Test Specifications for Highly Automated Driving Functions: Highway Pilot

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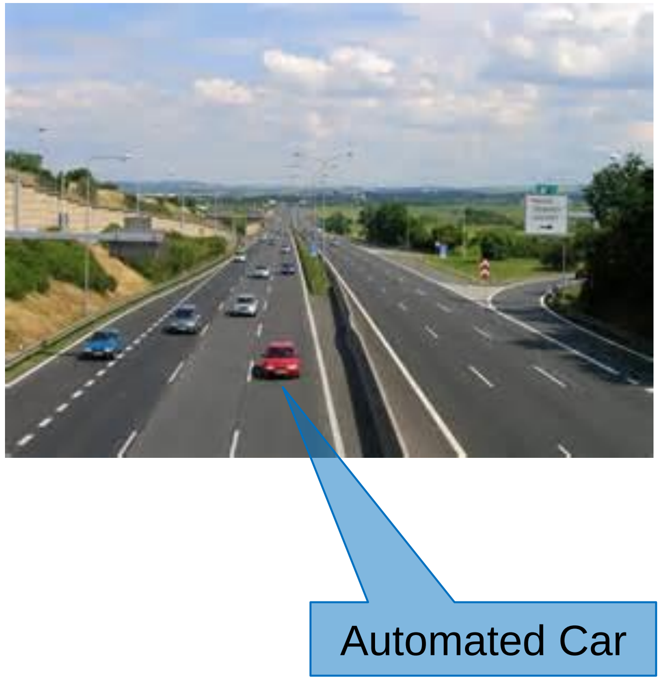
DLR

Introduction
Application: Highway Pilot



- Automated driving on a highway under regular conditions (SAE level 3)
  - Passenger car
  - Highway or similar equipped road
  - Speed limited to 130 km/h
  - Ordinary weather conditions

Included

- Stop & Go
- Changing lanes
- Overtaking
- Emergency manoeuvers
  - 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

Introduction
Problem: How to prove safety of a Highway Pilot?

- **ISO 26262**: Standard „Road Vehicles – Functional Safety“ for developing systems with electronic elements
    - <u>Risk-based approach to safety</u>
        - Risk $\approx \sum_{h \in H} E_h * C_h * S_h$
            - 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)
    - <u>Safety requirement</u>:
        - The risk must be „minimized“
            - The definition of „minimal“ may vary
    - Proving safety of an implementation of the Highway Pilot
        - ¿Testing a Highway Pilot on the road under supervision of a safety driver?
            - May take a while (one estimate: some billion kilometers, $\sim 13 * 10^9$ [1])

[1] H. Winner et al., Safety Assurance for Highly Automated Driving, TRB Annual Meeting 2017

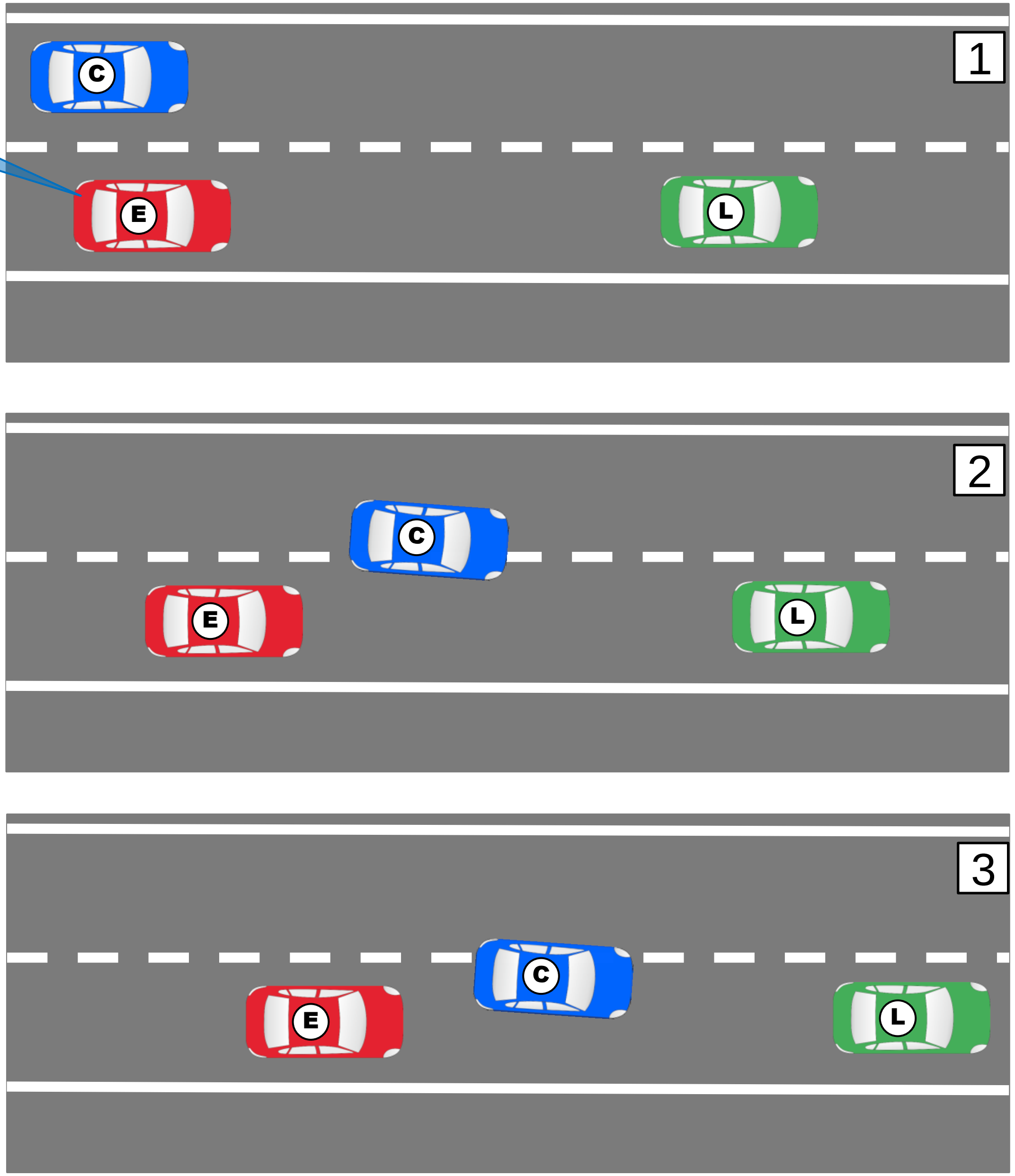
Approach
Specification Concept: Scenarios

