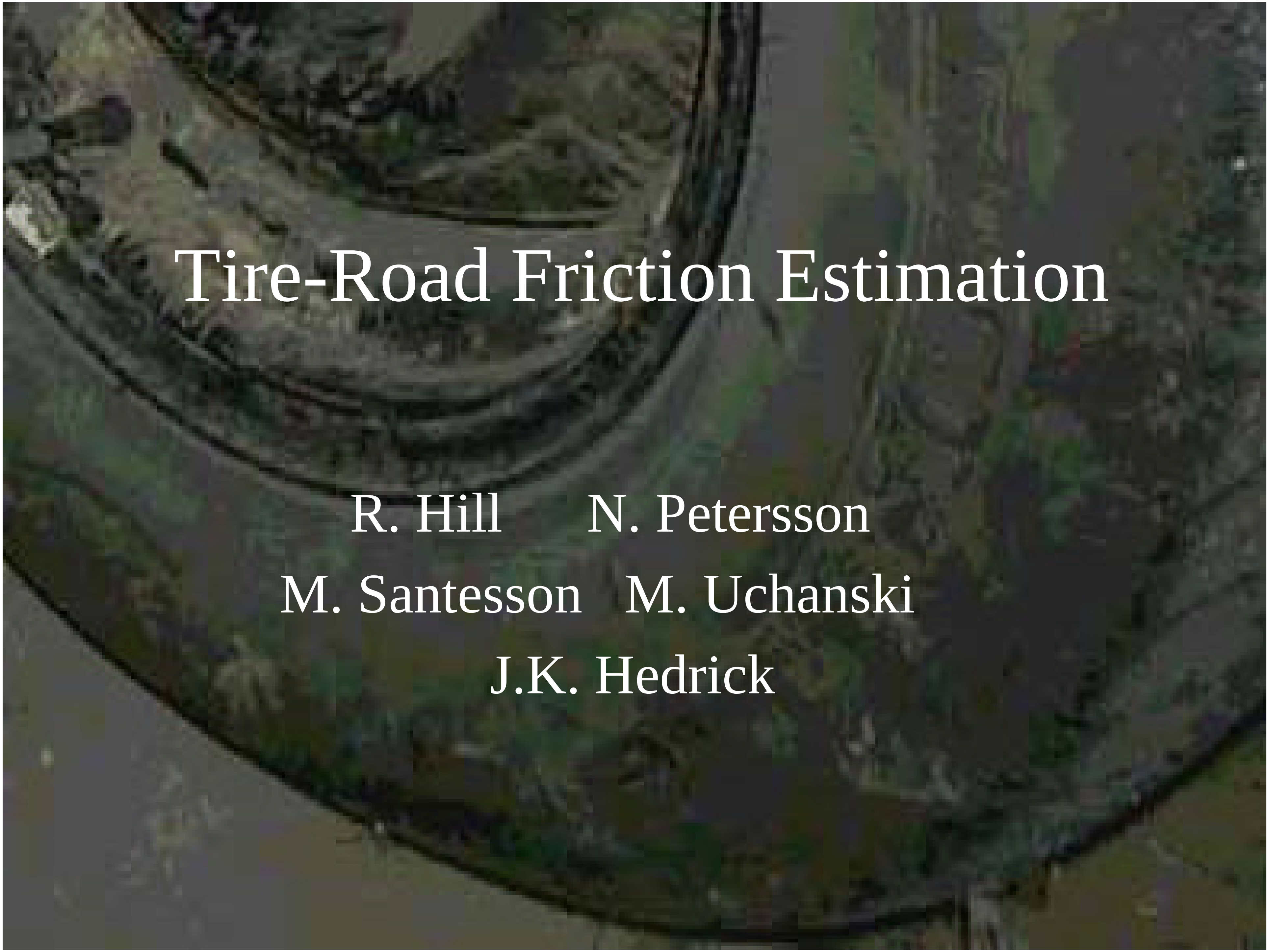

Tire-Road Friction Estimation

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Overview

- Why estimate friction? How?
- Longitudinal tire equations (slip curves)
- Literature review
- Our Approach---slip based
  - Slip data
  - Force data
    - Direct measurement
    - Estimation via adaptive algorithm
- Slip curves for wet and dry roads
- Wet/dry categorization
- Future directions--cooperative estimation

Why estimate road condition?

- Road condition is most important factor limiting vehicle accelerations
- For “driver assist” systems, road condition estimation optional
- AHS is a driver *replacement*--road condition estimation mandatory
- Better estimates => More effective AHS
  - Conservative estimates => Low throughput
  - Optimistic estimates => Dangerous driving

How to estimate road condition?

