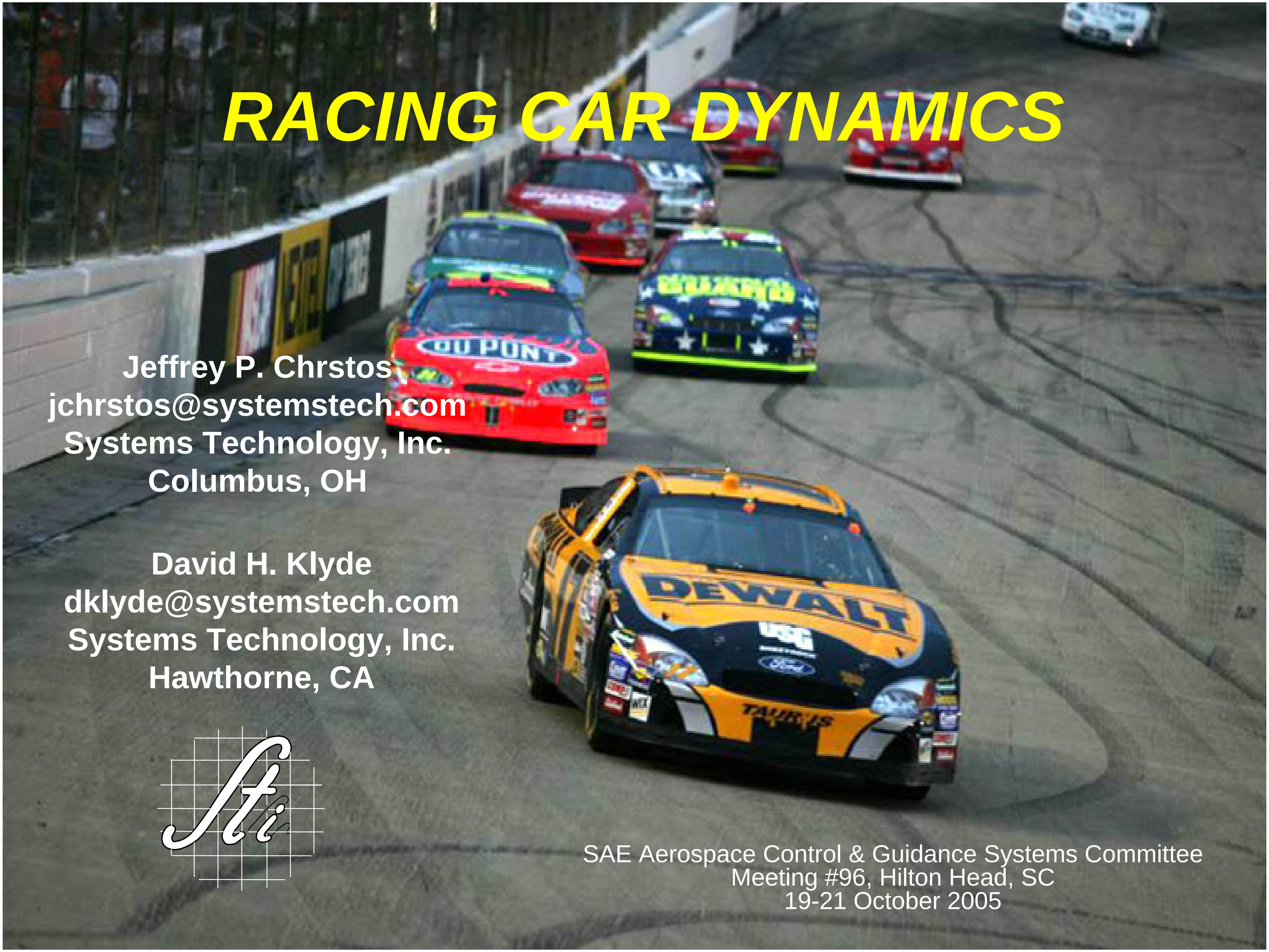

RACING CAR DYNAMICS

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SAE Aerospace Control & Guidance Systems Committee
Meeting #96, Hilton Head, SC
19-21 October 2005

PRESENTATION OUTLINE

- Background
- Performance and Vehicle Dynamics
- Tires and Aerodynamics
- Driver Vehicle Interactions and Handling
- Summary

BACKGROUND

RACING EXPERIENCE

Ford RACING

ROUSH Performance

JAGUAR RACING

TEAM Rahal

COMPARING THE SERIES

Series	NASCAR	Formula 1	IRL	Champ Car
				
Number of Races	37	19	17	14
Track Types	19 Oval Tracks & 2 Road Courses	Road Courses & 1 Street Circuit	Oval Tracks & 2 Road Course	Street Circuits, Road Courses, & 1 Oval Track
Cars per Race	43	20	~22	18
Race Locations	All in USA	17 Countries	USA + 1 Japan	USA + 7 races in 3 Countries
Spectators per Race	~180K Gate	~175K Gate	~60K Gate	~150K Gate
TV Viewers per Race	6 to 15 Million	~800 Million	? Million	? Million

