Formalizing scenarios for safety testing of automated driving functions

Hardi Hungar
Institute of Transportation Systems
German Aerospace Center (DLR)

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Automated Driving System (ADS) Example: Highway Pilot

- **Highly automated driving** on a highway under regular conditions
  - Passenger car
  - Highway or similarly equipped road
  - Speed limited to 130 km/h
  - Ordinary weather conditions

**Included**
- Stop & Go
- Changing lanes
- Overtaking
- Emergency manoeuvres
  - Braking
  - Evasive actions
- Fallback when reaching system boundaries:
  - Driver (with sufficient takeover time)
  - Risk minimizing maneuver (if driver does not respond)

**Excluded**
- Entering the highway
- Exiting the highway
- Bad weather
  - (very) Slippery surface
  - Heavy rain, snow, fog
SAE: Levels of automation

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Narrative definition</th>
<th>DDT</th>
<th>OEDR</th>
<th>DDT fallback</th>
<th>ODD</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>No Driving Automation</td>
<td>The performance by the driver of the entire DDT, even when enhanced by active safety systems.</td>
<td>Driver</td>
<td>Driver</td>
<td>Driver</td>
<td>n/a</td>
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<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>The sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT but not both simultaneously with the expectation that the driver performs the remainder of the DDT.</td>
<td>Driver and System</td>
<td>Driver</td>
<td>Driver</td>
<td>Limited</td>
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<td>2</td>
<td>Partial Driving Automation</td>
<td>The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.</td>
<td>System</td>
<td>Driver</td>
<td>Driver</td>
<td>Limited</td>
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**DDT**
- dynamic driving task

**OEDR**
- object and event detection and response

**ODD**
- operational driving domain

Driver responsibility

System responsibility

Highway Pilot

Highly automated driving
Safety target for automated driving

Ethics Commission on Automated Driving set up by the German Federal Ministry of Transport and Digital Infrastructure (BMVI)

Fully automated driving systems:

1. [...] [Their] primary purpose [...] is to **improve safety** for all road users.

2. [...] produce at least a diminution in harm compared with human driving, in other words a **positive balance of risks**.
The “standard” approach – ISO 26262

  - Risk-based approach to safety
  
  - Risk $\approx \sum_{h \in H} E_h \cdot C_h \cdot S_h$
    - $H$: Set of harmful events $h$
    - $E$: probability of occurrence (precisely: expected number per time unit)
    - $C$: controllability (here: probability of not avoiding an accident)
    - $S$: severity of event (injuries, fatalities)
Safety target (illustration)

Risk chart human driver

Risk chart ADS

Positive balance

Improvement in each category

Automation errors: Sensor error, misinterpretation etc.

Obstruction
Lane change
Cut in
Following
Weather
Obstruction
Lane change
Cut in
Following
Weather
Automation error
Safety gain
Risk assessment (commonly applied procedure)

- List all hazards
- Determine
  - Exposure
  - Criticality
  - Severity
- Sum up for overall risk

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<td>Cut in</td>
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<td>Cut through</td>
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<td>Overtaking</td>
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<td>Lane violation</td>
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Sum
Systematic computation of risk chart

1. Derive all potentially critical evolutions

2. Formalize the evolutions in precise descriptions of classes of evolutions

3. Exhaustive testing of evolution classes
   1. Derive concrete instantiations of a class
   2. Test concrete instances
   3. Identify critical instances

4. Analyze the critical instances
   1. Detailed evaluation
   2. Aggregate in risk chart

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Functional scenario “cut in“

- Rough storyboard of a cut-in evolution

- Sequence of events
  - C is approaching on left lane
  - C overtakes E
  - C changes to right lane in front of E

- Parametrizing and varying over discrete variants yields the concrete instantiations of a “cut-in“
Cut in: Example of a concrete instance

- Deriving a concrete test scenario
  - Street dimensions
  - Relative positions of vehicles (road and other vehicles)
  - Velocities of vehicles
  - Changes of the dynamic parameters over time
- The derivation process should be systematic
  - This necessitates a formal description of scenarios
Standard risk computation

- List all hazards
- Derive all concrete instances
- Determine
  - Exposure
  - Criticality
  - Severity

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A very long list!

