PRESENTATION OUTLINE

• Background
• Performance and Vehicle Dynamics
• Tires and Aerodynamics
• Driver Vehicle Interactions and Handling
• Summary
RACING EXPERIENCE
<table>
<thead>
<tr>
<th>Series</th>
<th>NASCAR</th>
<th>Formula 1</th>
<th>IRL</th>
<th>Champ Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Races</td>
<td>37</td>
<td>19</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>Track Types</td>
<td>19 Oval Tracks &amp; 2 Road Courses</td>
<td>Road Courses &amp; 1 Street Circuit</td>
<td>Oval Tracks &amp; 2 Road Course</td>
<td>Street Circuits, Road Courses, &amp; 1 Oval Track</td>
</tr>
<tr>
<td>Cars per Race</td>
<td>43</td>
<td>20</td>
<td>~22</td>
<td>18</td>
</tr>
<tr>
<td>Race Locations</td>
<td>All in USA</td>
<td>17 Countries</td>
<td>USA + 1 Japan</td>
<td>USA + 7 races in 3 Countries</td>
</tr>
<tr>
<td>Spectators per Race</td>
<td>~180K Gate</td>
<td>~175K Gate</td>
<td>~60K Gate</td>
<td>~150K Gate</td>
</tr>
<tr>
<td>TV Viewers per Race</td>
<td>6 to 15 Million</td>
<td>~800 Million</td>
<td>? Million</td>
<td>? Million</td>
</tr>
</tbody>
</table>
# Comparing the Cars

<table>
<thead>
<tr>
<th></th>
<th>NASCAR</th>
<th>Formula 1</th>
<th>IRL</th>
<th>Champ Car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Race Weight (lbs)</strong></td>
<td>3600</td>
<td>1600</td>
<td>1900</td>
<td>1900</td>
</tr>
<tr>
<td><strong>Chassis Construction</strong></td>
<td>Tubular Steel Frame</td>
<td>Carbon Fiber Monocoque</td>
<td>Carbon Fiber Monocoque</td>
<td>Carbon Fiber Monocoque</td>
</tr>
<tr>
<td><strong>Wheelbase (in)</strong></td>
<td>110</td>
<td>~120</td>
<td>~120</td>
<td>~125</td>
</tr>
<tr>
<td><strong>Track Width (in)</strong></td>
<td>60</td>
<td>58</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td><strong>Engine Type</strong></td>
<td>~6.0 liter V8</td>
<td>3.0 liter V10</td>
<td>3.0 liter V8</td>
<td>2.65 liter turbo V8</td>
</tr>
<tr>
<td><strong>Max Engine RPM</strong></td>
<td>~9600</td>
<td>19,000+</td>
<td>10,300 (limited)</td>
<td>12,500 (limited)</td>
</tr>
<tr>
<td><strong>Engine Power (hp)</strong></td>
<td>800+</td>
<td>900+</td>
<td>650+</td>
<td>~750</td>
</tr>
<tr>
<td><strong>Aerodynamic Downforce at 200 mph</strong></td>
<td>~2000</td>
<td>5000+</td>
<td>4000+</td>
<td>5500+</td>
</tr>
<tr>
<td><strong>Max Lateral Acceleration (g)</strong></td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
COSWORTH F1 ENGINE RPM TEST
DESIGN CONSIDERATIONS

Passenger Vehicles

- Safety; Do nothing “bad;” “easy” to drive; and “comfortable” ride
- 95% low acceleration
- Untrained drivers

Racing Vehicles

- Maximize horizontal performance
- 95% high acceleration
- Fast cars are comfortable!!
- Controllable by a skilled (and brave) driver. Trained?
PERFORMANCE AND VEHICLE DYNAMICS
RACING VEHICLE GOALS

• Maximize lateral and longitudinal acceleration capability & CONSISTENCY

• “DRIVEABILITY” or “CONTROLABILITY”
  – Manual Control Systems Analogies:
    ➢ Manageable workload
    ➢ Reduced system lag and/or required control system lead
    ➢ Example- night driving- less “lead” capability, therefore must slow down compared to daytime driving

• Note - strong bias toward performance in racing versus driver comfort/workload in passenger car
MAXIMIZE HORIZONTAL PERFORMANCE

Source – Ferrari Formula 1 by Peter Wright
(Michael Schumacher qualifying lap at Imola – 2000)
VEHICLE DYNAMICS 101

Typical vehicle degrees of freedom

Numerous axis systems - this is the ISO Vehicle coordinate system
VEHICLE “BALANCE”
UNDERSTEER

• **Steady State** Understeer
  - Driving a constant radius with increasing speed requires increasing steering angle to maintain radius
  - Limit understeer results in a path tangent to the desired arc
  - NASCAR boys call this “push”
  - Most predictable balance mode:
    - Least feedback lag
    - Always directionally stable with hands off
    - Most intuitive corrective means (braking or throttle lift helps restore control)
NEUTRAL STEER

• Steady State Neutral Steer
  – Driving a constant radius with increasing speed requires no steering angle change to maintain radius
  – Limit neutral steer results in 4 wheel drift/slide
  – NASCAR boys call this “fast”
  – Difficult to control:
    – Increased lag versus understeer
    – Often turns to oversteer due to driver interaction
OVERSTEER