COMPARING THE CARS

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

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

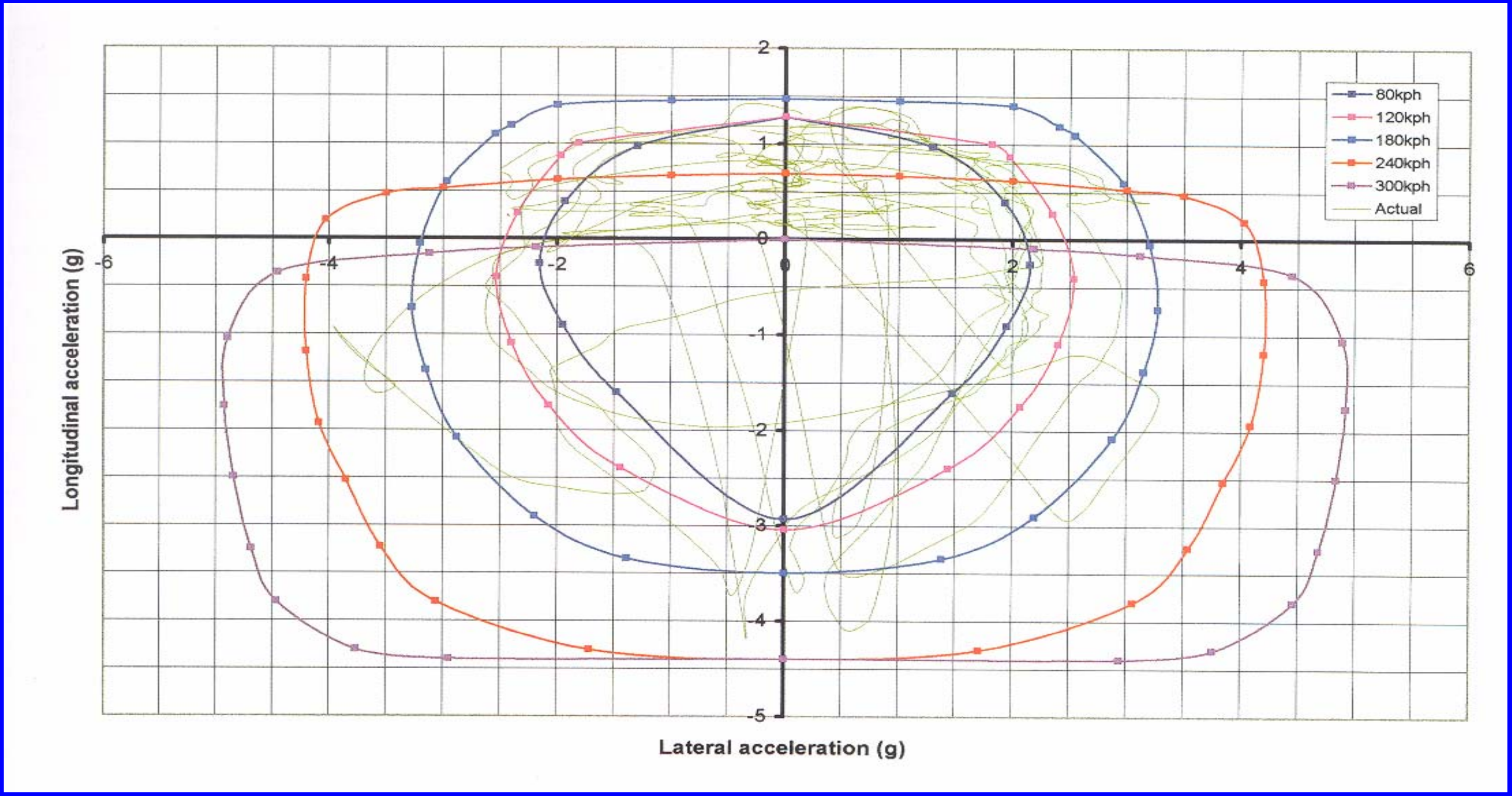
- Maximize horizontal performance
- 95% high acceleration
- Fast cars are comfortable!!
- Controllable by a *skilled* (and *brave)* driver. Trained?

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

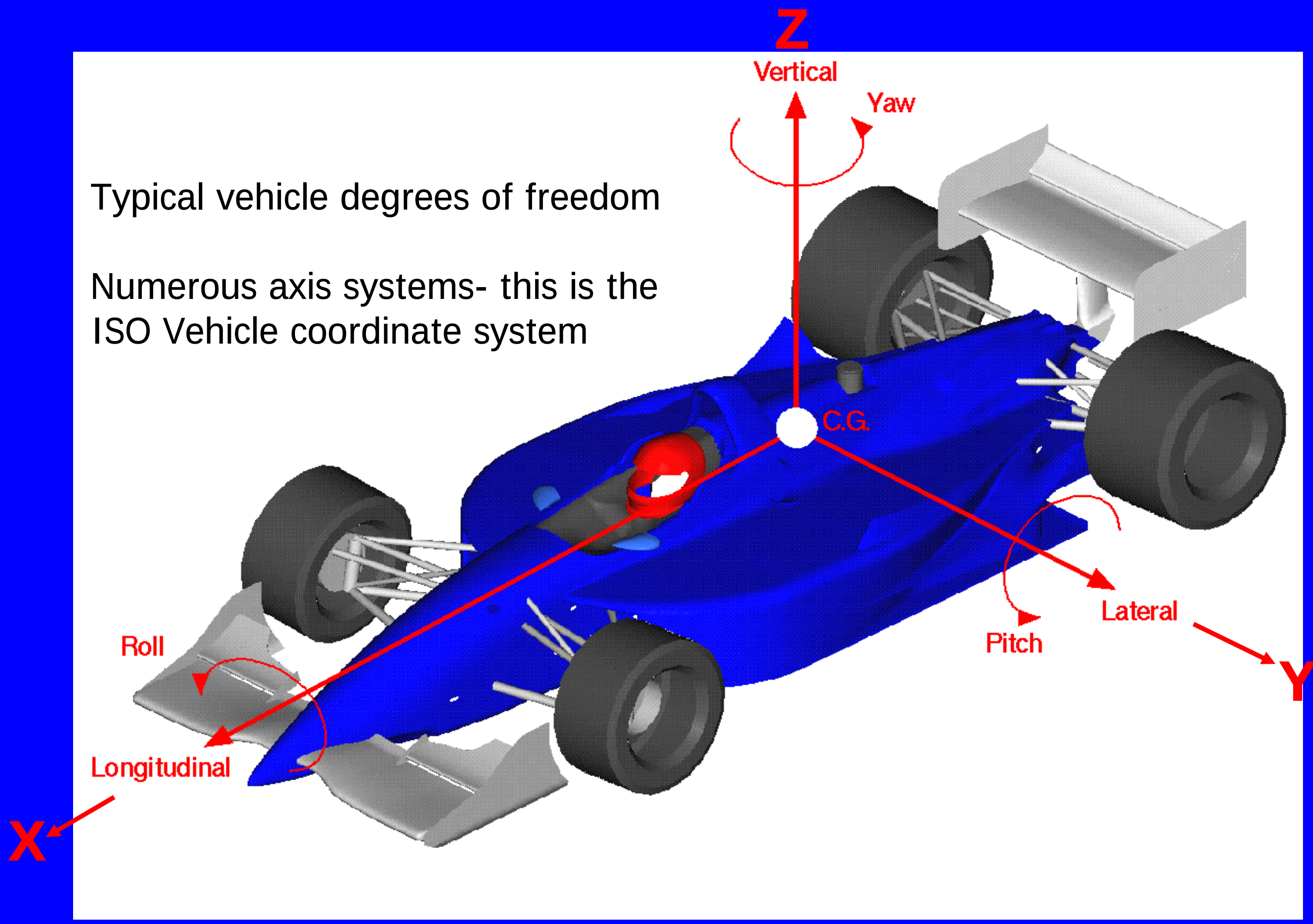


Source – Ferrari Formula 1 by Peter Wright
(Michael Schumacher qualifying lap at Imola – 2000)

