Submitted by the expert from Intel Corporation

18th of December, 2019

Document FRAV-02-04
2nd FRAV session, 14-15 January 2020
Agenda item 6.5.

Functional Performance Criteria Proposal

Automated Driving – UNECE FRAV Informal Working Group

Background

At its core, the Responsibility Safety Sensitive (RSS) model is designed to formalize common sense behavioral concepts of what it means to drive safely, in a way that aligns with human judgment of the same. The RSS model covers all driving situations and scenarios. With the RSS model, an AV can be programmed to follow parameterized definitions of safety, thereby making it possible for AVs to share the road in a culturally consistent manner with human drivers in the geography of deployment. The model explicitly defines notions of safe distance and safe gaps when merging and cutting in, right-of-way, safe driving with limited sensing and visibility, and more. This mathematical formalization is supported by a set of logical rules that, when followed correctly, provide a verifiable level of safety assurance in the decision-making capabilities of the. First, RSS defines Safe Distances for all driving scenarios, from one-way traffic to junctions and multiple geometry scenarios. Secondly, RSS defines a Dangerous Situation, where there is an increased risk of a collision. Finally, the third essential definition in the model is the Proper Response that needs to be taken in order to evade a Dangerous Situation. In doing so, RSS defines in advance and not after the fact, the necessary balance of safety, utility and efficiency for Automated Vehicles.

Response to Request

FRAV is seeking to understand how RSS can be applied to five principles: longitudinal control, lateral control, minimal risk manoeuvre and condition, driver handover and driver monitoring. RSS can be implemented within a safety assessment methodology and corresponding set of metrics to provide high-level, “pass or fail” guidelines aligned to the first three FRAV principles for carmakers to ensure basic roadworthiness in the early stages of automated vehicle deployment. These guidelines will have a strong influence on the metrics defined for the later stage homologation process. There is a deterministic, formulaic application of RSS to longitudinal and lateral safe distances, interpretation of a dangerous situation and application of a proper response that can be assessed through external observation or directly from within an AV. For minimal risk manoeuvres and minimal risk conditions, the RSS proper response can be partially applied to satisfy the FRAV principles concept as a resulting action to the dangerous situation or trigger.

Basic pass / fail criteria for automated vehicles based on RSS principles:

1. **Longitudinal control** (acceleration, braking, road speed, distance) – RSS can be applied

   Applying RSS to this first principle can be done using the concept of Longitudinal Safe Distance for cars traveling in the same direction as well as cars traveling in opposite directions.

   For an AV traveling in the same direction following another car, the longitudinal distance between the two cars is considered safe if an accident is not possible, even if the car it is following applies full braking force and during its response time the AV accelerates at maximum acceleration and then immediately brakes by at least the minimum reasonable braking force that is likely to be used by a human driver. This concept is formalized using the following equation that can be implemented within the AV itself or through external observation.

   The following must be true to attain a PASS criterion:

$$d_{\min} >= \left[v_r\,\rho + \frac{1}{2} a_{\max,\text{accel}}\,\rho^2 + \frac{(v_r + \rho\, a_{\max,\text{accel}})^2}{2a_{\min,\text{brake}}} - \frac{v_f^2}{2a_{\max,\text{brake}}} \right]_+$$

Definitions:

$d_{\min}$	Minimum safe distance between ego (AV) and car in front	$a_{\max,\text{brake}}$	Brake capability of car in front
v_r	Velocity of ego (AV) car	$a_{\min,\text{brake}}$	Brake capability of ego car
v_f	Velocity of car in front	$a_{\max,\text{accel}}$	Acceleration of ego (AV) car
ρ	Reaction time		

- Details describing the equation and variables (parameters) can be found in the paper: On a Formal Model of Safe and Scalable Self-Driving Cars.

2. **Lateral control** – RSS can be applied

Applying RSS to the second principle can be done using the concept of Lateral Safe Distance which can always be applied during the operation of an AV.

