AV Trajectories: Newtonian Mechanics vs. The Real World

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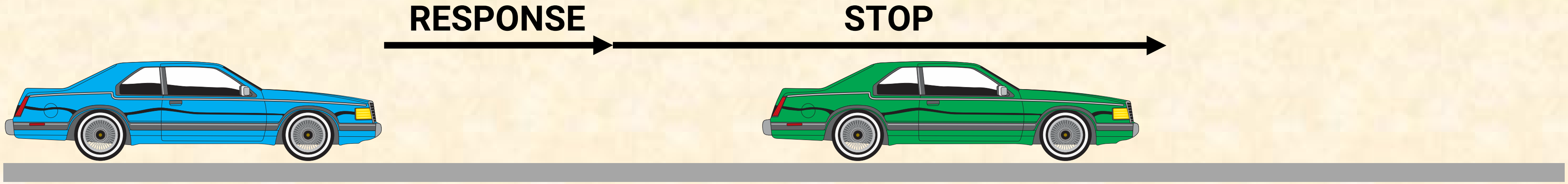
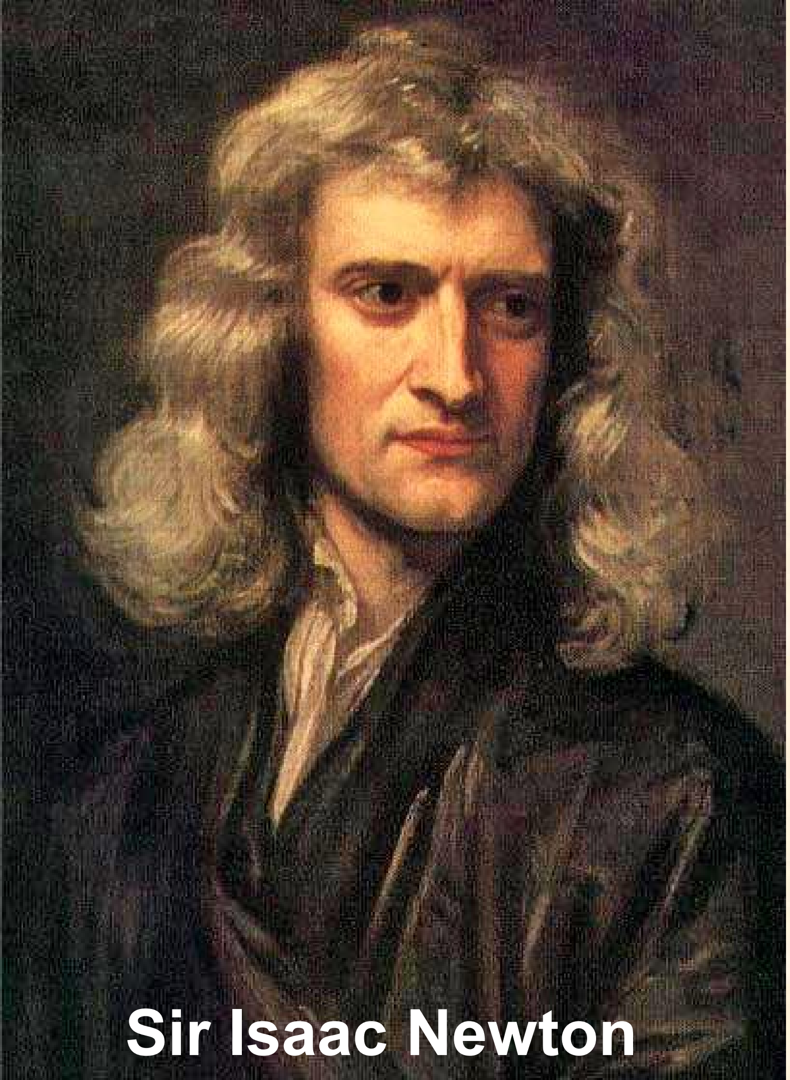
Overview

- **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



F=MA

Not Just
A Good Idea

…

It's the Law!

But, Where Does the "A" Come From?

