Metrics and Models to Evaluate Driving Safety

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Outline

- Background
- Types of metrics and models
- Three existing metric/model approaches
- Examples in simulation
- Challenges

- NHTSA-sponsored project being conducted by UMTRI with project partner SAE International.
Definitions

• **Metric:** The output of an ongoing calculation performed as a “vehicle under test” is operated.
  • Reflects safety-related interactions with other road users and other dynamic elements.

• **Models:** Many metrics use models (mathematical descriptions) of the expected motion behavior of other traffic and/or the vehicle under test.

• **Example:** Time to collision is a metric computed at time ‘0’ using one of many models:
  • Both vehicles remain at their current speeds (TTC), or
  • Both vehicles remain at their current accelerations (TTCa), or
  • Other traffic may suddenly maneuver, within specified bounds.

Test data → Metric calculations → Use of metrics for Safety Evaluations

Motion Behavior Models
• ego vehicle
• other vehicles
• VRUs
• other dynamic elements

Use of metrics for Safety Evaluations

TTC: Speed assumed constant in immediate future

TTCa: Acceln assumed constant in immediate future (to rest)

0
Metrics may depend on the data and the user

**Metrics may depend on:**

- Scale of driving exposure
- Completeness & accuracy of the data
- Knowledge of the ADS

**Presentation’s focus:**

- Extensive exposure: crash counts and injuries
- Limited exposure: surrogate metrics

- Completeness: White box, black box
- Accuracy, e.g., accelerations of other actors

- E.g., Modeling ADS response:
  - Simple models (acceleration bounds)
  - Vs. High-fidelity simulation models
Safe driving during early deployment may be defined along multiple dimensions:

- Defensive driving
- Crash-imminent situations
- Compliance with traffic rules
- Other responsible driving habits

Avoiding crashes, especially at-fault crashes

...and these dimensions may each require different metrics.
Types of Metrics and Dimensions of Safe Driving

One categorization of metric types:
- Kinematic metrics
- Traffic rule compliance metrics
- Crash involvement metrics

Mapping metric types to the dimensions of safe driving:

<table>
<thead>
<tr>
<th>Dimensions of safe driving</th>
<th>Metric Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defenitive driving</td>
<td>Primary</td>
</tr>
<tr>
<td>Crash-imminent response</td>
<td>Primary</td>
</tr>
<tr>
<td>Traffic rule compliance</td>
<td>Secondary</td>
</tr>
<tr>
<td>Responsible driving habits</td>
<td>Primary</td>
</tr>
</tbody>
</table>

- Kinematic Metrics
  - Defensive driving: Primary
  - Crash-imminent response: Primary
  - Responsible driving habits: Primary

- Traffic Rule Compliance
  - Defensive driving: Secondary
  - Crash-imminent response: Primary
  - Responsible driving habits: Secondary
## Continuum of Measures and Models
(from simple to complex)

<table>
<thead>
<tr>
<th>Observations</th>
<th>Decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct and instantaneous measurements</td>
<td>Safety-assuring models</td>
</tr>
<tr>
<td>“Instantaneous”</td>
<td>“Safety envelopes”</td>
</tr>
<tr>
<td>Simple ‘if’ metrics</td>
<td>Sophisticated “model-based” metrics</td>
</tr>
<tr>
<td>“1D”</td>
<td>“2D model-based”</td>
</tr>
<tr>
<td>Range, speed, lane position, post-encroachment, accel level</td>
<td>Responsibility-Sensitive Safety (RSS), Safety Force Field</td>
</tr>
<tr>
<td>Simple TTC, accel required</td>
<td>MPRISM, Pegasus criticality</td>
</tr>
<tr>
<td>(UMTRI &amp; others over decades)</td>
<td></td>
</tr>
<tr>
<td>What is happening.</td>
<td>What must happen, assuming...</td>
</tr>
<tr>
<td>What may happen if... (1-D assumptions).</td>
<td>What may happen if..., (2-D or model assumptions).</td>
</tr>
</tbody>
</table>
Responsibility-Sensitive Safety (RSS) Model (2017)

• Five safety rules of RSS
  1. Don’t hit the car in front of you.
  2. Don’t cut in recklessly.
  3. Right of way is given, not taken.
  4. Be cautious in areas with limited visibility.
  5. If you can avoid a crash without causing another one, you must.

• A snapshot is considered as not safe if both longitudinal and lateral safety distance are violated.

Pegasus Criticality Metric (PCM) (2018)

- The goal is to optimize the AV trajectory to minimize the criticality within a fixed look-ahead horizon subject to certain constraints (vehicle dynamics, safety):

$$\min_{u(k)=\{a_x(k), a_y(k)\}} \sum_{k=1}^{N} \left[ w_x R_x (k) + w_y R_y^2 (y) + w_{ax} \frac{a_x^2 (k)}{(\mu_{max} g)^2} + w_{ay} \frac{a_y^2 (k)}{(\mu_{max} g)^2} \right]$$

- Long. margin
- Lat. margin
- Long. accel.
- Lat. accel.

SV dynamics

1. State dynamics. 2. Kamm circle.

SV safety

Don’t hit objects or leave road.

Model Predictive Instantaneous Safety Metric (MPrISM) (2020)

• A model predictive TTC metric that considers the most dangerous maneuver of a background vehicle and the best response of the subject vehicle over a fixed look-ahead time horizon.

• Major Assumption: There exists only 1 non-cooperative background vehicle and all other vehicles will comply with the subject vehicle to avoid collisions.

• The optimization problem:

\[ h_i^*(t) = \min_{u_i} \max_{u_0} (h_i(x, u, t + T\Delta)), \]

where \( h_i(x, u, t) = \|x_i(t) - x_0(t)\|_2. \)

Vehicle dynamics

1. State dynamics. 2. Kamm circle.

Simulation of Different Safety Metrics

- The vehicle will be marked as all red when identified as not safe. Play speed: 0.5x.
Safety metric considerations

• Different categories of vehicles need to be considered
  • Subject vehicle (SV)
  • Background vehicles (BVs)
  • Principle other vehicle (POV)

• Behavior assumptions
  • Traffic rules
  • Responsible behaviors
  • Cooperative behaviors

• Model parameters
  • Vehicle types
  • Geographical differences

Example scenario: When the POV makes a cut-in maneuver, different behavior assumptions for the SV and BVs will lead to different safety metrics.
Additional Considerations

• Metrics should be aware that the subject vehicle may be constrained in its avoidance maneuver when other vehicles are nearby ("boxed in").

• Metrics should not reward avoidance maneuvers that result in a new and equal or greater risk of crash with a third vehicle.

• When defining or using metrics, consider how to normalize for exposure during testing, such as heavy congestion.
Next Steps

• Complete analysis of existing methods

• Propose enhanced versions of existing approaches

• Develop a holistic approach for consideration by the community including ideal properties for 3rd party evaluations
Study Partners

SAE International partner: Tim Weisenberger

NHTSA COR: Alrik Svenson
THANK YOU

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