- How do human drivers do it?
  - Accidents
  - Exceed road/tire's holding power
  - Use visual and weather clues to guess at μ
  - "Crescendo driving" and test skids
- How might an AHS do it? Similar...
  - Accidents => Avoid
  - Report use of emergency controllers like ABS or anti-spinout => Probably OK
  - Weather data with human or machine road monitors
  - "Slip" based methods
    - Same idea as test skids, but less severe
    - Note correlation between slip and tire force

Tire equations

For there to be longitudinal force, need longitudinal slip, λ

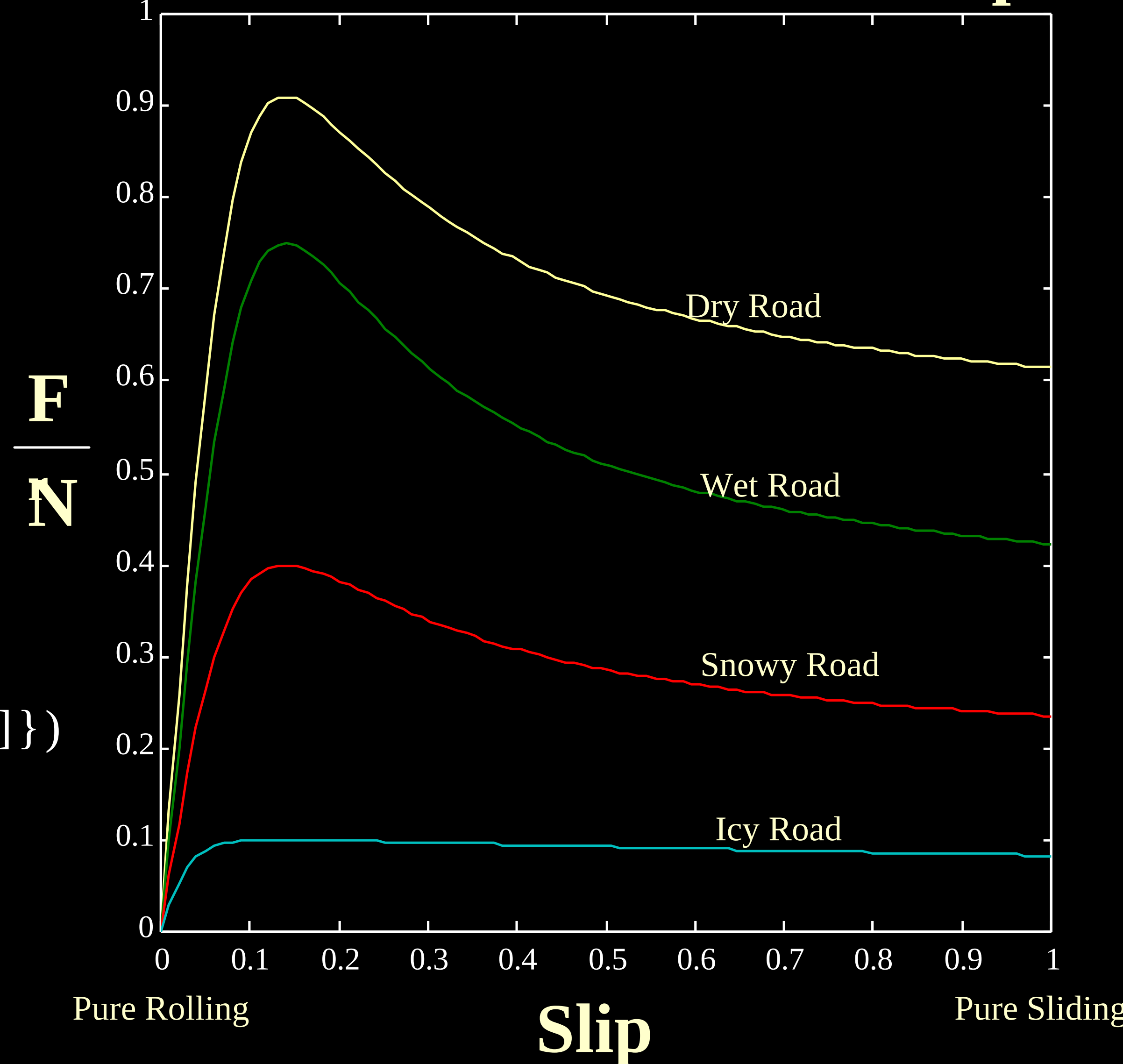
$$l = \frac{rw - v}{v}$$

Pacejka-Bakker "Magic Formula":

$$F = D \cdot \sin(C \cdot \tan^{-1}\{$$
$$B l - E \cdot [B l - \tan^{-1}(B l)]\})$$

There are other models for lateral forces and moments

Normalized Road Force vs. Slip



Results in literature

- Direct measurement of tire deformation:
  - B. Breuer, V. Eichorn and J. Roth "Measurement of tyre/road friction ahead of car and inside the tyre," *AVEC* 1992.
  - Employed a Hall effect type sensor embedded into tread of tire

- Optical sensors to look at road:
  - F. Holzwarth and V. Eichorn "Non-contact sensors for road conditions," *Sensors and actuators*, June-August 1993.
  - Optical sensors identify road type based on reflectivity of surface, spectra of light absorbed
  - Reviewed under MOU285

- Slip based method:
  - F. Gustaffson "Estimation and change detection of tire-road friction using wheel slip" Invited and submitted to *IEEE Control Systems*

Literature continued

- Initial slope of slip curve and noise level in measurements used to classify roads
- Kalman filter used as an averager to smooth slip slope estimates

