Autonomous Vehicles Meet The Physical World

SAFECOMP 2019
Philip Koopman, Beth Osyk, Jack Weast
Overview

- Intro to RSS
  - Physics-based safety envelope approach

- Following distance as an example
  - Finding an RSS edge case

- But, the physical world is more complex
  - Assumptions & probabilities involved in making assurances

https://bit.ly/2kiarDs
The 2 Second Rule

- 2 (or 3) second following distance
  - Allows for human reaction time
  - Differences in vehicle performance

Typical Stopping Distances

- 20 mph (32 km/h): 6 m (6 m = 12 metres (40 feet) or three car lengths)
- 30 mph (48 km/h): 9 m (14 m = 23 metres (75 feet) or six car lengths)
- 40 mph (64 km/h): 12 m (24 m = 36 metres (118 feet) or nine car lengths)
- 50 mph (80 km/h): 15 m (38 m = 53 metres (175 feet) or thirteen car lengths)
- 60 mph (96 km/h): 18 m (55 m = 73 metres (240 feet) or eighteen car lengths)
- 70 mph (112 km/h): 21 m (75 m = 96 metres (315 feet) or twenty-four car lengths)

[UK Highway Code]
Rules of Thumb ≠ Guarantee

A bad case is:
- High performance vehicle executing a panic braking
- Followed by low brake performance heavy vehicle

Is 2 seconds enough?
Responsibility-Sensitive Safety rules (Mobileye):
- Safe distances based on physics
- Definition of dangerous situations (possible collision)
- Definition of proper response to evade a dangerous situation

Example: single-lane following:
This yields a minimum following distance (id., Lemma 2):

\[
d'_{\text{min}} = \text{MAX} \left\{ 0, \left( v_f \rho + \frac{1}{2} a_{\text{max,accel}} \rho^2 + \frac{(v_r + \rho a_{\text{max,accel}})^2}{2a_{\text{min,brake}}} - \frac{v_f^2}{2a_{\text{max,brake}}} \right) \right\}
\] (1)

Where in our case the ego vehicle is the following ("rear") vehicle, and:

- \( d'_{\text{min}} \) is the minimum following distance between the two vehicles for RSS
- \( v_f \) is the longitudinal velocity of the lead ("front") vehicle
- \( v_r \) is the longitudinal velocity of the following ("rear") vehicle
- \( \rho \) is the response time delay before the ego (rear) vehicle starts braking
- \( a_{\text{max,brake}} \) is the maximum braking capability of the front vehicle
- \( a_{\text{max,accel}} \) is the maximum acceleration of the ego (rear) vehicle
- \( a_{\text{min,brake}} \) is the minimum braking capability of the ego (rear) vehicle
Follower stops with space left behind leader

- Different initial speeds
- Follower initially accelerating during response time
- Different braking capabilities
- Considered safe if any gap between vehicles at rest
What About Edge Cases?

- Initial spreadsheet model
  - Sweep parameters
  - Discovered a small edge case

- Modeled in Ptolemy II
  - Hybrid state + continuous modeling
    - State machine: response time, braking, final stop
    - Continuous system: acceleration dynamics, braking dynamics
  - Actor-oriented design (each car is an actor)
  - Simulation campaign sweeping parameters...
    - Discovered the edge case was more general
High performance vehicle approaching from behind

- Initially approaching at high speed
- Can collide during response time...
  ... and still have shorter total calculated stopping distance

Intuition:

- Special case: Original RSS solves for distance at end
- General case: minimum distance at equal speed (not necessarily 0)
\[ d'_{\text{min}} = \text{MAX}\left\{0, \left( v_r \rho + \frac{1}{2} a_{\text{max, accel}} \rho^2 + \frac{(v_r + \rho a_{\text{max, accel}})^2}{2a_{\text{min, brake}}} - \frac{v_f^2}{2a_{\text{max, brake}}} \right) \right\} \] (1)

\[ d''_{\text{min}} = (v_r - v_f) \rho + \frac{(a_{\text{max, accel}} + a_{\text{max, brake}}) \rho^2}{2} \] (2)

\[ d'''_{\text{min}} = (v_r + a_{\text{max, accel}} \rho) t_r - \frac{a_{\text{min, brake}} t_r^2}{2} \]
\[ - \left( (v_f - a_{\text{max, brake}} \rho) t_f - \frac{a_{\text{max, brake}} t_f^2}{2} \right) \] (3)

\[ t = \frac{(v_r - v_f) + (a_{\text{max, accel}} + a_{\text{max, brake}}) \rho}{a_{\text{min, brake}} - a_{\text{max, brake}}} \] (4)

\[ d_{\text{min}} = \begin{cases} \text{MAX}[d'_{\text{min}}, (d''_{\text{min}} + d'''_{\text{min}})] & \text{; special case} \\ d'_{\text{min}} & \text{; otherwise (Original RSS)} \end{cases} \] (5)
But, Where Does the “A” Come From?

- **F = MA** → **A = M / F**
  - F is limited by tire friction force

\[
F_{\text{friction}} = \mu \times F_{\text{normal}} \tag{6}
\]

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

**Depends upon:**
- Ability of vehicle to exert force on roadway \( (F_{\text{friction}}) \)
- Ability of driver to exert that much force (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 \( \mu = 0.1 - 0.15 \)
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 across axles, ...

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

- Other factors: aerodynamics, suspension, debris, ...
Epistemic Uncertainty – Vehicles

- Own vehicle weak braking (less than expected)
  - Break 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
  - Type of vehicle and standard braking
  - 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


A Worse Case

- Sports car with good tires & brakes, uphill
  - Followed by heavy truck with worn brakes and bald tires down an icy hill
Conclusions

- Proofs are great, but they rely upon assumptions
  - Need to find edge cases
  - Need to information about the physical world
  - Permissiveness vs. safety tradeoff in real vehicles

- Proving moves uncertainty into the assumptions
  - Uncertainty about own system
  - Uncertainty about other actors
  - Uncertainty about the environment

- The math applies whether you use RSS or not
  - You might forget the edge cases. But they won’t forget you!
  - Future work: addressing the uncertainty
F=MA

It’s not just a good idea.

It’s the Law!