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- **F = MA ➔ A = M / F**
  - BUT … F is limited by tire friction force

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

where:

- $F_{friction}$ is the force of friction exerted by the tires against the roadway
- μ is the coefficient of friction, which can vary for each tire
- F_{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 ($F_{friction}$)
  - Driver applying full $F_{friction}$ via brakes (braking capacity)

Road Conditions Affecting Braking

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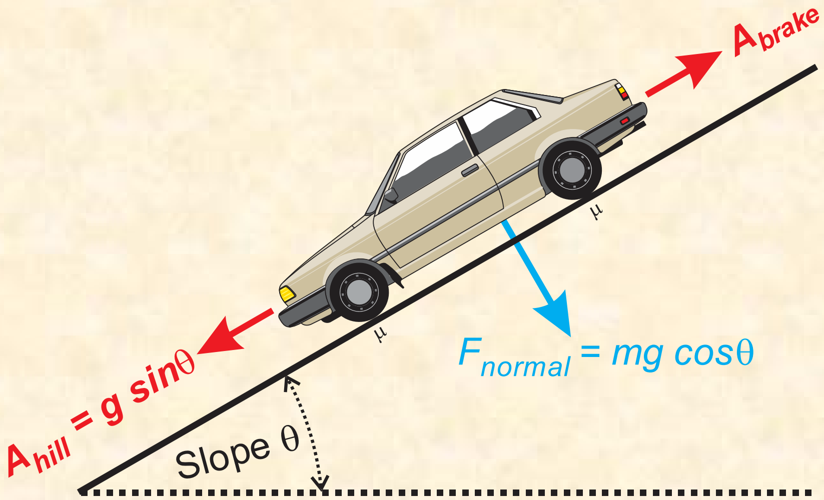
- **Slopes**
  - Decreases friction AND pulls car
- **Curves:**
  - Friction maintains centripetal force
  - Banking (superelevation)
    - – Reverse bank reduces normal force
- **Road surface condition**
  - Dry concrete μ = 0.75
  - Snow μ = 0.2 – 0.25
  - Ice μ = 0.1 – 0.15



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

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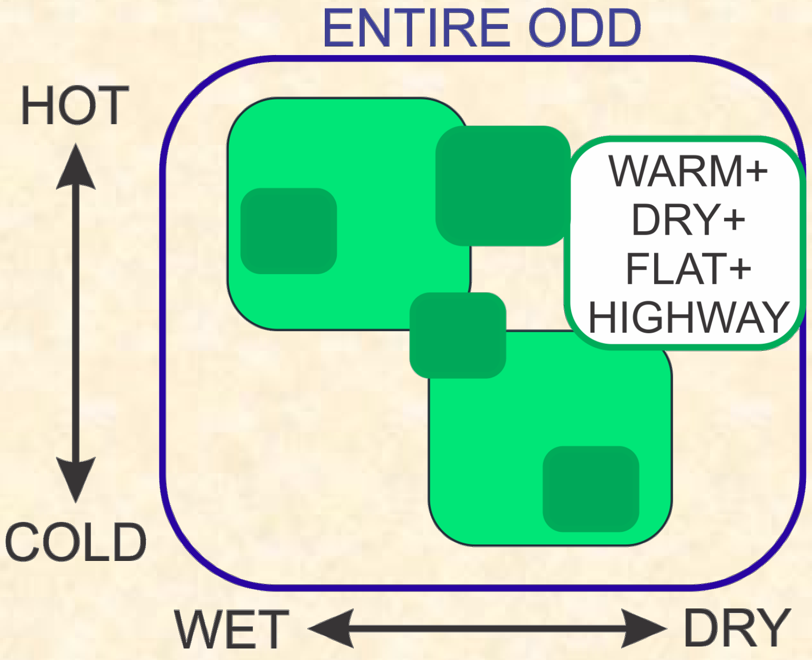
- **Own vehicle weak braking (less than expected)**
  - Brake wear & failures
  - Loss of brake assist
  - High tire pressure / bald tires
  - Brakes hot from recent use
  - Brakes wet from recent puddle
- **Other vehicle strong braking**
  - Braking capability for vehicle type
  - Aftermarket brake 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

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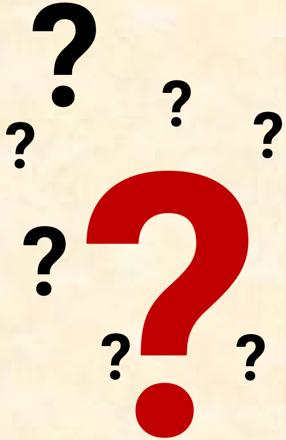
- **Turns ODD growth on its head:**
  - Over time: Improve permissiveness for fixed ODD size
  - Operate across a diverse ODD safely (and cautiously!)
  - Incrementally improve performance in high value ODD segments
  - Use finer grain ODD segments for high value operational situations
    - Note: important to address transition between segments
- **References:**
  - Micro-ODD paper: https://arxiv.org/abs/1911.01207
  - ODD parameter paper: https://bit.ly/33K26uA
  - 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!