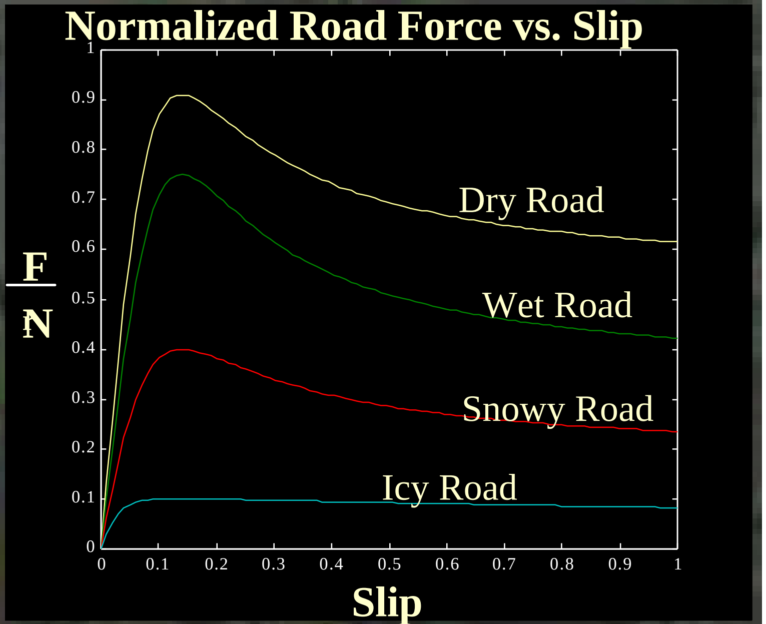
- Method based on torque converter/powertrain model:
  - K. Yi, K. Hedrick, and S. Lee "Estimation of tire-road friction using observer based identifiers" *Vehicle System Dynamics*, April 1999.
  - Force axis of slip curve estimated from an observer based on model of torque converter

- Least squares based approach:
  - H. Lee and M. Tomizuka "Adaptive Traction Control" *California PATH Research Report UCB-ITS-95-82*.

Our approach

- Slip based => fewer sensors

- Force-slip data taken during braking

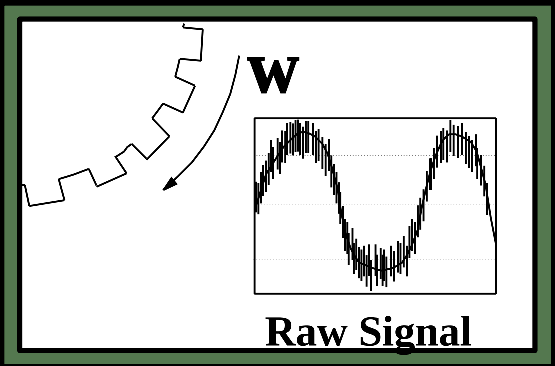


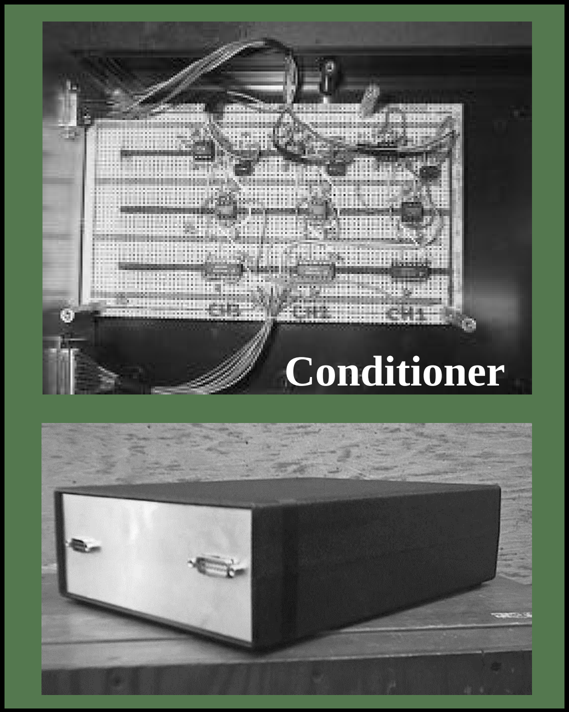
- Longitudinal only

- Use vehicle data to generate slip curve then classify road based on the shape of curve

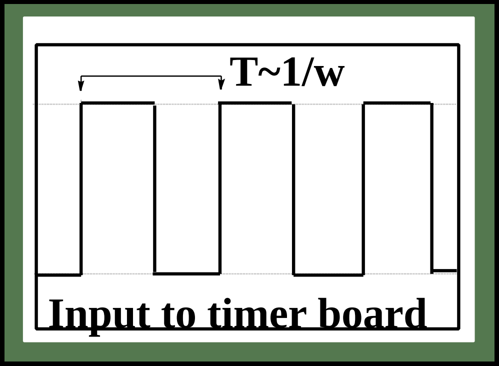
- After this first step, exploit communication abilities of AHS for "cooperative" estimation
  - More data may give better estimates
  - Estimates may be better localized