- A *scenario* (after [2]) describes a traffic sequence
  - Here: always with one distinguished *ego car*
  - Consists of
    - scenes (snapshots), connected by
    - actions of the ego car, and
    - events coming from the environment (traffic participants or other)

- Example scenario „Cut In“ (*Illustration*)
  - 1: Ego vehicle is following Lead vehicle, other vehicle is approaching from behind
  - 2: Other vehicle overtakes and moves into ego lane (events)
  - 3: Other vehicle has cut in (event)

[2] S. Ulbrich et.al., Defining and Substantiating the Terms Scene, Situation and Scenario for Automated Driving, ITSC 2015

Ego vehicle



E Ego vehicle
L Lead vehicle
C Cut-in vehicle

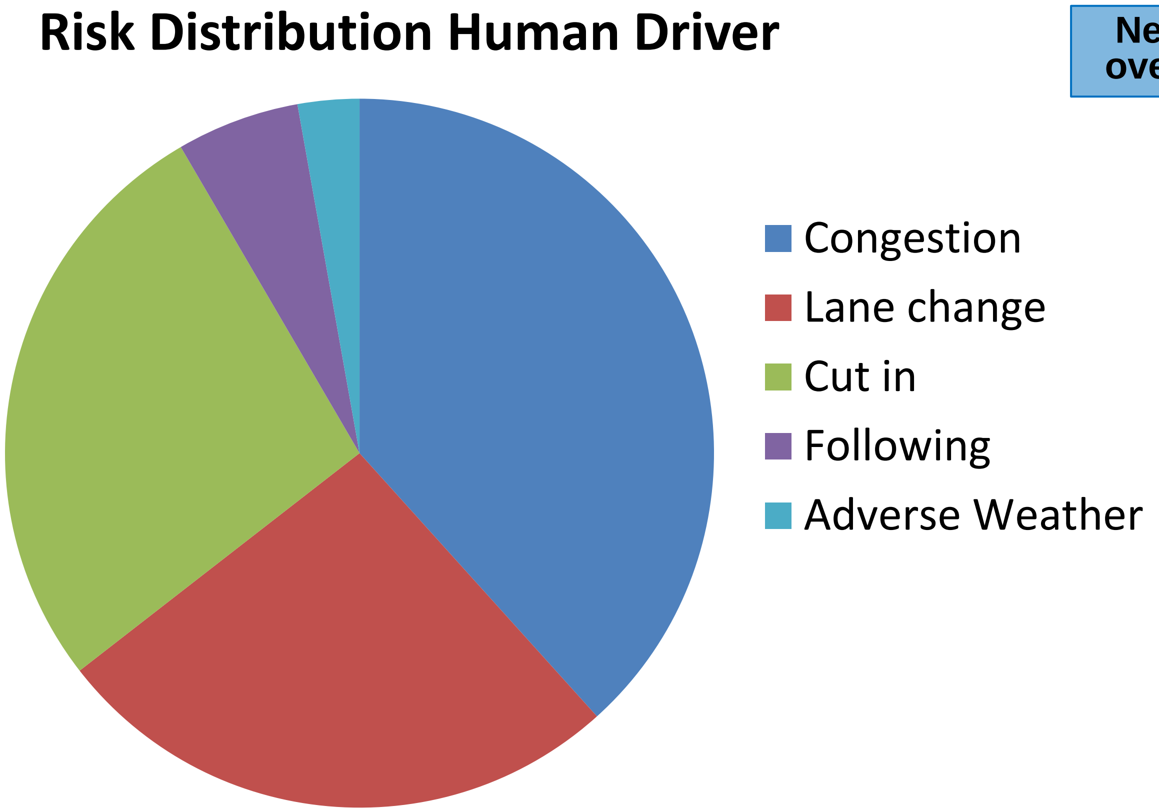
Approach
Hierarchy of Tests: Virtual, Proving Ground, Field

- **Simulation**
  - Embed HAF control into traffic simulation software
  - Run extensive tests

- **Proving Ground**
  - Targeted experiments in controlled environments
  - Validation of simulation results

- **Field Data**
  - Measuring parameters of exposure
  - Evaluating accident data
  - Validating simulation results in reality