Automation needed
Risk computation illustration
Scenario “Cut-in“:
Accident probability (“C“)

Cut-in (left, from behind)
• Step 1:
  • Velocity [m/sec]: E, L: [22]; C-E: [1,45];
  • Position [m]: L-E: [33,100]; E-C: [0,30];
  • …
• Step 2: Cut-in starts (C crosses lane marking) \(\Delta t\): [2,20]
  • Velocity [m/sec]: \(\Delta L\): [-7,+7]; \(\Delta C\): [-40,+4];
    C-E: [-5,2]; C-L: [-9,12]
  • Position [m]: L-E: [25,110]; C-E: [3,12]; L-E: [15,100]
  • …
• Step 3: Cut-in completed (C has crossed lane marking halfway) \(\Delta t\): [0.5,4]
  • Velocity [\(\Delta\) m/sec]: …
  • …

\[ C \approx \] accident probability

\( C \approx \Delta \) v [m/sec]
\( \Delta p - 4 \)

\[ \text{gap} = \Delta p - 4 \]
Risk computation illustration
Scenario “Cut-in“:
Exposure (“E”)

Visualization of frequency of cut-in depending on

• $\Delta v \ [m/sec]$: velocity difference between Ego vehicle and Cut-in vehicle
  - The frequency decreases for relatively slower Cut-in vehicle
  - Usually, the Cut-in vehicle is faster than the Ego vehicle (negative values of $\Delta v$)

• gap [m]: gap between Cut-in and Ego vehicle:
  - The frequency increases with gap size
  - Usually, the gap is reasonably large
Risk computation illustration
Scenario “Cut-in“: Risk

Visualization of risk* of cut-in

- Risk is highest for
  - a rather high velocity difference
    \( \Delta v \approx 4 \, [\text{m/sec}] \)
  - A narrow (but not minimal) gap
    \( \text{gap} \approx 9 \, [\text{m}] \)
  - The highly dangerous situations occur less often
- The numeric risk is to be computed as the integral of the risk function

* The severity is assumed to be constant, here
Risk computation illustration
Scenario „Cut-in“:
Risk integration by simulation

Computation by approximate discrete summation

- Like Riemann integral approximation
- Each column represents the result of a test run (simulation / proving ground / field)
- Lower test density in regions with low accident probability
Risk computation illustration
Scenario „Cut-in“:
Risk integration by simulation

This would work, if

- we had a reliable simulation tool
- we had a complete test specification
- we could estimate the accident probability ("C") of each simulated scenario
- we knew the frequency of each scenario ("E")
- we could judge the accident severity ("S")
Risk computation illustration
Scenario „Cut-in“:
Risk integration by simulation

This would work, if

• we had a reliable simulation tool
• we had a complete test specification
• we could estimate the accident probability ("C") of each simulated scenario
• we knew the frequency of each scenario ("E")
• we could judge the accident severity ("S")

Can be measured by testing

Few valid data available

Only rough models available

To be constructed

Few valid data available

Can be measured by testing

To be constructed
Formalization of scenarios: Description layers

• **L1**: Street layer:
  • Geometry, topology, material

• **L2**: Infrastructure:
  • Boundaries, traffic signs, markings

• **L3**: Temporary modification of elements of L1 and L2 (example: installations of construction sites)

• **L4**: Moving objects:
  • Types and specifics, dynamics

• **L5**: Environment conditions:
  • Weather, light

Layer definition after: Schuldt et al. Effiziente systematische Testgenerierung für Fahrerassistenzsysteme in virtuellen Umgebungen, AAET 2013. (further developed in PEGASUS)
Scene: snapshot of evolution

- **Traffic participants**
  - T, E, L

- **Positions on the street**
  - Distance from road edge

- **Velocities**
  - Acceleration
  - Deceleration

- **Positions**
  - (here: relative to E)

More complex: links between scenes
Maneuver macros:
Linking scenes to evolutions

Program-like descriptions of vehicle behavior

a. Geometry:
   - Lateral position
   - Discrete shape type: straight, sinusoidal, etc.
   - Modifiers: distortions, deviations

b. Execution:
   - time profile
   - Completion condition (e.g.: time slot, space limitations)
   - Absolute or relative to other traffic participants

c. End and exit conditions

Examples

(1) Constant drive
   a. Lane 1, straight, low lateral deviations
   b. constant velocity, low deviation
   c. --

(2) Following
   a. Lane 1, straight, low lateral deviations
   b. Velocity adjusted on distance to lead vehicle
   c. Lane change of lead vehicle

(3) Lane change
   a. Lane 2, sinusoidal negative, low lateral deviations
   b. constant velocity, low deviation
   c. Completion of trajectory

discrete parameter  numerical parameter
Example scenario: conflicting lane changes

0. The ego vehicle E follows L on the right lane
   T is driving on the middle lane with the same velocity

1. C overtakes T,
   L decelerates, which might provoke E to change lanes

2. C and E both move towards the middle lane
Example scenario: conflicting lane changes
Programming the scenario with maneuver macros

0. **L**: constant drive
   **T**: constant drive
   **C**: lane following with goal constellation depending on (C, T, E)

1. **L**: lane following, decelerating
   **T**: constant drive
   **C**: lane following with goal constellation depending on (C, T, E)

   **C** reaches goal constellation / **E** veers out

1. **L**: lane following, decelerating
   **T**: constant drive
   **C**: lane change
Precisely specifying the test space with logical scenarios