Slip axis: wheel speeds

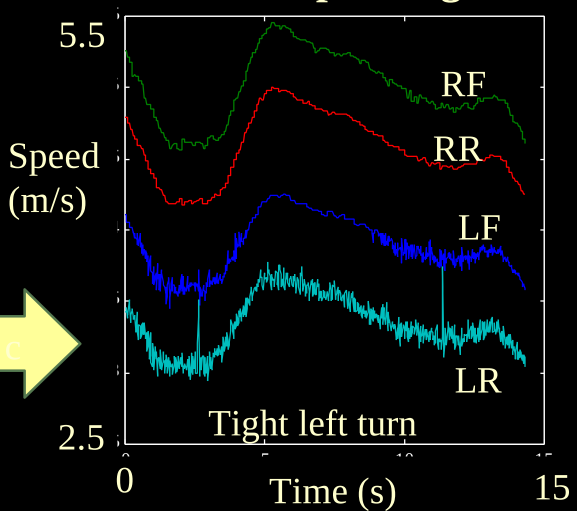




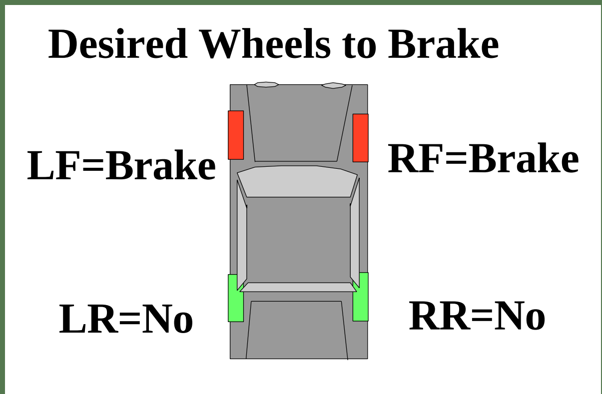
- Raw signals obtained from standard 50 tooth inductive ABS wheel speed sensors
- Raw signal = sine wave with frequency proportional to speed
- Raw signal filtered, squared up and timed