Approach
Safety Goal: Outperform the Human Driver



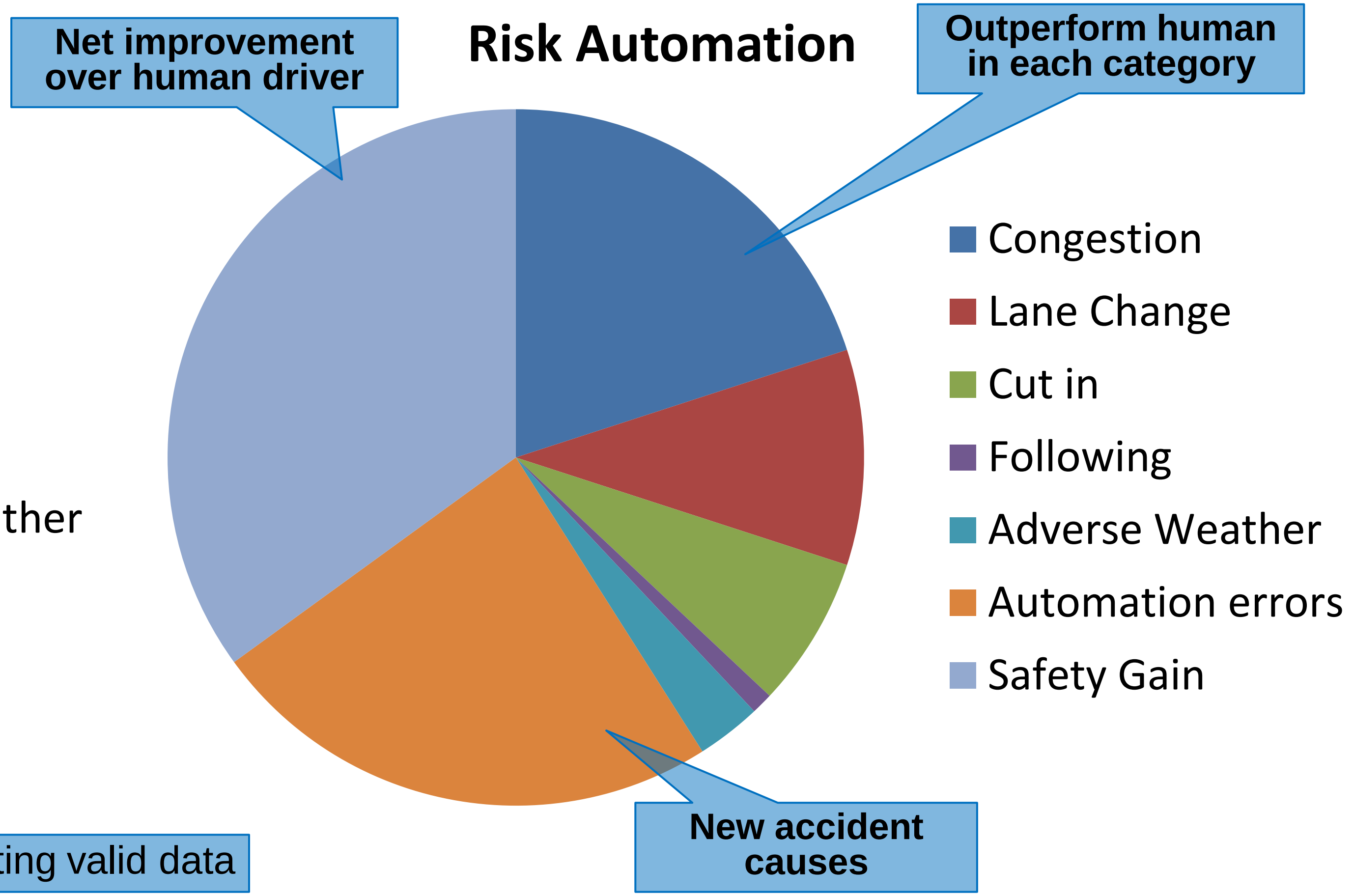
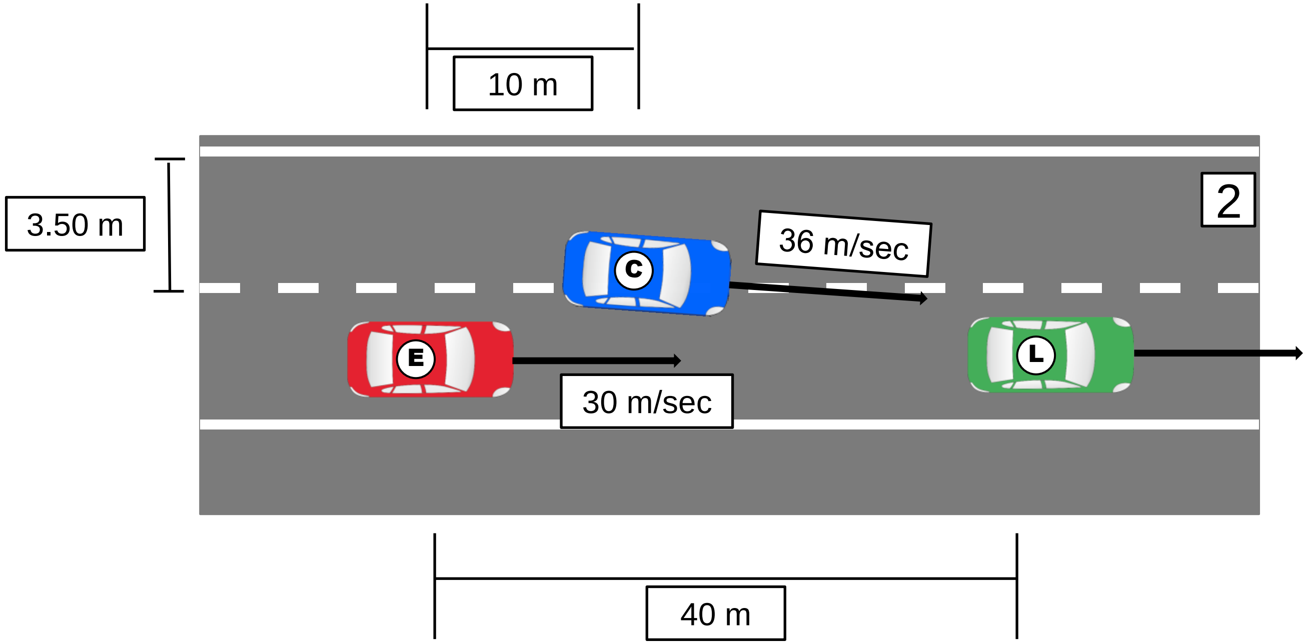


Illustration – not representing valid data

Scene Definition

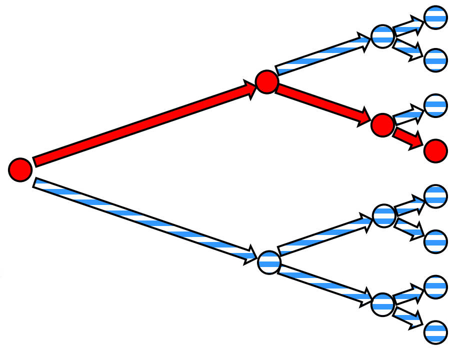
- A *Scene* describes a particular state
  - Traffic infrastructure
    - Lanes, regulations
    - Geometry: curvature, elevation
  - Environment conditions
    - Surface grip (wetness, …)
    - Perception: Light, sun, fog, sensor obstacles, etc.
  - Traffic
    - Vehicles: Ego and usually other
      - Type
      - Position, speed, orientation
      - Blinker, brake lights