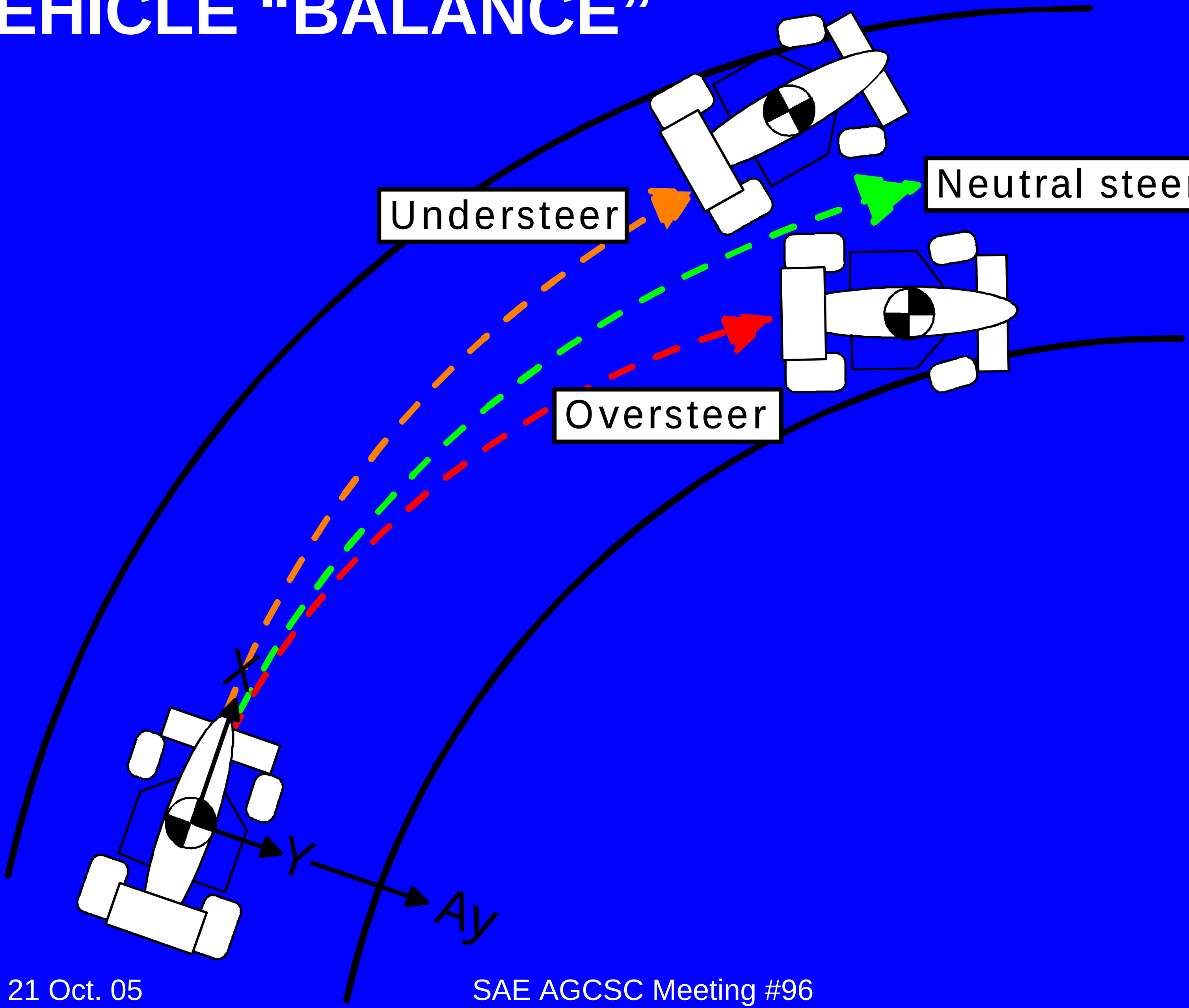
VEHICLE DYNAMICS 101

Typical vehicle degrees of freedom

Numerous axis systems- this is the ISO Vehicle coordinate system

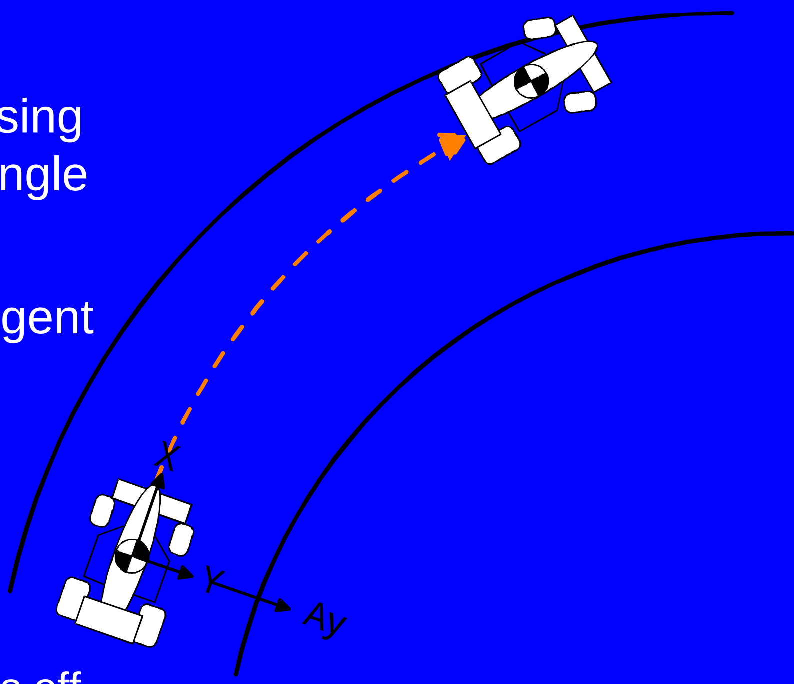


VEHICLE “BALANCE”



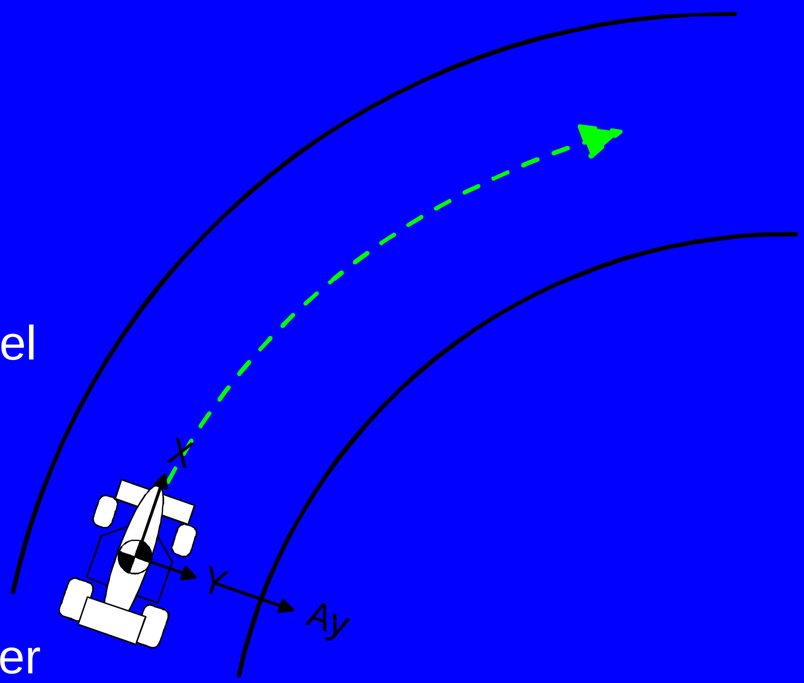
UNDERSTEER

- 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)