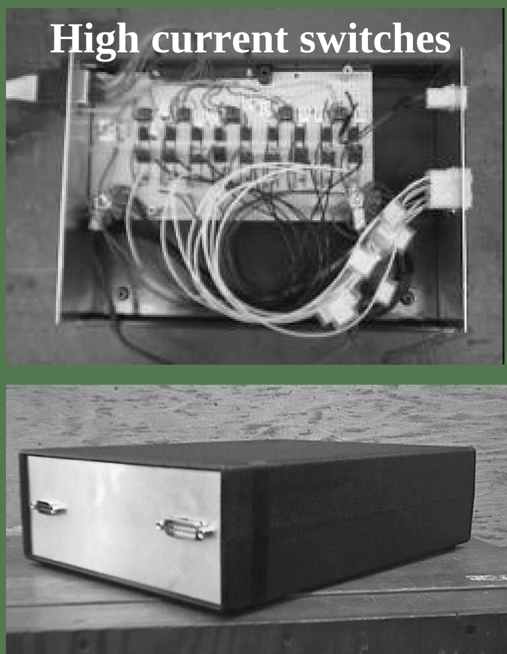


Four wheel speed signals

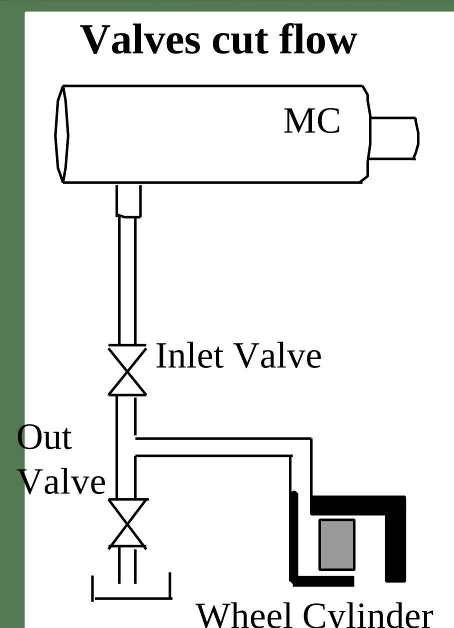


Slip Axis: Vehicle speed



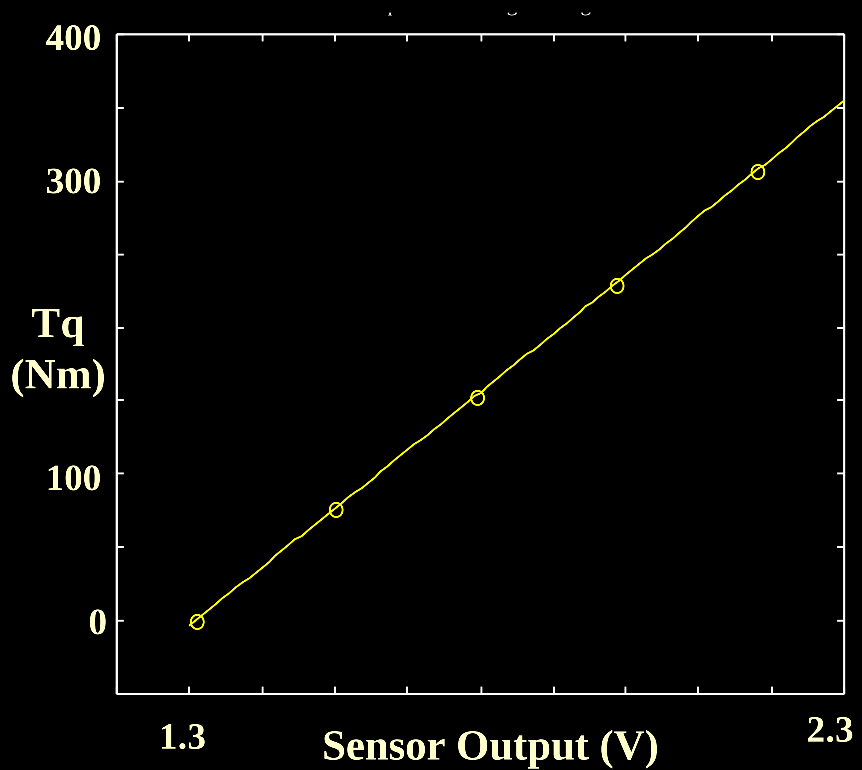


- $\lambda = \dfrac{r\omega - v}{v}$, so need velocity
- Braking done with only front wheels and rear wheels allowed to roll
- Differential braking done by over-riding ABS controller
- Replace with velocity observer



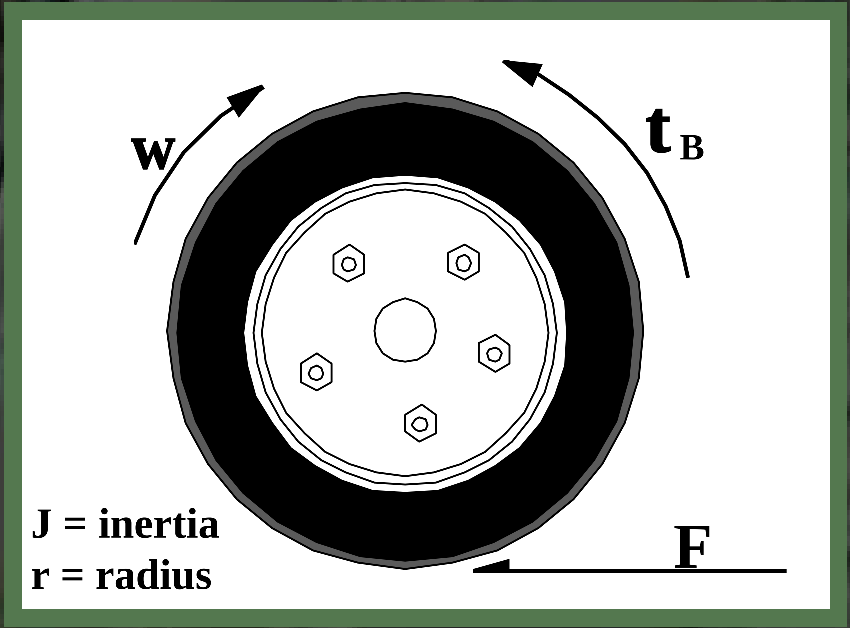
Force axis via torque sensor

- Can directly measure brake torque
- This method not practical for implementation
- Good for verification purposes



Force axis via pressure (1)

- Intuition: "Push harder on brakes, get larger road force"



- Actually is true for brake torque, τ_B

$$\tau_B = K_B \cdot P_B$$

Varies

- Brake torque related to road force by $J\dot{w} = F \cdot r - K_B \cdot P_B$
- So, if wheel accelerations are small and K_B known, pressure is good enough

Force axis via pressure (2)

- Since K_B unknown, use an adaptive control algorithm to estimate it
- Intuitively, algorithm uses current estimate of K_B, $\hat{K}_B$, for velocity control and adjusts the estimate based on error in velocity error
- Designed to be stable using Lyapunov function