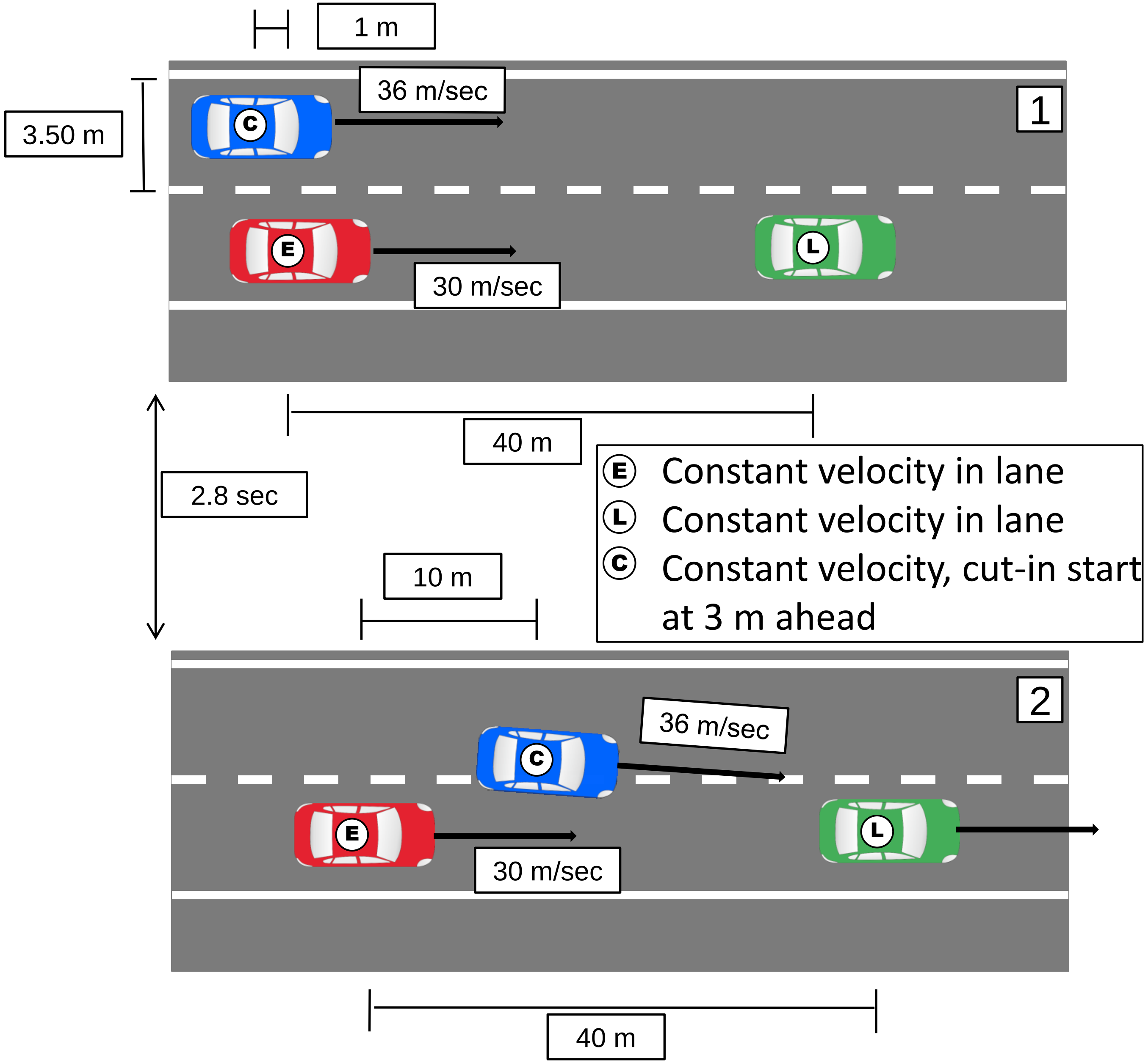


Scenario Definition

- A *Scenario* describes a particular evolution of scenes
- It consists of
  - A (finite) timed sequence of scenes
  - A fully defined *start scene*
  - Transitions between subsequent scenes, with
    - Actions of the ego vehicle
    - Events from the environment (other vehicles, conditions)
    - Evolutions (passage of time)

- One line of evolution (of potentially many)