• **Building blocks of logical scenarios**
  • Maneuver macros as *elementary constituents*
  • Scenario definition by *composing* maneuver macros

• **Logical scenarios** are similar to programs
  • Defining logical scenarios needs testing them (no reasonably complex program will be correct on first writing)

Comments

• The formalization may be seen as a *domain-specific language*

• The use of macros results in *comprehensible definitions*

• That maneuver macros capture real behaviors realistically can be validated on a reasonably small set of observation data.
Precisely specifying the test space with logical scenarios

• **Building blocks of logical scenarios**
  - Maneuver macros as elementary constituents
  - Scenario definition by composing maneuver macros

• **Logical scenarios** are similar to programs
  - Defining logical scenarios needs testing them (no reasonably complex program will be correct on first writing)

• **Coverage of the test space** by complementary scenario spaces
  - Manually manageable set of logical scenarios (though certainly large)

Comments

• The formalization may be seen as a domain-specific language

• The use of macros results in comprehensible definitions

• That maneuver macros capture real behaviors realistically can be validated on a reasonably small set of observation data.
Scenario branching: Example

1. E follows L on the right lane
   S decelerates
   L changes lanes

1.2 E changes lanes
   L decelerates

1.1 E decelerates
   L decelerates

1.1.1 L changes back

1.1.1.1 L decelerates

1.2.1 L decelerates hard
   F accelerates on right lane
   (closing gap)
Scenario branching: Tree structure

1. **E** follows **L** on the right lane
   - **S** decelerates
   - **L** changes lanes

1.1 **E** decelerates
   - **L** decelerates

1.1.1.1 **L** changes back

1.1.1 **L** decelerates

1.2 **E** changes lanes
   - **L** decelerates

1.2.1 **L** decelerates hard
   - **F** accelerates on right lane
     - (closing gap)
Scenario branching: Specification by two scenarios

1. **E** follows **L** on the right lane
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   - **L** changes lanes

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   - **L** decelerates

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Scenario branching: Specification by two scenarios

1.1 E decelerates
   L decelerates

1.1.1 L changes back

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IF [E changes lanes] THEN BREAK
Scenario branching: Specification by two scenarios

IF not([E changes lanes]) THEN BREAK

1. E follows L
   S decelerates
   L changes lanes

1.2 E changes lanes
   L decelerates

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   F accelerates on right lane
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Scenario branching: Specification by two scenarios

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   F accelerates on right lane
   (closing gap)

Different logical scenarios are distinguished by different discrete actions of E (and the other vehicles, of course).

Not a formal definition - yet
Logical scenarios as test specification

1. Capture all dynamic evolutions in discrete event structures (functional scenarios)

2. Extract linear evolutions by splitting branches

3. Formalize linear evolutions in parameterized programs (logical scenarios)

4. Instantiate scenarios for complete set of test cases
Computing the risk

- List all hazards
- Determine
  - Exposure
  - Criticality
  - Severity

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Formalized scenario descriptions enable automated test case generation

Splitting scenarios helps in keeping test cases disjoint
Computing the risk

- List all hazards
- Determine
  - Exposure
  - **Criticality**
  - Severity

- Extract **relevant row sets**

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Sum
Computing the risk

- List all hazards
- Determine
  - **Exposure**
  - Criticality
  - **Severity**
- Extract relevant row sets
- Detailed **analysis of risk** in critical scenarios

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Sum
Computing the risk

- List all hazards
- Determine
  - Exposure
  - Criticality
  - Severity
- Extract relevant rows
- Detailed analysis of risk in critical scenarios
- Sum up for aggregated risk chart

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<td>0.12</td>
<td>1.3</td>
<td>0.003</td>
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<tr>
<td>Ego: 130 km/h, Cut-in-veh.: 90 km/h</td>
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<tr>
<td>Cut-in from left lane, decelerating</td>
<td>0.01</td>
<td>0.15</td>
<td>1.4</td>
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<tr>
<td>Ego: 110 km/h, Cut-in-veh.: 115 km/h</td>
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</table>

Sum
Conclusion

1. Capture all potentially critical evolutions in functional scenarios

2. Formalization of functional scenarios in precisely defined logical scenarios using maneuver macros

3. Identify all critical scenarios by systematic testing

4. Build the risk chart by analyzing and rating the critical scenarios
Contact info

PD Dr. Hardi Hungar
German Aerospace Center
Institute of Transportation Systems
hardi.hungar@dlr.de
Risk computation

- List all hazards
- Determine
  - Exposure
  - Criticality
  - Severity
- Sum up for overall risk

Few valid data available

Can be measured by testing

Only rough models available

<table>
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<tr>
<th>Hazard</th>
<th>E</th>
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<th>S</th>
<th>Risk</th>
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<td>Cut-in by vehicle entering highway</td>
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<td>Cut-in by vehicle concealed by truck</td>
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<td>Cut-in from left lane, decelerating</td>
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