
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<tr>
<td>Rack height above LCA</td>
<td>3.5 in</td>
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<tr>
<td>Tire</td>
<td>205 / 80.12</td>
</tr>
<tr>
<td>Offset</td>
<td>5</td>
</tr>
<tr>
<td>Camber</td>
<td>-1 deg</td>
</tr>
<tr>
<td>Scrub radius</td>
<td>0 in</td>
</tr>
<tr>
<td>Kingpin Inc. and length</td>
<td>13.5 deg 8 in</td>
</tr>
<tr>
<td>St. arm / LCA offset</td>
<td>6.125 in</td>
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</tbody>
</table>
Full Compression

Figure 9: Full Compression
Full Droop

Figure 10: Full Droop Analysis
Front Suspension Geometry

Figure 11: Front Suspension Geometry (Front-view)
Front Suspension Geometry

Figure 12: Front Suspension Geometry (Back-view)
Front Suspension Geometry

Figure 13: Front Suspension Geometry (Iso-view)
Expected Drop Forces

Drop Test Assumptions:
• $F_i = \text{Force of impact}$
• $F_s = 500 \text{ lb Weight}$
• $h = 6 \text{ ft Drop Height}$
• $K = 160 \text{ lbin Spring rate constant (using shocks from Polaris RZR 570)}$
• Force assuming worst case landing on one wheel

$$F_i = F_s + \left( (F_s)^2 + 2 \times K \times 12 \times F_s \times h \right)^{1/2} \text{ (Source SAE Brasil)}$$
• $F_i = 1022.53 \text{ lb}$
Upper Arm from bottom

- Upper arm
- loaded at 700 lbf from bottom
- FS=1.05

Figure 13: FEA of Upper A Arm (Bottom)
Lower Arm from bottom

- Lower arm
- loaded at 700 lbf from bottom
- FS = 1.07

Figure 14: FEA of Lower A Arm (Bottom)
Expected Impact Forces

Max speed is ~ 35MPH = 51.33Ft/s

\[ M = \frac{500\text{lb}}{32.2} = 15.53\text{slug} \]

\[ T = 0.2\text{s} \]

\[ F_{\text{impact}} = M \left( \frac{V}{T_{\text{impact}}} \right) \]

\[ F_{\text{impact}} = 15.53 \left( \frac{51.33}{0.2} \right) = 3985.77\text{lbf} \]
Upper Arm from front

- Upper arm
- loaded At 1000 lbf front front
- FS=1.56

Figure 15: FEA of Upper A Arm (front)
Lower Arm from Front

- Lower arm
- Loaded at 1000 lbf from front
- FS=1.82

Figure 16: FEA of Lower A Arm (Front)
Analysis: Tie Rod

- AISI 4130 (Chromoly)
- Diameter = 0.7”
- Maximum Axial Deformation @ 3000 lbf = 0.13mm
Rack and Pinion Geometry

- Rack and Pinion with Casing and steering shaft
- Bare Rack and Pinion

Figure 19: Rack and Pinion (Enclosed)

Figure 20: Rack and Pinion (Inside)
Rack and Pinion Geometry

- Rack and Pinion
  - Designed but most likely buy
  - Assumptions: No crown, Hardened, Not operating at high temp’s, Range for force applied
  - Force by Driver: 0.1-10 lbf
  - Rack teeth => pinion turns 360 degrees max, both sides
    - if circumference of pinion=4.64in, rack ~ 9in
## Rack and Pinion Geometry

### Table 6: Dimensions of Pinion and Rack

<table>
<thead>
<tr>
<th></th>
<th>Teeth Number</th>
<th>Face Width (in.)</th>
<th>Bending Stress (kpsi)</th>
<th>Radii for Pitch Circle (in)</th>
<th>Radii for Base Circle (in)</th>
<th>Adden. (in.)</th>
<th>Dedden (in)</th>
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</thead>
<tbody>
<tr>
<td>pinion</td>
<td>20</td>
<td>0.74</td>
<td>0.04 - 3.9</td>
<td>0.787</td>
<td>.739</td>
<td>0.078</td>
<td>0.098</td>
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<tr>
<td>rack</td>
<td>40</td>
<td>0.74</td>
<td>-</td>
<td>inf</td>
<td>inf</td>
<td>0.078</td>
<td>0.098</td>
</tr>
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</table>
Rack and Pinion Geometry

- Rack: approx. 9 inches

Figure 21: CAD Front Assembly
Cost of Front Suspension

• Fox Podium X Shocks
• Wheel hubs
• Bearing Carrier
• Heim joints
• Uniball Joints
• Brake Caliper and master cylinder
• 10 Ft of 1.25” .065” thick 4130 steel tubing

<table>
<thead>
<tr>
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<th>Full Retail</th>
<th>Sponsorship Rate</th>
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<td>Prices:</td>
<td>$2529.33</td>
<td>$1440.33</td>
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</table>
Cost of Rear Suspension

- Fox Podium X shocks
- Bearing Carrier
- Wheel hub
- Heim Joints
- 1.5” diameter
- .0625” thick 4130 Steel tubing

<table>
<thead>
<tr>
<th></th>
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<td>Prices:</td>
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<td>$1067.67</td>
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Table 8: Rear Suspension Cost
Cost Steering

- Rack and Pinion
- Tie Rods
- Heim Joints

Table 9: Steering Cost

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<tr>
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<td>Prices:</td>
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<td>$324.60</td>
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Benjamin 40
Total Cost Analysis

- We estimate that the total cost of the suspension, brakes, and steering to be
  - $2832.60 at sponsorship rates
  - $5046.67 at full retail
Figure 22: Rear Suspension Geometry
Rear Suspension Geometry

Figure 23: Rear Suspension Geometry
Final Rear Suspension

Figure 24: Rear Suspension

Figure 25: Rear Suspension
Spring 2014 Project Plan

- Finish Shock Calculations
- Further Design Refinement
- Completed Frame by January 31
- Completed Suspension Members by February 24
- SAE Cost Report by March 3
- SAE Design Report by March 20
- Competition on April 24
Conclusion

• SAE International is the client, NAU SAE is a stakeholder, and Dr. John Tester is the project advisor.
• Material Selection - AISI 4130 steel tubing for suspension members 1.25” - 1.50” O.D. and 0.065” - 0.083” wall thickness.
• Create a Baja design with an adequate weight and steering radius
• Front Suspension: Double A-Arms
• Rear Suspension: Trailing Arms
• Steering System: Rack and Pinion
• Analysis Results for optimization of design
• Cost analysis for economics of design
References

References (Cont.)

- Olsen, Stu, “Cinders Recreation Area” 2009, Photograph
References (Cont.)