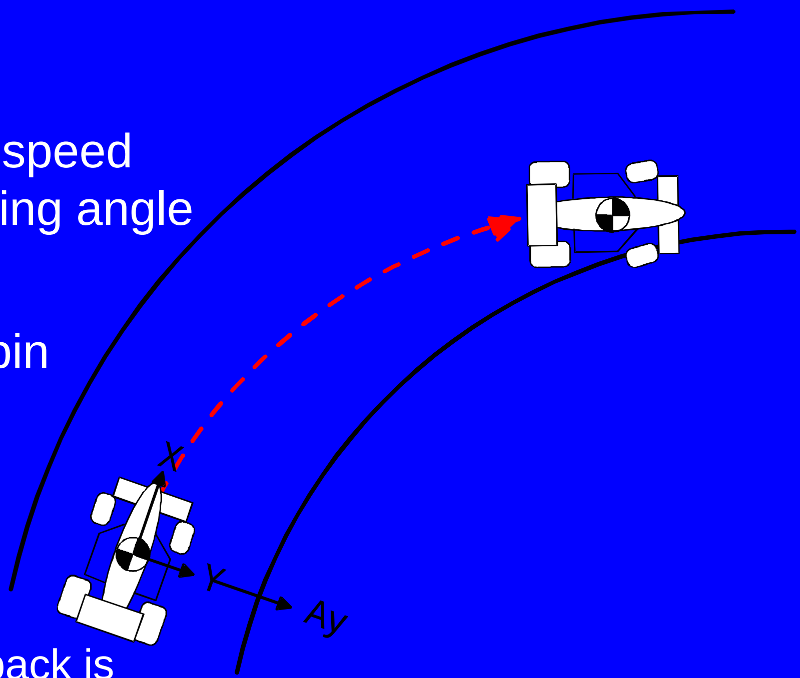
NEUTRAL STEER

- 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)

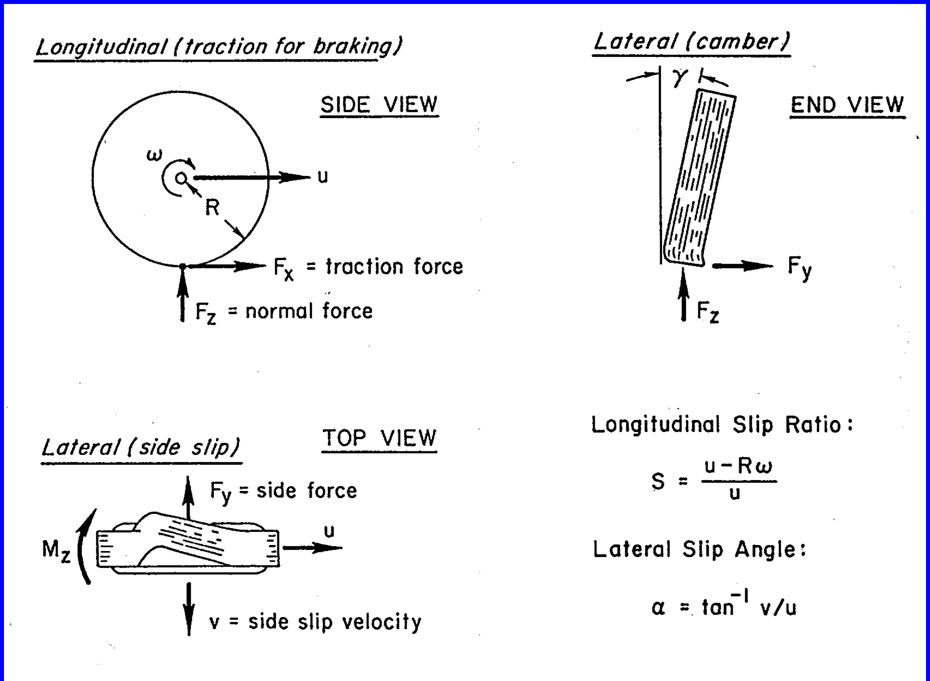


F1 OVERSTEER SPIN AND RECOVERY

TIRES AND AERODYNAMICS

TIRE CHARACTERISTICS

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



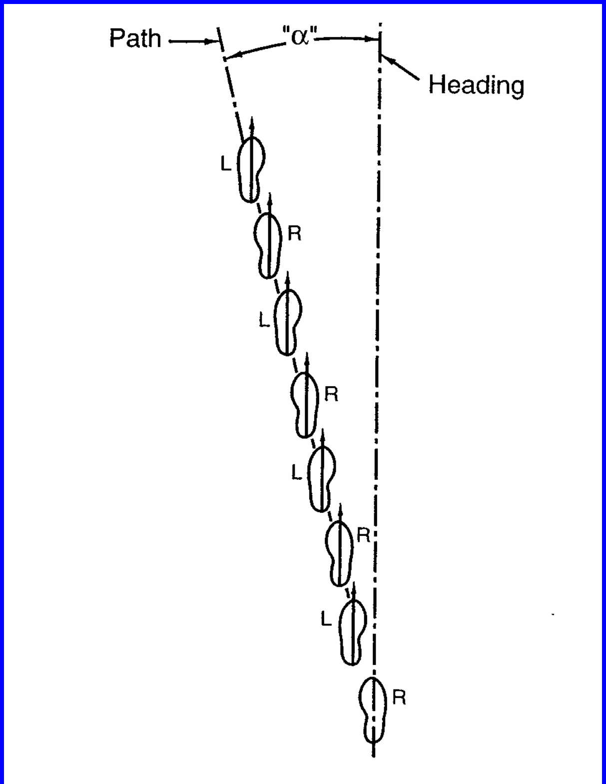


Figure 2.3 Walking analogy to tire "slip angle."