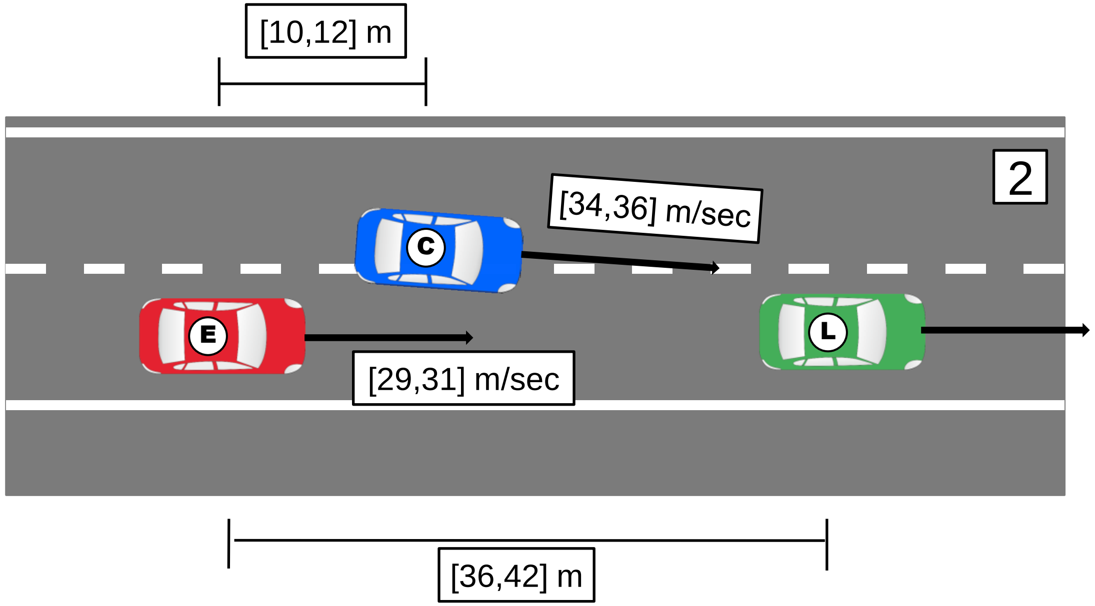


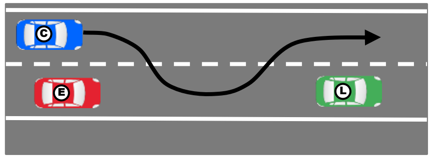


Scenes and Scenarios Definition (Elaboration)

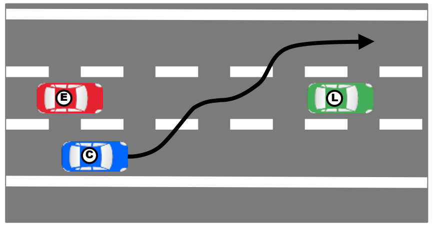
- **Scene** parameters need not be fully defined
  - Field data: Precise values (ground truth) are not always available
  - Specifications: Ranges serve to capture a class of similar situations

- **Scenarios**
  - Action, event and time parameters can be imprecise
  - The discrete structure remains **fixed** in one scenario
    - E.g.: Lane change performed vs. lane change aborted go into different scenarios
  - Discrete variability captured in sets/**classes** of scenarios





Cut-through left-left



Cut-through right-left

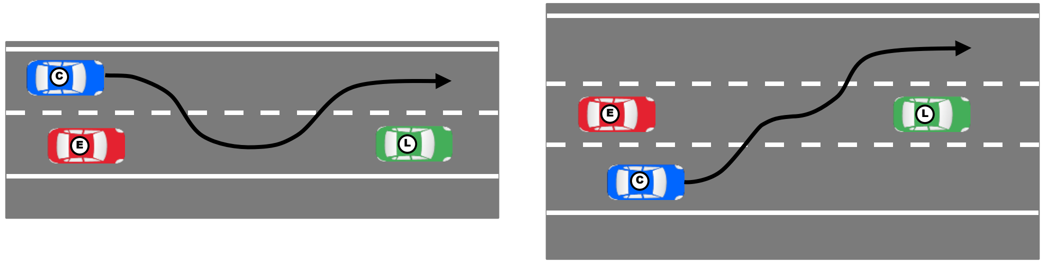
Scenario Classes
Functional and Concrete Scenarios

- **Functional Scenario**
  - Textual / graphical description of a class of scenarios
  - Rough parameter ranges (if at all restricted)
  - May include discrete variability
  - **Usage**: High-level specification
  - Examples: Cut-in, Cut-through, Lane Change, Overtaking, etc.

Capture and discuss different classes of evolutions

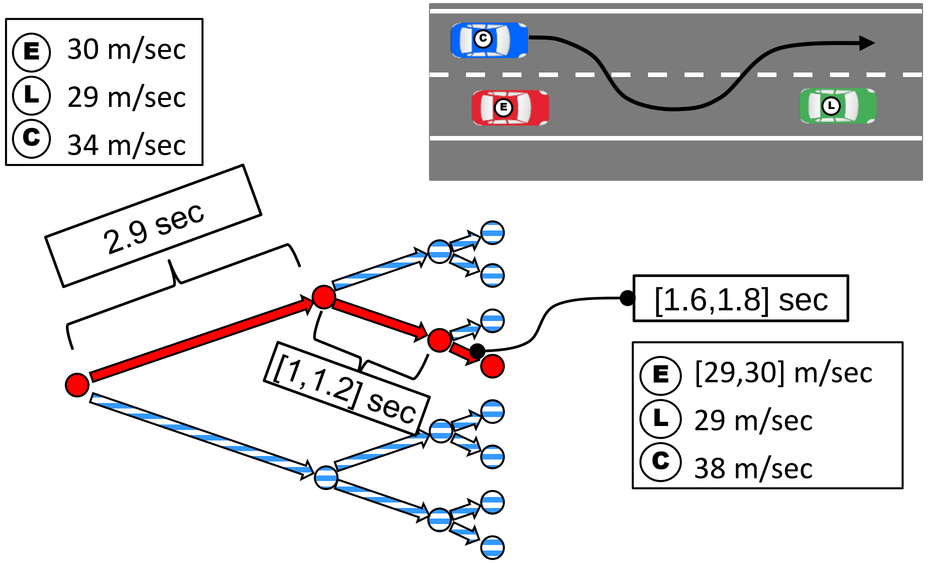
- **Concrete Scenario**
  - Fully defined sequence
  - Parameters within tight bounds
  - One line of evolution
  - **Usage**:
    - Capture field data or simulation runs
    - Define test cases

Essentially one specific evolution



Cut-through

One functional scenario describes a large set of conrete scenarios



Scenario Classes
Functional Scenarios

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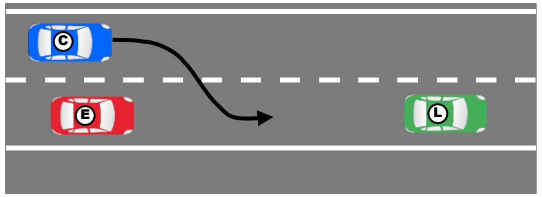
- **List of functional scenarios**
  - Free driving
  - Following
  - Lane change
  - Overtaking
  - Cut-in
  - Leave lane
  - Cut-through
  - Slow traffic
  - Stop & Go
  - Jam
  - Lane violation
  - Incident traffic
  - Wrong-way driver
  - Obstacle
  - Incident environment