For an AV that is moving, the lateral distance between two cars is considered safe if both cars apply the maximum acceleration during their respective response time and then immediately braking by at least the minimum reasonable braking force until they reach zero lateral velocity without colliding. This concept is formalized using the following equation that can be implemented within the AV itself or through external observation.

The following must be true to attain a PASS criterion:

$$d_{\min} >= \mu + \left[\frac{v_1 + v_{1,\rho}}{2}\rho + \frac{v_{1,\rho}^2}{2a_{\min,\text{brake}}^{\text{lat}}} - \left(\frac{v_2 + v_{2,\rho}}{2}\rho - \frac{v_{2,\rho}^2}{2a_{\min,\text{brake}}^{\text{lat}}} \right) \right]_+$$

Definitions:

$d_{\min}$	Minimum safe distance between ego (AV) and car in front	$a_{\min,\text{brake}}^{\text{lat}}$	Lateral acceleration
v_1	Velocity of ego (AV) car	ρ	Reaction time
v_2	Velocity of car in front		
μ	Lane width		

- Details describing the equation and variables (parameters) can be found in the paper: On a Formal Model of Safe and Scalable Self-Driving Cars.

3. **Minimal risk manoeuvre cases (triggers) and minimal risk condition** – RSS can be partially applied

RSS can be partially used to evaluate this third principle based on the first two principles and the basic definitions of keeping a safe distance. Given this, we can now define what constitutes a Dangerous Situation which would be similar to a "trigger" for a minimal risk manoeuvre. RSS determines that a situation is dangerous for two cars if both the longitudinal and lateral distances between them are non-safe.

RSS can be partially applied to the concept of "minimal risk condition" in that the model defines a Proper Response which is a set of actions that the AV must take in order to avoid a collision as a result of being in a Dangerous Situation. RSS does not evaluate the concept of minimal risk condition in the purist sense of its current definition which is related more to system failure as described here, "Minimal risk condition means low-risk operating condition that an automated driving system automatically resorts to either when a system fails or when the human driver fails to respond appropriately to a request to take over the dynamic driving task."

The following must be true to attain a PASS criterion:

> An AV executes a Proper Response (to be specified in the FRAV standard or referenced RSS standard) when it encounters a Dangerous Situation.

4. *Driver handover cases – RSS is not applicable*
5. *Driver monitoring performance – RSS is not applicable*

The above concepts can be applied to other driving scenarios such as cars driving in opposite directions and multiple route geometries such as intersections. A detailed paper, Implementing the RSS Model on NHTSA Pre-Crash Scenarios, describes the application of the RSS model across the NHTSA pre-crash scenarios that includes the identification of a dangerous situation and the proper response that an AV should take given the various scenarios. In the paper, we aim to go beyond the conceptual and demonstrate the RSS methodology using real-world pre-crash scenarios in order to demonstrate the soundness of the model. The goal is to show that when the model determines that an agent responded properly to any of a vast variety of pre-crash scenarios, a human in the same situation would have reached the same conclusion.

ANNEX

The following tables depict the situations where RSS can be applied:

a) NHTSA’s behaviour mapping
b) “California PATH Minimum Behavioral Compentencies”
c) 37 NHTSA pre-crash scenarios as a basis to ensure consistency and support by NHTSA

ANNEX

Annex provides the following tables, which depict the situations where RSS can be applied:

a) USDOT-NHTSA Behaviour Mapping
b) California PATH Minimum Behavioral Compentencies

NHTSA Behaviour Mapping – RSS coverage and applicability

Table 56. L3 Traffic Jam Drive Failure Mode/Effects Summary

Behavior Failure	Effects	RSS
Fail to maintain lane	Impact adjacent vehicle or infrastructure	Yes
Fail to maintain safe following distance	Impact lead vehicle	Yes
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles	Partial
Fail to detect relevant obstacles in or near lane	Impact obstacles	N/A
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities	N/A