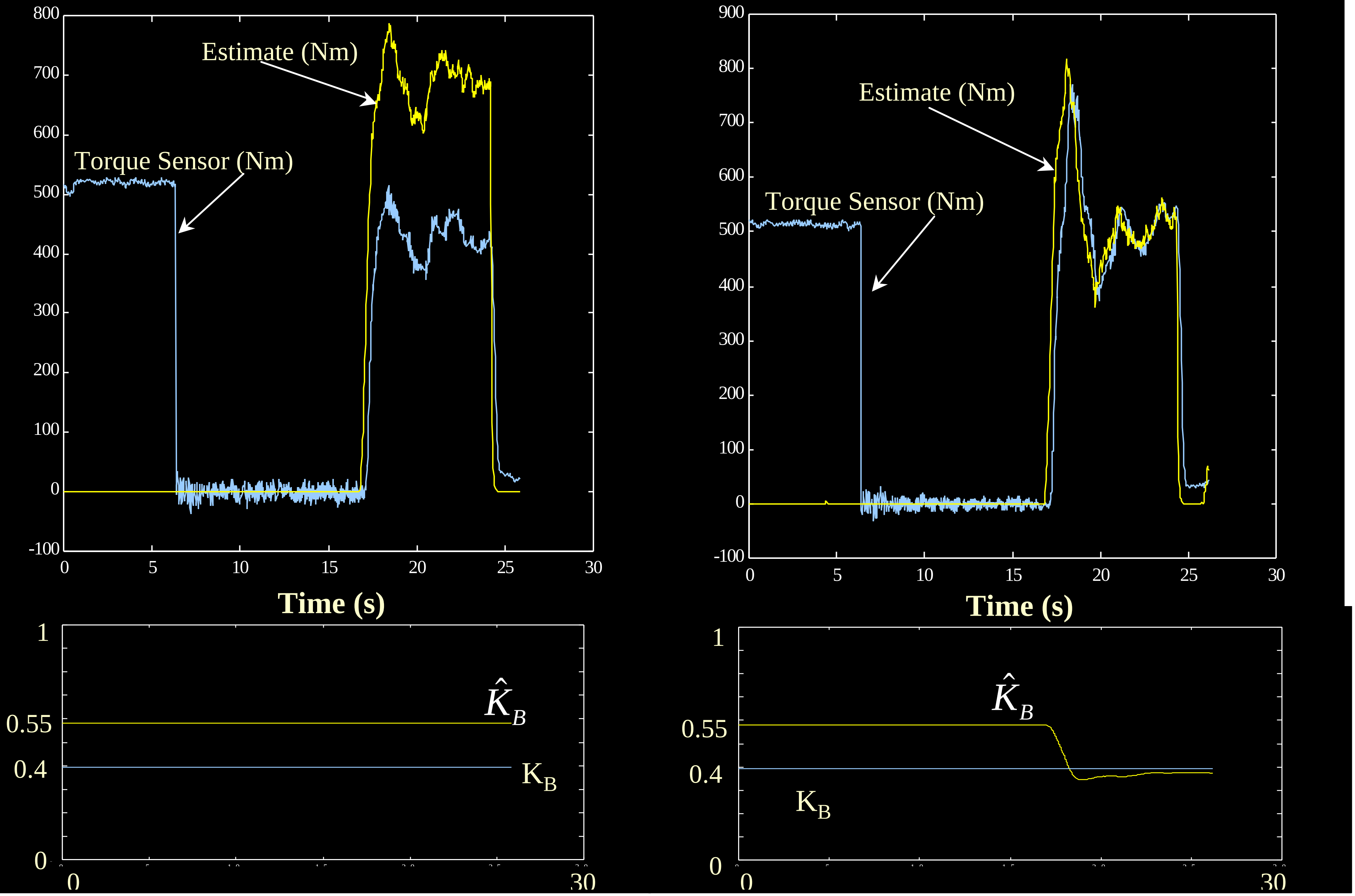
$$V = \frac{1}{2} e_v^2 + \frac{g}{2} \tilde{K}_B^2, \quad \tilde{K}_B = K_B - \hat{K}_B$$

- Rule to adjust $\hat{K}_B$:

$$\dot{\hat{K}} = -\frac{e_v}{\gamma \cdot \hat{K}_B}\left(\frac{1}{\beta}(T_e - M - T_{drag} + \lambda e_v - a_{des}\right)$$

- Persistence of excitation demonstrated experimentally, but not yet analytically

Force axis via pressure (3)



