AV Trajectories: Newtonian Mechanics vs. The Real World
Overview

- Limits on trajectory control
  - Vehicle capability
  - Environmental conditions

- Uncertainty
  - About vehicle conditions
  - About environment

- Managing ODD variations
  - Micro-ODDs as an approach
Example: Safe Following Distance

- Follower stops with space left behind leader (RSS example)
  - Different initial speeds
  - Follower initially accelerating during response time
  - Different braking capabilities
  - Considered safe if any gap between vehicles at rest
Sir Isaac Newton

F=MA

Not Just
A Good Idea
...

It’s the Law!
But, Where Does the “A” Come From?

- $F = MA \Rightarrow A = M / F$
  - BUT ... $F$ is limited by tire friction force

$$F_{\text{friction}} = \mu \times F_{\text{normal}} \quad (6)$$

where:
- $F_{\text{friction}}$ is the force of friction exerted by the tires against the roadway
- $\mu$ is the coefficient of friction, which can vary for each tire
- $F_{\text{normal}}$ is the force with which the vehicle presses itself onto the road surface

Example: braking depends upon:
- Ability of vehicle to exert force on roadway ($F_{\text{friction}}$)
- Driver applying full $F_{\text{friction}}$ via brakes (braking capacity)
Road Conditions Affecting Braking

- **Slopes**
  - Decreases friction AND pulls car

- **Curves:**
  - Friction maintains centripetal force
  - Banking (superelevation)
    - Reverse bank reduces normal force

- **Road surface condition**
  - Dry concrete $\mu = 0.75$
  - Snow $\mu = 0.2 - 0.25$
  - Ice $\mu = 0.1 - 0.15$

\[ F_{\text{normal}} = mg \cos \theta \]
\[ A_{\text{hill}} = g \sin \theta \]
Other Factors Affecting Brake Force

- Braking capability:
  - Tire capability (“sticky” tires might have $\mu > 1$)
  - Brake maximum friction (pad wear)

- Equipment condition
  - Tire condition: temperature, pressure, tread
  - Brake condition: hot, wet, damaged, ...
  - Vehicle suspension, weight distribution, ...

- Braking controls
  - Driver leg strength and willingness to brake hard
  - Braking assist force (multiplies driver leg strength)

- Aerodynamics, suspension, debris, ...
Epistemic Uncertainty – Vehicles

- Own vehicle weak braking (less than expected)
  - Brake wear & failures
  - Loss of brake assist
  - High tire pressure / bald tires
  - Brakes hot from recent use
  - Brakes wet from recent puddle

- Other vehicle strong braking
  - Braking capability for vehicle type
  - Aftermarket brake upgrade?
  - Aftermarket tire upgrade? Low tire pressure?
  - Leg strength of lead driver to press brakes?

Epistemic Uncertainty – Environment

- Road surface of own vehicle
  - Might not be same as lead vehicle surface
- Road surface of lead vehicle
  - Might have dramatically different friction properties
Segmenting Into Micro-ODDs

- A single huge ODD leads to poor permissiveness
  - Want better performance on a warm dry day
- Approach: break up ODDs into pieces
  - Default cautious behavior
  - Prove safe trajectory for an ODD segment
  - Optimize segments based on customer value
Micro-ODD Benefits

- Turns ODD growth on its head:
  - Over time: Improve permissiveness for fixed ODD size
  - Operate across a diverse ODD safely (and cautiously!)
  - Incrementally improve performance in high value ODD segments
  - Use finer grain ODD segments for high value operational situations
    - Note: important to address transition between segments

- References:
  - UL 4600
    - Sections 8.2 (ODD) & 8.8 (Trajectory & Control)
Conclusions

- Proofs are great, but rely upon assumptions
  - In particular, about environment & behaviors
  - Permissiveness vs. safety tradeoffs

- Proofs push uncertainty into the assumptions
  - Uncertainty about own system
  - Uncertainty about other actor behaviors
  - Uncertainty about the environment

- You might forget the edge cases...
  ... but they won't forget you!