Source- "Race Car Vehicle Dynamics" by Milliken/Milliken

TIRE SIDE FORCE & AERODYNAMIC LIFT

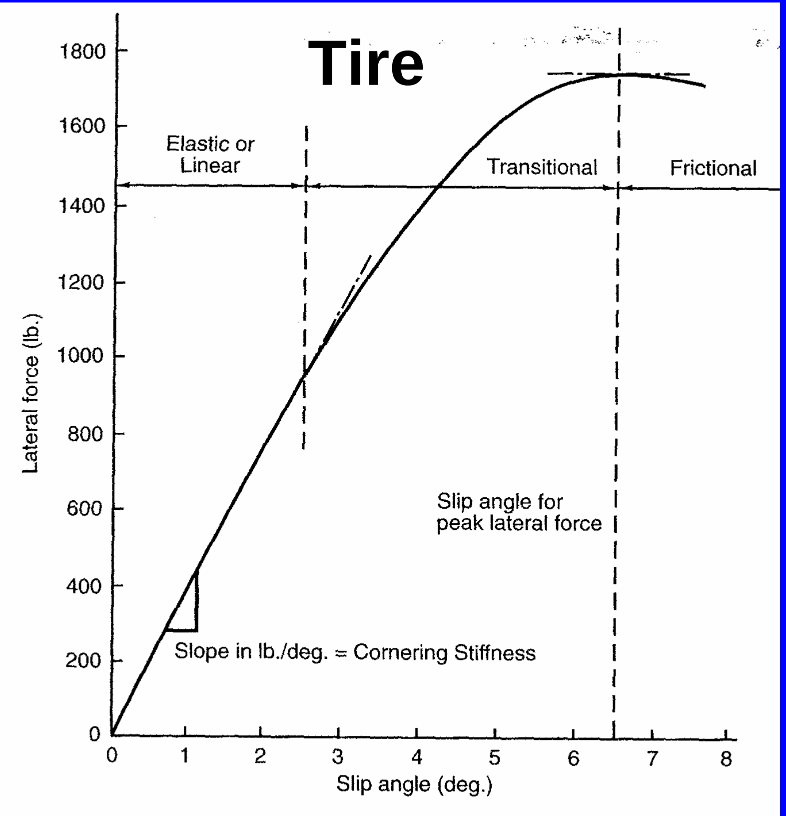
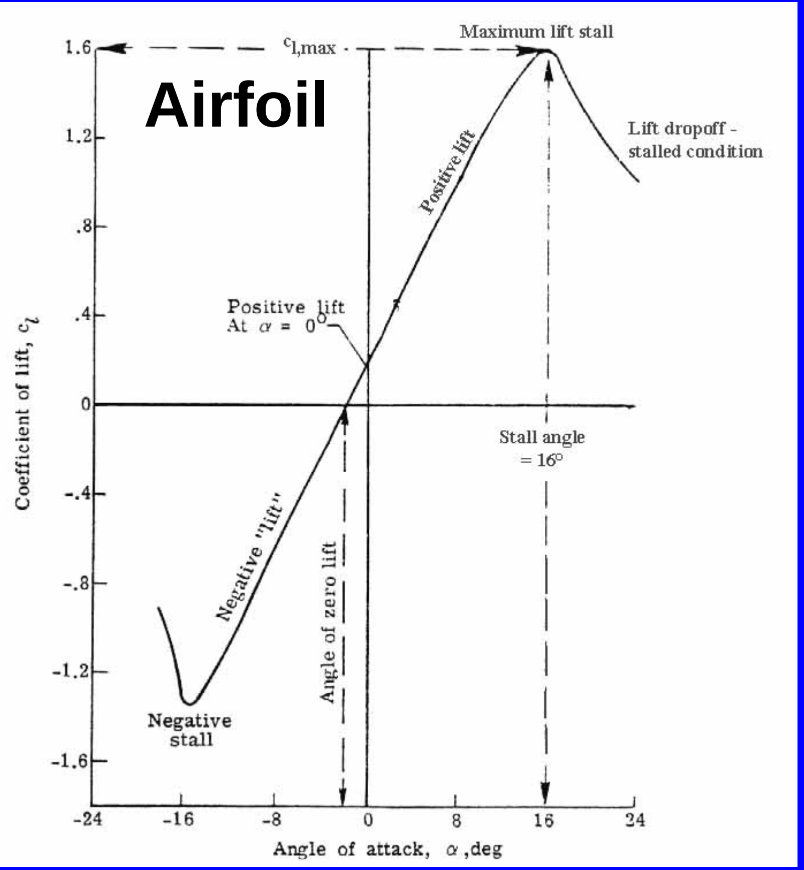


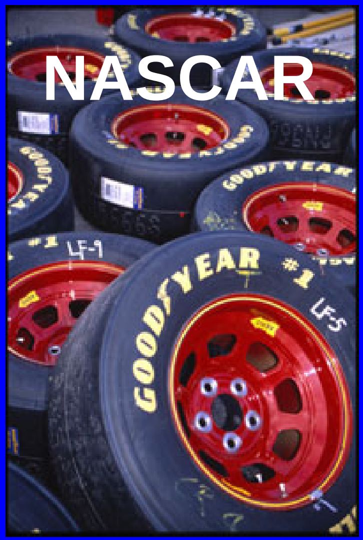
Figure 2.7 Lateral force vs. slip angle for a racing tire.



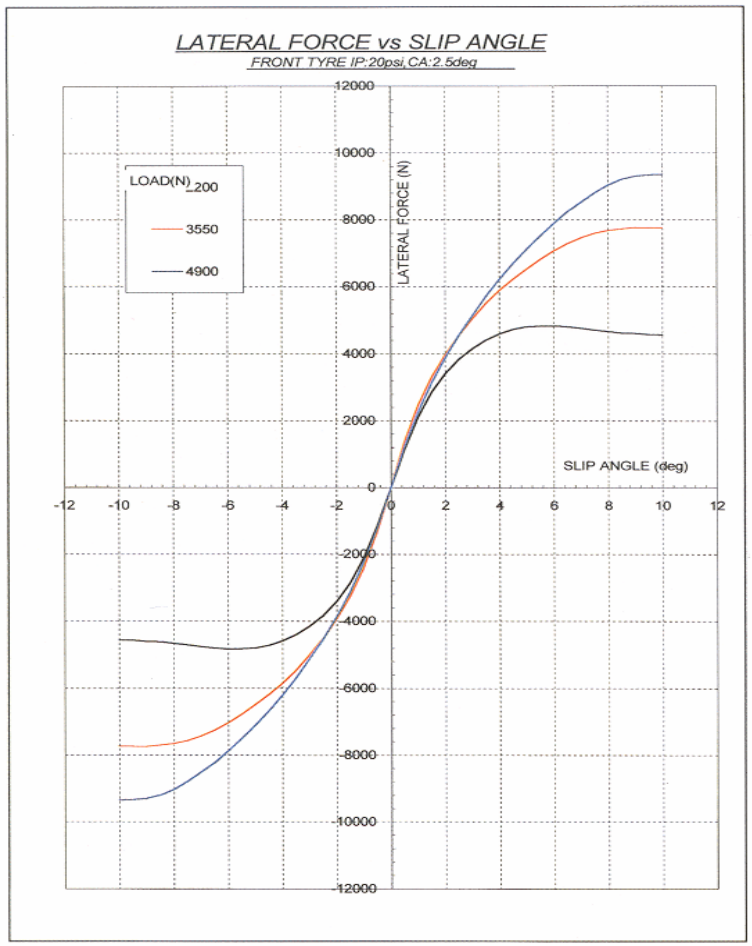
Source - "Race Car Vehicle Dynamics" by Milliken/Milliken