Scenario Classes
Functional Scenario Examples: Cut-in / Incident Environment

Cut-in

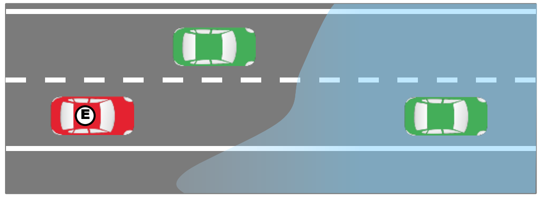
- Start situation
  - Ego car (**E**) drives on highway lane
  - Other vehicle (**C**) on adjacent lane
  - Potentially further vehicles involved
- Evolution
  - **C** moves into E-lane in front of **E**
- Criticalities
  - **C** cuts in with little distance to **E**
  - **C** brakes after cutting in
  - Low TTC(**E**,**C**)

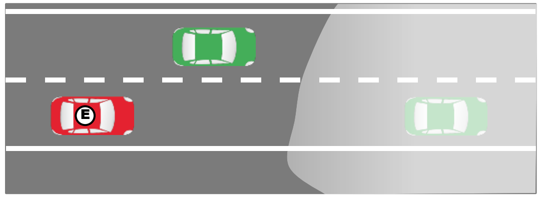


TTC: Time to collision

Incident Environment

- Start situation
  - Ego car (**E**) drives on highway lane
  - Varying traffic situations
- Evolution
  - Sudden change of environment conditions affecting traffic
    - Heavy rain/snow
    - Fog, low standing sun
    - Wet road surface, ice/white frost
- Criticalities
  - Sensor reliability reduced
  - Grip reduced/lost



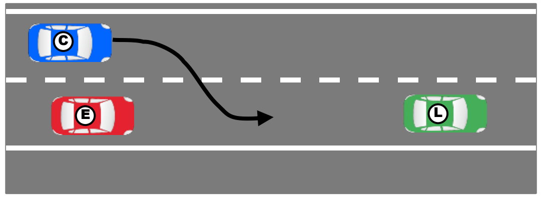


Scenario Classes
Logical Scenarios

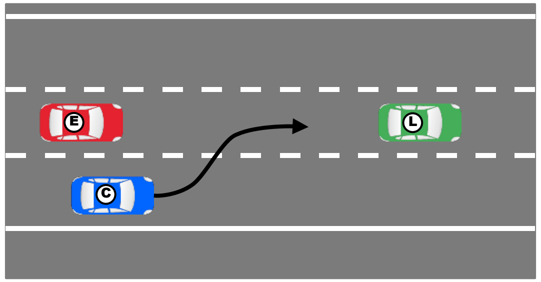
- **Functional Scenario**
  - **Usage**: High-level specification
- **Logical Scenario**
  - One line of evolution
  - Parameter ranges with occurrence probability distributions
  - Represents set of concrete scenarios
  - **Usage**: Main constituent in the <u>test specification</u>

Precise definition of sets of scenarios

- **Concrete Scenario**
  - **Usage**:
    - Define <u>test cases</u>



Cut-in



Cut-in (left, from behind) (regular traffic situation)

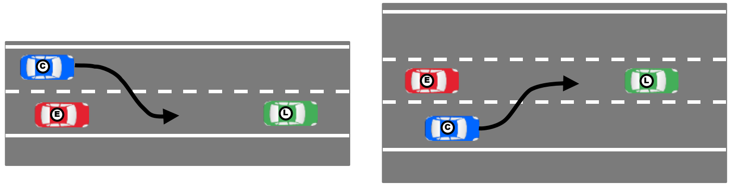
- Step 1:
  - Velocity [m/sec]: E , L: [22-36]; E-L: [-4,4]; C: [23-67]; C-E: [1,45];
  - Position [m]: L-E: [33,100]; E-C: [0,30];
  - Distributions: may be multivariate binomial (nontrivial correlations), or multivariate gamma-distributions
  - …
- Step 2: Cut-in starts (C crosses lane marking) Δt: [2,20]
  - Velocity [Δ m/sec]: L: [-7,+7]; C: [-50,+5]; C-E: [-5,40]; C-L:[-12,50]
  - Position [m]: L-E: [25,110]; C-E: [1,60]; L-E: [5,100]
  - …
- Step 3: Cut-in completed (C has crossed lane marking halfway) Δt: [0.5,4]
  - Velocity [Δ m/sec]: …
  - …

Figures given as illustration

Deriving Scenarios

Logical Scenarios are derived systematically from Functional Scenarios

- One Functional Scenario (or a combination of Functional Scenarios) gives rise to a number of Logical Scenarios



- Cut-in (left, from behind)
- Cut-in (left, front)
- Cut-in (left, fall-back)
- Cut-in (right, from behind)
- …

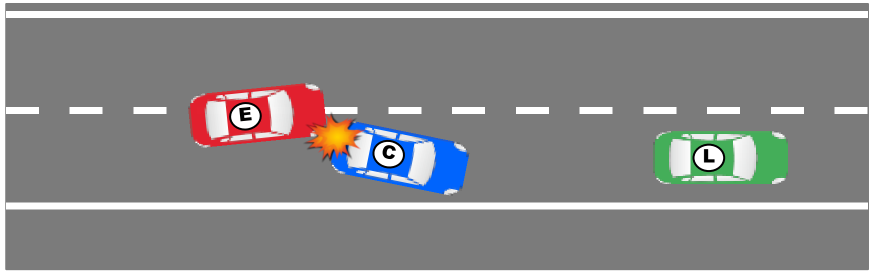
Concrete Scenarios are instantiations of Logical Scenarios

- One Logical Scenario represents a large (infinite) number of Concrete Scenarios

- Step 1:
  - Velocity [m/sec]: E , L: [22-36]; E-L: [-4,4]; C: [23-67]; C-E: [1,45];
  - Position [m]: L-E: [33,100]; E-C: [0,30];
  - Distributions: may be multivariate binomial (nontrivial correlations), or multivariate gamma-distributions