Table 57. L3 Highway Drive Failure Mode/Effects Summary

Behavior Failure	Effects	RSS
Fail to maintain lane	Impact adjacent vehicle or infrastructure	Yes
Fail to maintain safe following distance	Impact lead vehicle	Yes
Fail to maintain appropriate/safe speed	Exceed speed limit, lose stability, impact lead vehicle	N/A
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles	Partial
Fail to detect relevant obstacles in or near lane	Impact obstacles	N/A
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities	N/A

Table 58. L4 Highly Automated Vehicle/TNC Failure Mode/Effects Summary

Behavior Failure	Effects	RSS
Fail to maintain lane	Impact adjacent vehicle or infrastructure	Yes
Fail to maintain safe following distance	Impact lead vehicle	Yes
Fail to maintain appropriate/safe speed	Exceed speed limit, lose stability, impact lead vehicle	N/A
Fail to maneuver appropriately/safely (e.g., lane change, intersection)	Impact vehicles or infrastructure	Yes
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles	Partial
Fail to detect relevant obstacles in or near lane	Impact obstacles	N/A
Fail to obey traffic rules and etiquette	Impact vehicles	N/A
Fail to recognize and respond to nonstandard hazards (e.g., work zones, emergency vehicles)	Navigate unsafely, impact obstacles	N/A
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities	N/A

California PATH Minimum Behavioral Competencies

Critical Driving Maneuvers	Freeway	Rural Highway	City Streets	Valet Parking	Low-Speed Shuttles
Detect System Engagement/Disengagement Conditions Including Limitations by Location, Operating Condition, or Component Malfunction	✓	✓	✓	✓	✓
Detect & Respond to Speed Limit Changes (Including Advisory Speed Zones)	✓	✓	✓		✓
Detect Passing and No Passing Zones					
Detect Work Zones, Temporary Lane Shifts, or Safety Officials Manually Directing Traffic	✓	✓	✓		
Detect and Respond to Traffic Control Devices		✓	✓		
Detect and Respond to Access Restrictions such as One-Way Streets, No-Turn Locations, Bicycle Lanes, Transit Lanes, and Pedestrian Ways			✓	✓	✓

Critical Driving Maneuvers	Freeway	Rural Highway	City Streets	Valet Parking	Low-Speed Shuttles
Perform High Speed Freeway Merge					
Perform a Lane Change or Lower Speed Merge			✓		
Park on the Shoulder or Transition the Vehicle to a Minimal Risk State (Not Required for SAE L3)					
Navigate Intersections & Perform Turns			✓		✓
Navigate a Parking Lot & Locate Open Spaces				✓	
Perform Car Following Including Stop & Go and Emergency Braking	✓	✓	✓	✓	
Detect & Respond to Stopped Vehicles	✓	✓	✓	✓	✓
Detect & Respond to Intended Lane Changes/Cut-Ins	✓	✓	✓		
Detect & Respond to Encroaching Oncoming Vehicles		✓	✓	✓	
Detect & Respond to Static Obstacles in Roadway	✓	✓	✓	✓	✓
Detect & Respond to Bicycles, Pedestrians, Animals, or Other Moving Objects		✓	✓	✓	✓
Detect Emergency Vehicles	✓	✓	✓		

Note: RSS does not apply to the "Detect" concept for "Critical Driving Maneuver" in the tables above. RSS does not evaluate the correctness of the sensing capabilities used in an AV.

RSS can be implemented to analyze the results from the planning capabilities of an AV related to the "Respond", "Navigate" and "Perform" concepts described in the tables above. A series of "pass / fail" criteria can be developed based on these scenarios by assigning values to the RSS equation parameters described in the body of this document.

Source: Thorn, Kimmel, Chaka, A Framework for Automated Driving System Testable Cases and Scenarios, NHTSA, Sept. 2018.