• Steady State Oversteer
  – Driving a constant radius with increasing speed requires decreasing (counter-steer) steering angle to maintain radius
  – Limit oversteer results in high yaw or a spin
  – NASCAR boys call this “loose”
  – Difficult to control due:
    – More lag in feedback
    – Threshold speed where closed loop feedback is required to maintain directional stability
    – Often counterintuitive corrective measures (braking or throttle lift often exaggerates issue - throttle application may help)
F1 OVERSTEER SPIN AND RECOVERY
TIRES AND AERODYNAMICS
TIRE CHARACTERISTICS

- Tire Slip Angle - Lateral tire force capability is proportional to slip angle below its capability limit

\[ S = \frac{u - R\omega}{u} \]

Lateral Slip Angle:
\[ \alpha = \tan^{-1} \frac{v}{u} \]

Source - “Race Car Vehicle Dynamics” by Milliken/Milliken

Figure 2.3 Walking analogy to tire “slip angle.”
TIRE SIDE FORCE & AERODYNAMIC LIFT

**Figure 2.7** Lateral force vs. slip angle for a racing tire.

Source - “Race Car Vehicle Dynamics” by Milliken/Milliken

Source - NASA
TIRE TESTING – CALSPAN TIRF
TIRE – EFFECT OF NORMAL LOAD

Source – Ferrari Formula 1 by Peter Wright

21 Oct. 05 SAE AGCSC Meeting #96
TIRE – COMBINED BEHAVIOR

Source – Ferrari Formula 1 by Peter Wright

21 Oct. 05

SAE AGCSC Meeting #96
AERODYNAMICS

Wind Tunnel

Computational Fluid Dynamics
RIDE HEIGHT SENSITIVITY
RIDE HEIGHT SENSITIVITY GONE BAD
DRIVER-VEHICLE INTERACTION AND HANDLING
DRIVER/VEHICLE INTERACTION

Driver

Desired Performance

Visual Observations

Road Irregularities

Wind Gusts

Vehicle

Driver Inputs:
Steering, Throttle, Brake

Steering Torque
Pedal Forces

Chassis State

Noise and other vehicle feedbacks
1ST ORDER HANDLING
– MINIMIZE MASS –

• If traction surplus (no wheelspin on throttle)
  – F=MA
• Cornering, braking or traction deficit (wheelspin on throttle)
  – Tire lateral and longitudinal capability (grip) are a function of normal (vertical) load and coefficient of friction at the limit
  – Tire’s coefficient of friction is reduced with increasing vertical load
• Most racing series have a minimum weight rule
1ST ORDER HANDLING
– MINIMIZE CG HEIGHT TO MAXIMIZE 4 TIRE USAGE –

• Minimize lateral weight transfer (function of track width and CG height)
• Minimize longitudinal weight transfer (function of wheelbase and CG height)
• Not necessarily true when maximum acceleration is required – drag racing trade-off with controllability
1st ORDER HANDLING
– BALANCE LATERAL WEIGHT TRANSFER –

• Proportion front and rear lateral weight transfer to optimize vehicle balance and cornering capability through:
  – Total lateral load transfer function of cg height and vehicle track width
  – Front versus rear roll stiffness
    ➢ Spring rate adjustments
    ➢ Anti-roll bar adjustments
  – Suspension member force reaction
    ➢ Roll center height
LATERAL WEIGHT TRANSFER

\[
\% \text{Front WT} = \frac{\text{WTfront}}{\text{WTtotal}} \times 100
\]

Note - Increasing %Front Weight Transfer increases understeer due to tire non-linearities.
1ST ORDER HANDLING
– OPTIMIZE CG LONGITUDINAL PLACEMENT –

• Accelerating, decelerating and cornering considerations (optimum heavily influenced by tire properties)
  – Acceleration: rearward bias allows superior power application performance through greater rear tire vertical loading
  – Deceleration: rearward bias allows superior braking performance through improved rear tire vertical loading (better usage of front AND rear after weight transfer during braking)
  – Cornering compromise: rearward bias tends toward steady state oversteer
SUSPENSIONS

- Not necessary if very smooth road?
- However, most roads have significant roughness
- Allows control of lateral weight transfer distribution
- Need suspension to yield “controlled” vertical compliance to minimize vertical tire loading variation—filter disturbances and consequently minimize lateral tire force variation
- Worst case scenario: tires lose ground contact and vehicle control is completely lost
SUSPENSIONS

• The Challenge:
  - Allow controlled vertical compliance yet minimize tire geometry/attitude change wrt ground (Wheel control- three translation axis degrees of freedom and 2 rotational axis degrees of freedom)
  - Minimize lash (free-play) and uncontrolled compliance while increasing the number of joints and complexity
POOR HANDLING = POOR FINISH
SUMMARY

• Race Cars in different series vary greatly, but all obey the same law: $F = m \cdot a$
• Aerodynamics significantly increase race car performance
• Horizontal performance approaches 5 g’s
• Strong analogy between vehicle tires and airplane wings as primary force generators
• Suspension is used to distribute normal load between the tires to achieve desired handling characteristics
QUESTIONS?