- Parameter instantiations
  - Relative frequencies according to probability distributions

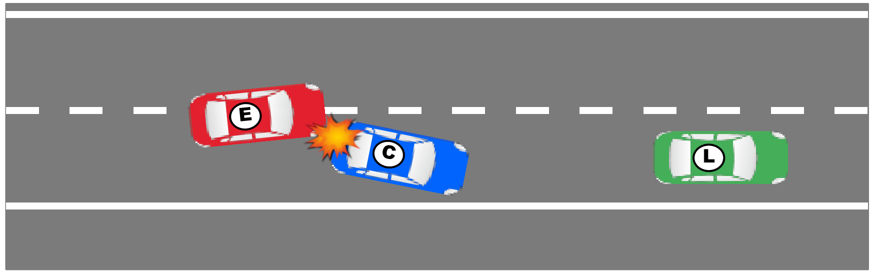
Criticality of Scenarios



- **Criticality** of a scenario
  - $\sum_{h \in H} C_h * S_h$
    - H: Set of harmful outcomes h
    - C: probability of occurrence of the outcome
    - S: severity of the outcome (injuries, fatalities)
- **Severity**
  - Classes in ISO 26262
    - S0: No injuries
    - S1: Light and moderate injuries
    - S2: Severe and life-threatening injuries (survival probable)
    - S3: Life-threatening injuries (survival uncertain), fatal injuries

- Refined severity classes required, e.g.:
  - S0, S1 remain
  - S2A: Severe injuries
  - S2B: Potentially life-threatening injuries
  - S3A: Life-threatening injuries
  - S3B: Probably fatal injuries
  - S3C: Fatal injuries
- Numeric scale for summation required (tbd.)
  - E.g. based on Abbreviated Injury Score

Criticality of Scenarios



- **Criticality** of a scenario
  - $\sum_{h \in H} C_h * S_h$
    - H: Set of harmful outcomes h
    - C: probability of occurrence of the outcome
    - S: severity of the outcome (injuries, fatalities)
- **Probability**
  - Classes in ISO 26262 (controllability)
    - C0: controllable in general
    - C1: Simply controllable (≥ 99 % of all drivers)
    - C2: normally controllable (≥ 90 % of all drivers)
    - C3: difficult to control or uncontrollable (< 90 % of all drivers)

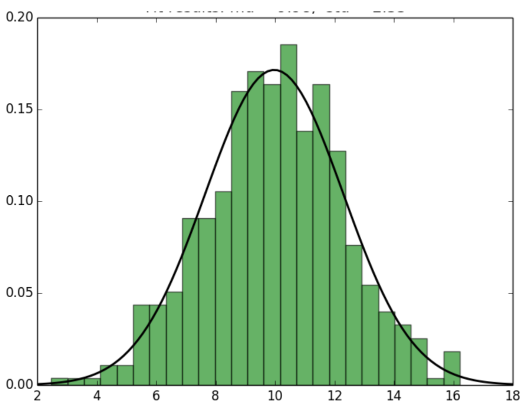
- Numeric probabilities required, or refined semi-numeric scale
  - Estimated range: 10^{-10} to 1 (= 10^{0})

Frequency of Scenarios

A logical scenario is to be weighted with two **frequency** figures (exposure): expected number of occurrence per time unit

- E_{driver} : average over human drivers
- E_{HAF} : automation to be tested

- Together with **severity** and **probability** this fixes the **risk** associated with the scenario.



Determining frequencies

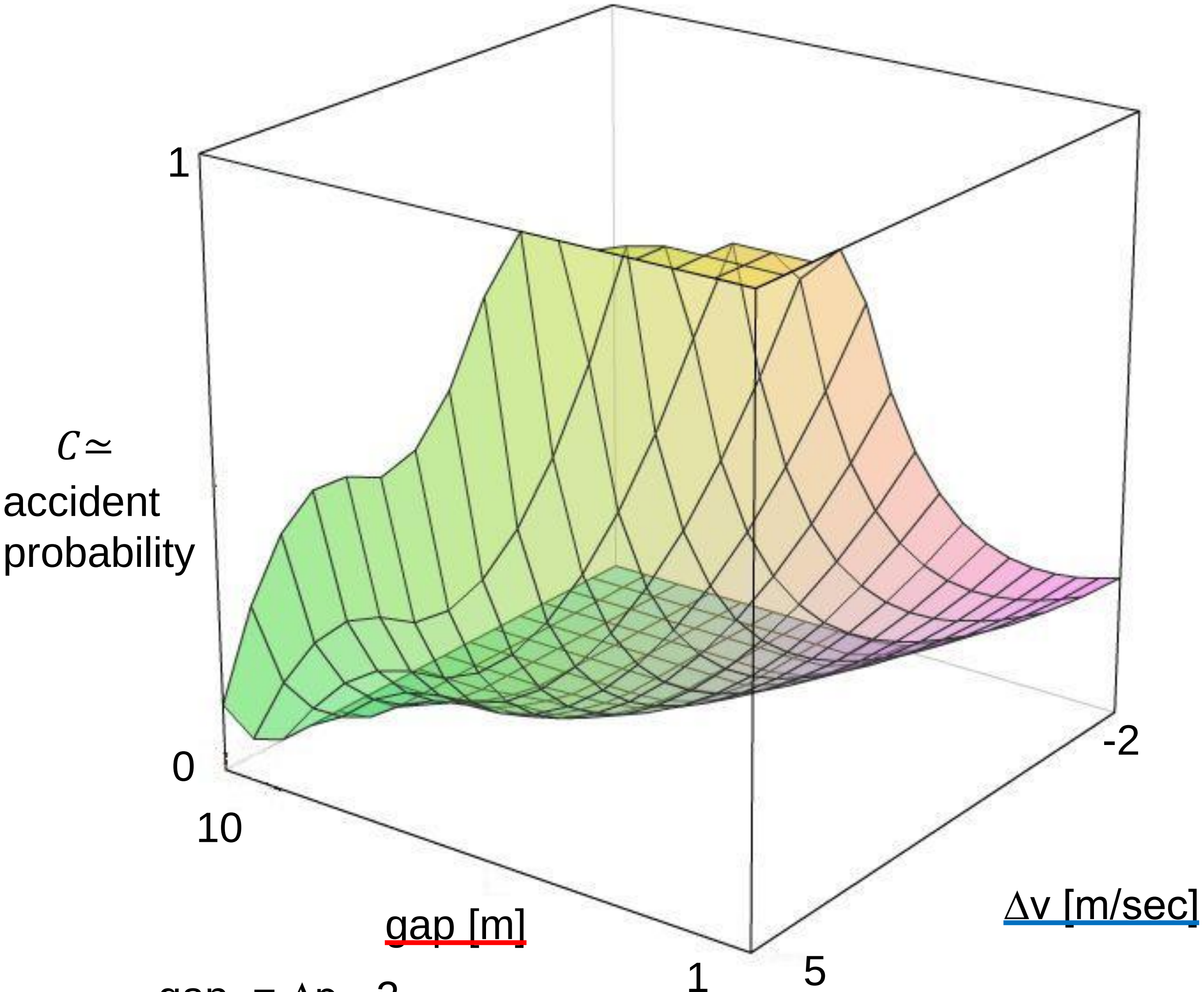
- E_{driver} : average over human drivers
    - Field data
    - Simulations with validated driver models
    - Adjustments/estimations by experts