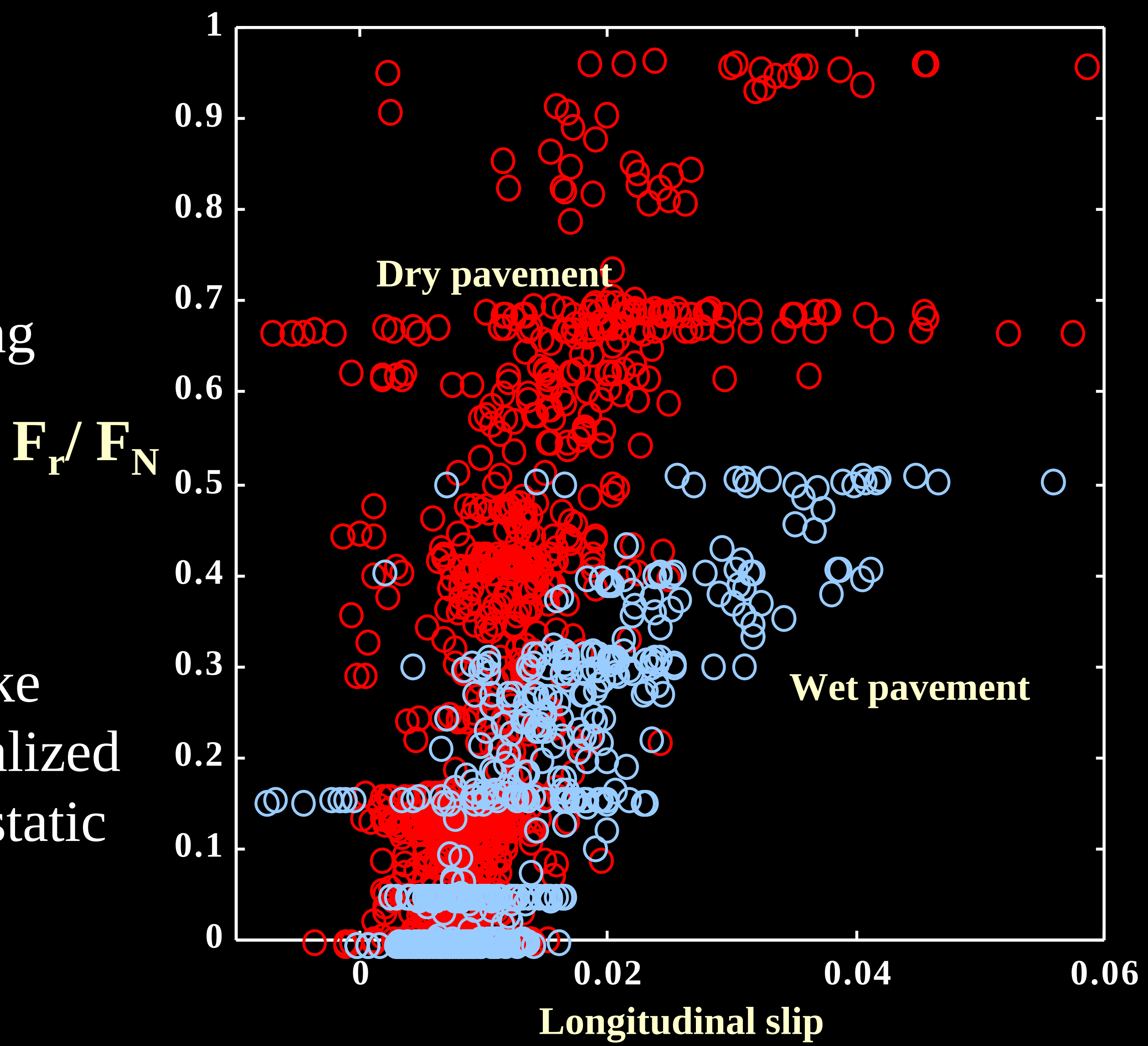
Raw force vs. slip data

- Two front wheels braking

- Manual driving => wide range of braking pressures

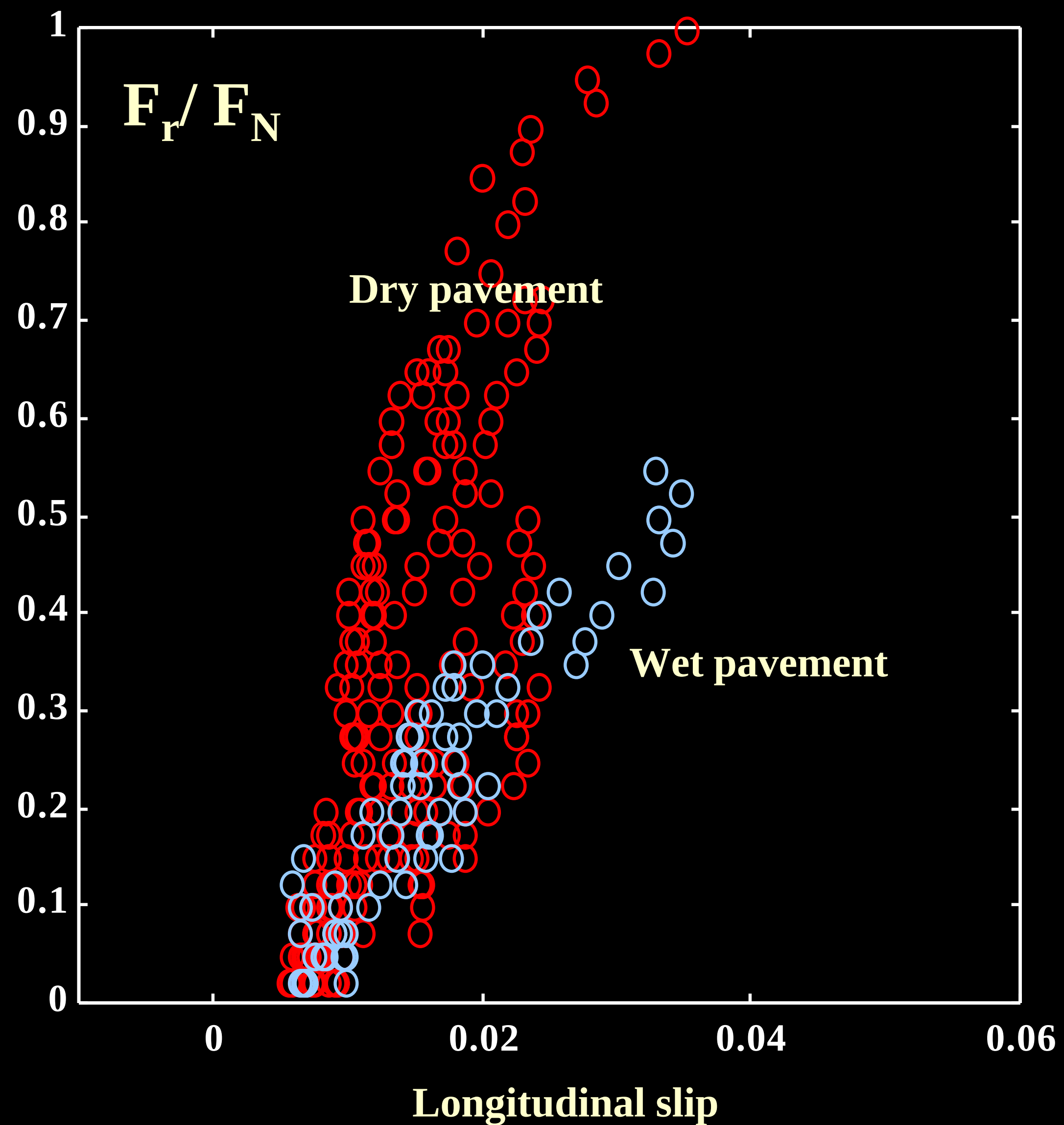
- Slip axis measured

- Force axis from brake pressure and normalized according to quasi-static weight distribution