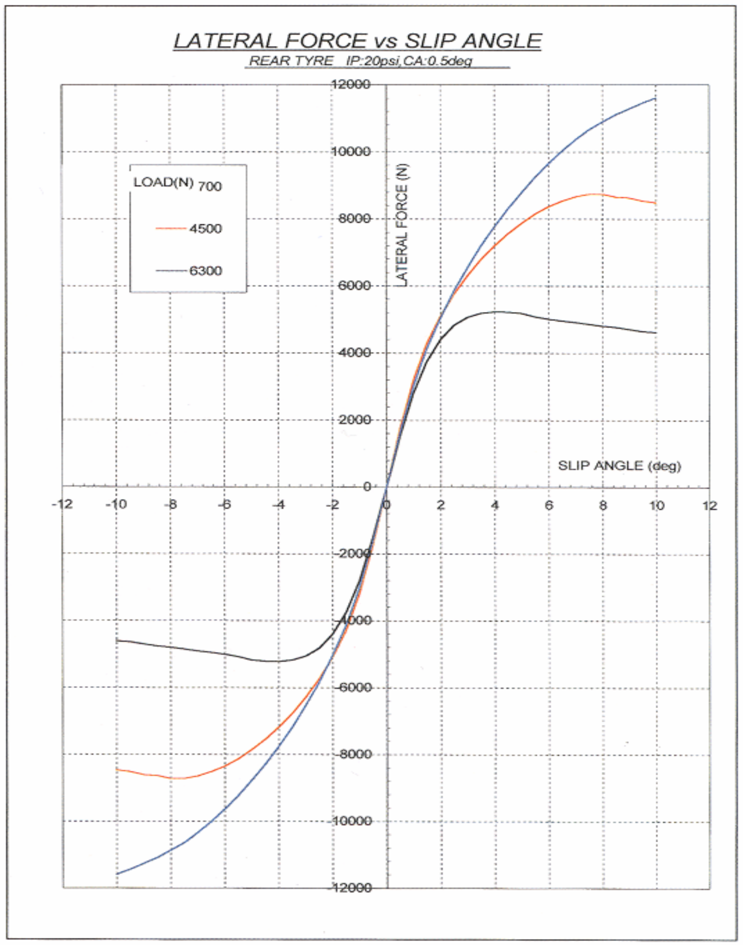
Source - NASA

TIRE TESTING – CALSPAN TIRF



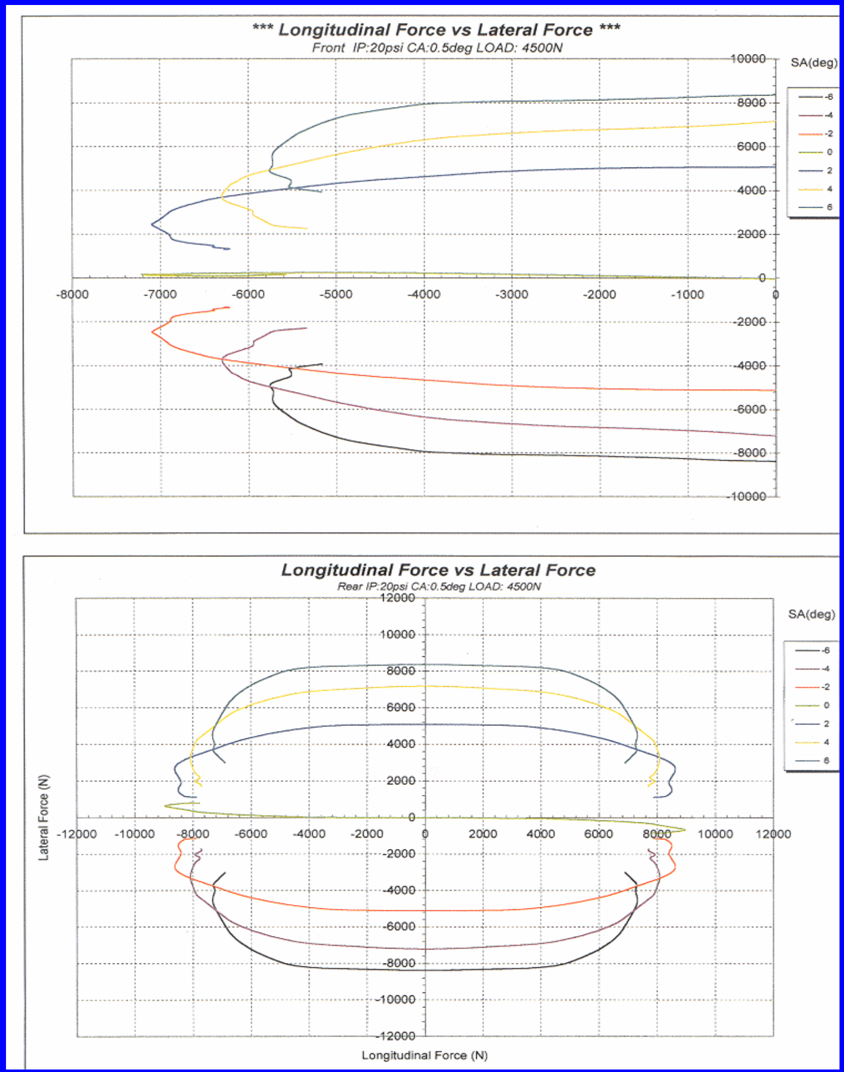
TIRE – EFFECT OF NORMAL LOAD





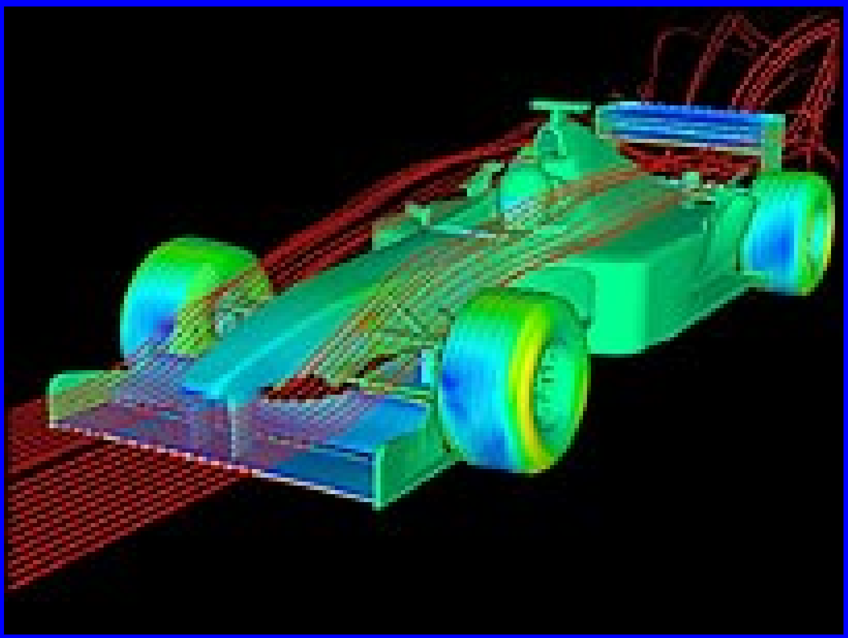
Source – Ferrari Formula 1 by Peter Wright

