AN OPEN, TRANSPARENT, TECHNOLOGY NEUTRAL INDUSTRY-DRIVEN APPROACH TO SAFETY

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HUMAN DRIVING TODAY
The balance between safety & efficiency
What do humans do?
Explicit Traffic Rules

Establish **priority of road agent interests** to avoid collisions

- Come to complete stop at red lights
- Don't cross a double-yellow line
- Obey posted speed limits
- Yield to other road users when posted

Set limits on vehicle operation
Implicit Rules of the Road

A general set of principles applied by the driver

• Keep a safe distance from the car in front of you
• Drive cautiously under limited visibility
• Don’t drive slow in the fast lane
• Don’t cut off other drivers

Flexible, culturally dependent
Implicit Rules of the Road
Essential for Navigating Complex Scenarios
How do we formalize these concepts so AVs can safely and efficiently navigate?
RESPONSIBILITY SENSITIVE SAFETY

An open, transparent, technology neutral safety model for autonomous driving

RSS digitizes the implicit rules of the road, providing a check on AV decision-making, and a technology-neutral performance benchmark for regulators.
On a Formal Model of Safe and Scalable Self-driving Cars

Shai Shalev-Shwartz, Shaked Shammah, Amnon Shashua

Mobileye, 2017

Abstract

In recent years, car makers and tech companies have been racing towards self-driving cars. It seems that the main parameter in this race is who will have the first car on the road. The goal of this paper is to add to the equation two additional crucial parameters. The first is standardization of safety assurance — what are the minimal requirements that every self-driving car must satisfy, and how can we verify these requirements. The second parameter is scalability — engineering solutions that lead to unleashed costs will not scale to millions of cars, which will push interest in this field into a niche academic corner, and drive the entire field into a “winter of autonomous driving”. In the first part of the paper we propose a white-box, interpretable, mathematical model for safety assurance, which we call Responsibility-Sensitive Safety (RSS). In the second part we describe a design of a system that adheres to our safety assurance requirements and is scalable to millions of cars.

http://arxiv.org/abs/1708.06374
RESPONSIBILITY SENSITIVE SAFETY (RSS)

**FORMALIZE**
Human notions of safe driving

**IDENTIFY**
A Dangerous Situation

**EXECUTE**
The Appropriate Response

**Keep a safe distance longitudinally & laterally**

**Safe distance compromised in both directions**

**Brake to restore safe longitudinal distance**
RULES OF RSS
Rules to verify AV safety & performance

1. Do not hit someone from behind
2. Do not cut-in recklessly
3. Right-of-Way is given, not taken
4. Be careful in areas with limited visibility
5. If you can avoid a crash without causing another, you must
Breaking Down RSS’s Architecture

Safety Envelope
Defining the threshold between safety and danger

Doer-Checker

Is my proposed action safe?

Yes

No

AI-Based Planner

Am I in danger?

Yes

Yes

Proper Response

Determine the Proper Response based on the rule that was violated
What Determines Safe Distance?

If the silver car slams on the brakes, how much space do I need to avoid hitting it?

<table>
<thead>
<tr>
<th>Reaction time</th>
<th>Velocity</th>
<th>Braking needed to avoid crash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

- Velocity
- Braking needed to avoid crash
- Max braking capability
What Determines Safe Distance?

\[ d_{\text{min}} = [v_r \rho + \frac{1}{2} \alpha_{\text{max}} \rho^2 + \frac{(v_r + \rho \alpha_{\text{max}})^2}{2 \beta_{\text{min}}} - \frac{v_f^2}{2 \beta_{\text{max}}}]^+ \]

Any additional acceleration of the blue car during reaction time.
Time $t$ is dangerous for cars $c_1, c_2$ if both longitudinal and lateral distances between them are non-safe.
DERIVE A PROPER RESPONSE

Though the silver car initiated the dangerous situation, the blue car still ought to brake to return to a safe distance.
LIMITED VISIBILITY & OCCLUDED AREAS

When sensing capabilities are physically limited,
We must exhibit caution
Does it work?
What’s the catch?
What’s the catch?
What is \( B_{\text{max}} \)?

Values for braking, acceleration, reaction time are not static, but dynamic based on the situation.

How do we determine the reasonable expectations of other agents?
EXPECTATION #1: BRAKING CAPABILITY

Different cars have different braking. Different braking means different stopping distances.
### NOT ALL CARS ARE CREATED EQUAL

What should we assume for \( \beta_{\text{max}} \) as a result?