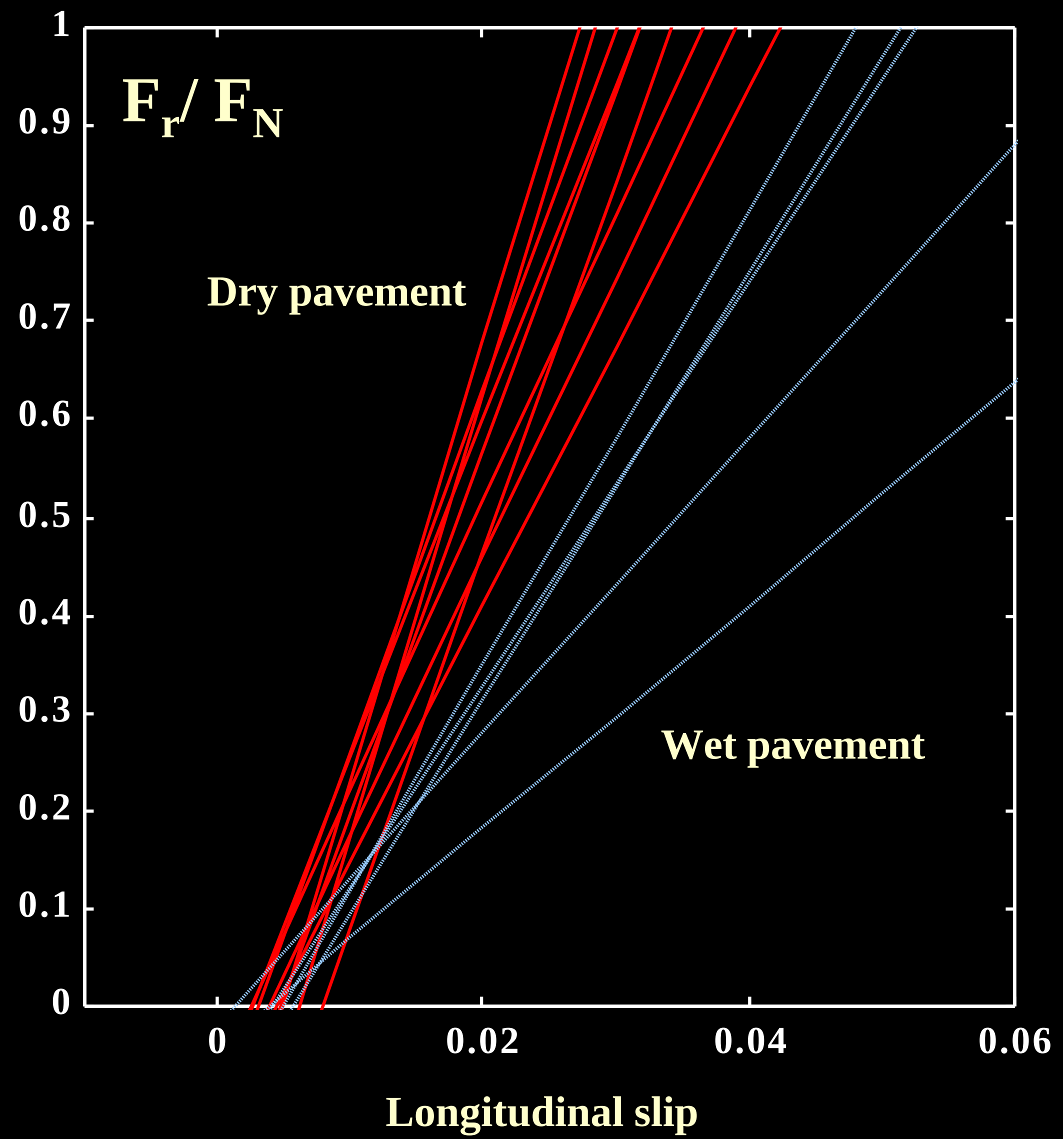
Force vs. averaged slip

- 15 tests shown
- Divide force axis into several “bins” and average slip values for all points in each bin
- Larger variance at high forces due to change in tire radius due to
  - Tire radius changes
  - Wheel accelerations
  - Side slip



Categorization

- One least squares line for each test
- A simple slope-based identifier would be a good starting point
- Car to car variance could be used to determine our confidence in an estimate



Future directions

- Development of a Kalman Filter to improve resolution of data
  - More confidence in classifications
  - Less excitation needed
- Classification of roads based on slope of best fit lines
- More sophisticated classification techniques
- Cooperative friction estimation--communication enables data sharing