TIRE – COMBINED BEHAVIOR



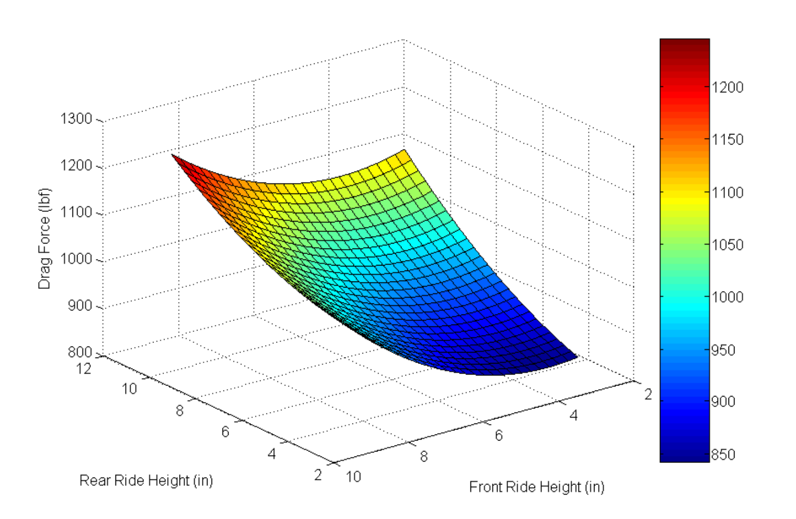
Source – Ferrari Formula 1 by Peter Wright