<table>
<thead>
<tr>
<th>Car Model</th>
<th>Max Braking Force (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 Porsche 911 GT3¹</td>
<td>12.57</td>
</tr>
<tr>
<td>2018 Corvette C6 Z06¹</td>
<td>12.45</td>
</tr>
<tr>
<td>2016 Mazda CX5²</td>
<td>10.17</td>
</tr>
<tr>
<td>2016 Jeep Cherokee²</td>
<td>9.67</td>
</tr>
<tr>
<td>2015 Ford F150³</td>
<td>8.84</td>
</tr>
<tr>
<td>1996 Honda Civic⁴</td>
<td>8.19</td>
</tr>
</tbody>
</table>


Calculations were made using initial velocity, \( v_i \) (100kph or 60mph) and stopping distances, \( d \), with the formula: \( \text{force} = \frac{v_i}{d(2/v_i)} \).
### NOT ALL CARS ARE CREATED EQUAL

A Porsche stops 13m sooner than a Civic

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>Stopping Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Porsche 911 GT3¹</td>
<td>30.70</td>
</tr>
<tr>
<td>2018</td>
<td>Corvette C6 Z06¹</td>
<td>31.00</td>
</tr>
<tr>
<td>2016</td>
<td>Mazda CX5²</td>
<td>35.36</td>
</tr>
<tr>
<td>2016</td>
<td>Jeep Cherokee²</td>
<td>37.19</td>
</tr>
<tr>
<td>2015</td>
<td>Ford F150³</td>
<td>40.70</td>
</tr>
<tr>
<td>1996</td>
<td>Honda Civic⁴</td>
<td>43.90</td>
</tr>
</tbody>
</table>


Calculations were made using initial velocity, \( v_i \) (100kph or 60mph) and stopping distances, \( d \), with the formula: \( f = \frac{v_i}{d} \) (\( f \) in \( \frac{v}{d} \))
Sometimes breaking a traffic rule is socially acceptable, and can be the safer choice.
We typically forgive drivers that violate the rules in this context.

Will we grant autonomous vehicles the same forgiveness?
EXPECTATION #3: OBJECTS IN THE ROAD

When tire treads, debris, and other things can appear in the blink of an eye, what do we do?
WHEN WE HAVE THE SPACE

Our proper response can be an evasive maneuver

What if we do not have the space?
IF WE DON’T, WE MAY HAVE NO CHOICE

So the question remains:

How should AVs respond to these scenarios?
EXPECTATION #4: PEDESTRIANS

How the traits of the road dictate our assumptions about pedestrian behavior
Neighborhoods without sidewalks are likely to have people walking along & playing in the street.
Neighborhoods with Sidewalks

Pull people away from the street, allowing cars to safely operate at higher speeds
RSS: A FORMAL MODEL FOR AV SAFETY

A mathematical model that formalizes common notions of safe driving

RSS can help answer important questions for AVs:

What does it mean to drive safely?
What constitutes a dangerous situation?
What is the proper response to a dangerous situation?
What does it mean to be reasonably cautious?
What assumptions can the AV make about the behavior of others?
In the hands of regulators, RSS provides an objective, technology neutral, performance benchmark.

ASSESS SAFETY PERFORMANCE OF AVs
Announcing...
**C++11 RSS LIBRARY**

Standalone Open Source Library currently covering a subset of RSS rules

1. Longitudinal scenarios
   - Same and opposite direction
2. Lateral scenarios & Multilane roads
3. Intersection handling

https://intel.github.io/ad-rss-lib/
C++ RSS Library Overview

**Plan**
- Perception
- World Modeling
- Driving Behavior

**Sense**
- Extract RSS World Model
- Receive Sensor Data

**AD RSS LIB**
- Extract Situations
- Check Situations
- Resolve Responses
- Transform Response

**Act**
- Enforce RSS Restrictions
- Create Actuator Commands

**Real Vehicle or Simulator**
AV SAFETY: AN ISSUE LARGER THAN ONE COMPANY

What are we doing

**INDUSTRY**
Engaging with customers, competitors and consortia to have an open dialogue on AV safety

**ACADEMIA**
RSS Research Centers at Universities in USA, PRC and EU

**GOVERNMENT / NGO’S**
Understanding government expectations on transparency and verification of AV safety

**REAL WORLD**
Deploying RSS in our on AV Fleet in very challenging environments
2018 Rand Report:
Measuring Automated Vehicle Safety

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https://www.rand.org/pubs/research_reports/RR2662.html
## A Safety Framework

<table>
<thead>
<tr>
<th>Stage</th>
<th>Setting</th>
<th>Leading measures</th>
<th>Lagging measures</th>
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<td></td>
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<td>Infractions</td>
<td>Roadmanship</td>
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<td>Deployment</td>
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<tr>
<td></td>
<td>Public roads</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

* This column assumed that, in the closed course and public road settings, a safety driver is available (either in the vehicle or remotely). If a safety driver is not present, this entire column would be N/A.

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Drive Safely

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