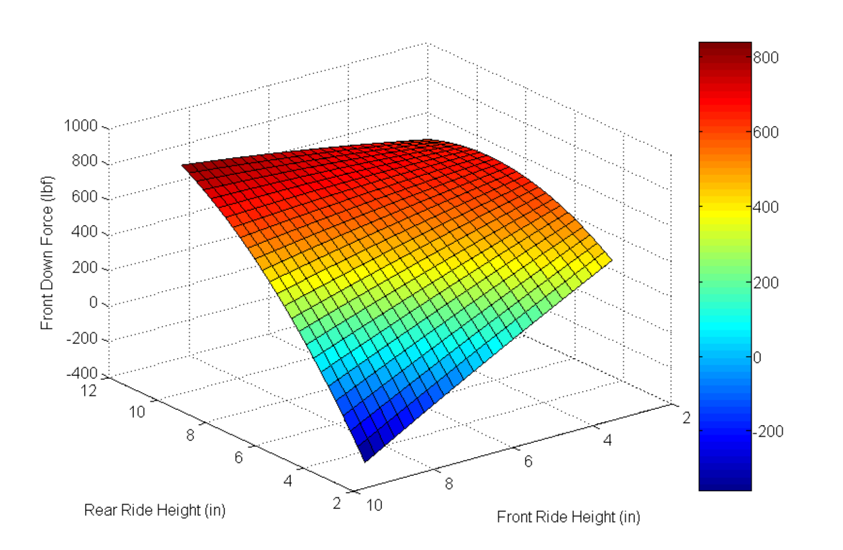
AERODYNAMICS

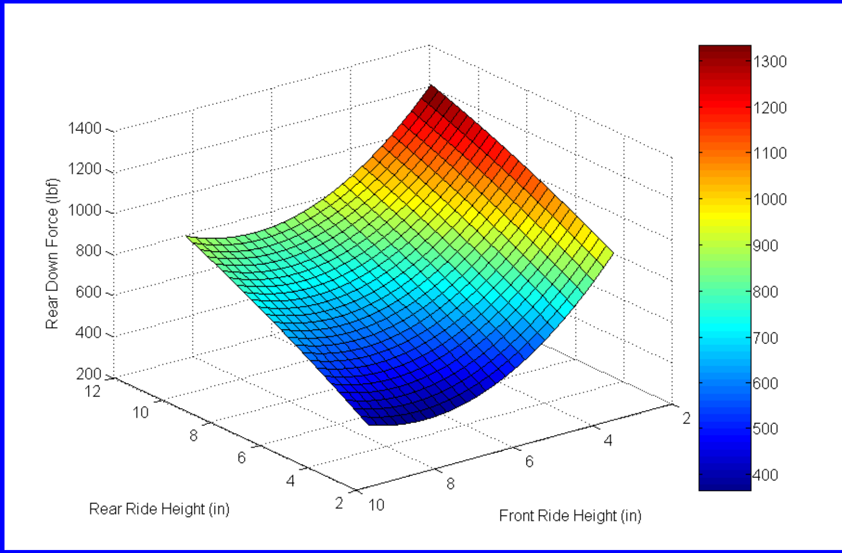


Wind Tunnel **Computational Fluid Dynamics**

RIDE HEIGHT SENSITIVITY



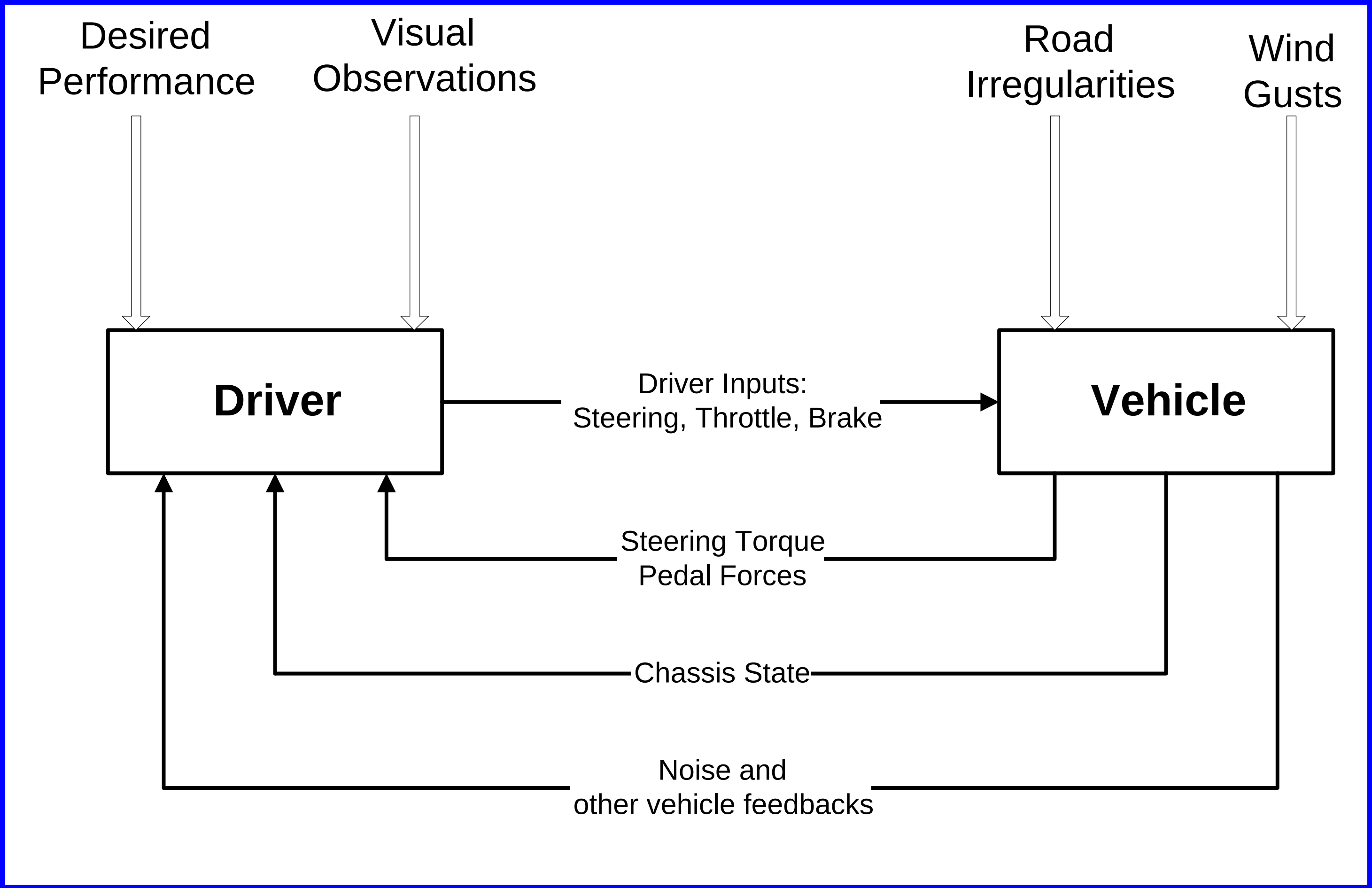




RIDE HEIGHT SENSITIVITY GONE BAD

DRIVER-VEHICLE INTERACTION AND HANDLING

DRIVER/VEHICLE INTERACTION



DRIVER/VEHICLE INTERACTION VIDEO EXAMPLE

Marcus Gronholm Peugeot 206, Finland

1^{ST} 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

1^{ST} ORDER HANDLING

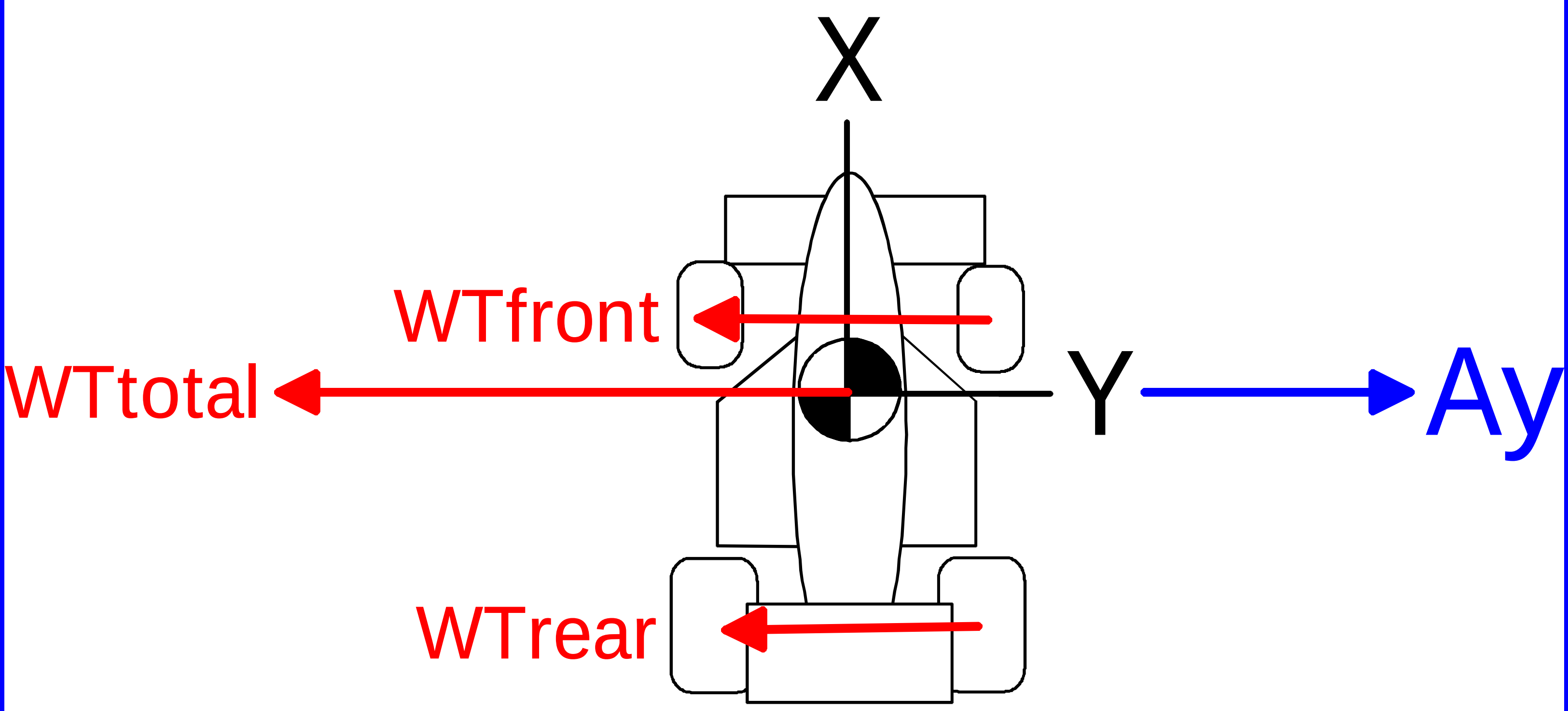
– MINIMIZE CG HEIGHT TO MAXIMIZE 4 TIRE USAGE –

- 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

1^{ST} 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



%Front WT = WTfront/(WTtotal)*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*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?