- E_{HAF} : automation to be tested
    - Simulations with HAF
    - Adjustments/estimations by experts

Risk Computation Illustration Scenario „Cut-in“: Accident Probability

Visualization of accident probability for cut-in depending on

- Δv [m/sec]: velocity difference between Ego and Cut-in vehicle:
  - “5“ means: Cut-in vehicle is 5 m/sec slower (dangerous)
- gap [m]: gap between Cut-in and Ego vehicle
  - “1” means: Cut-in happens with minimal distance (dangerous)

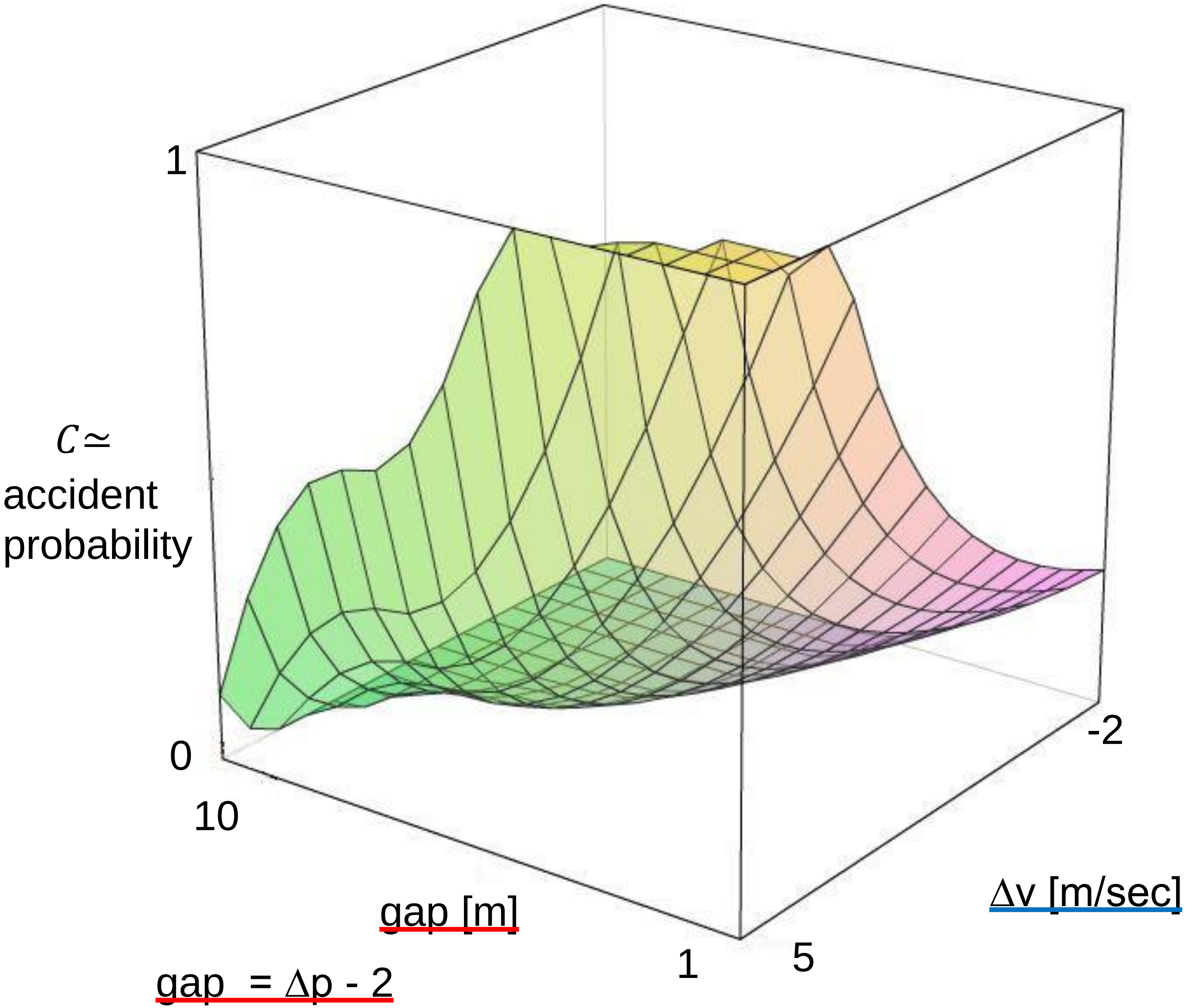


gap = Δp - 2

Risk Computation Illustration Scenario „Cut-in“: Accident Probability

Cut-in (left, from behind)

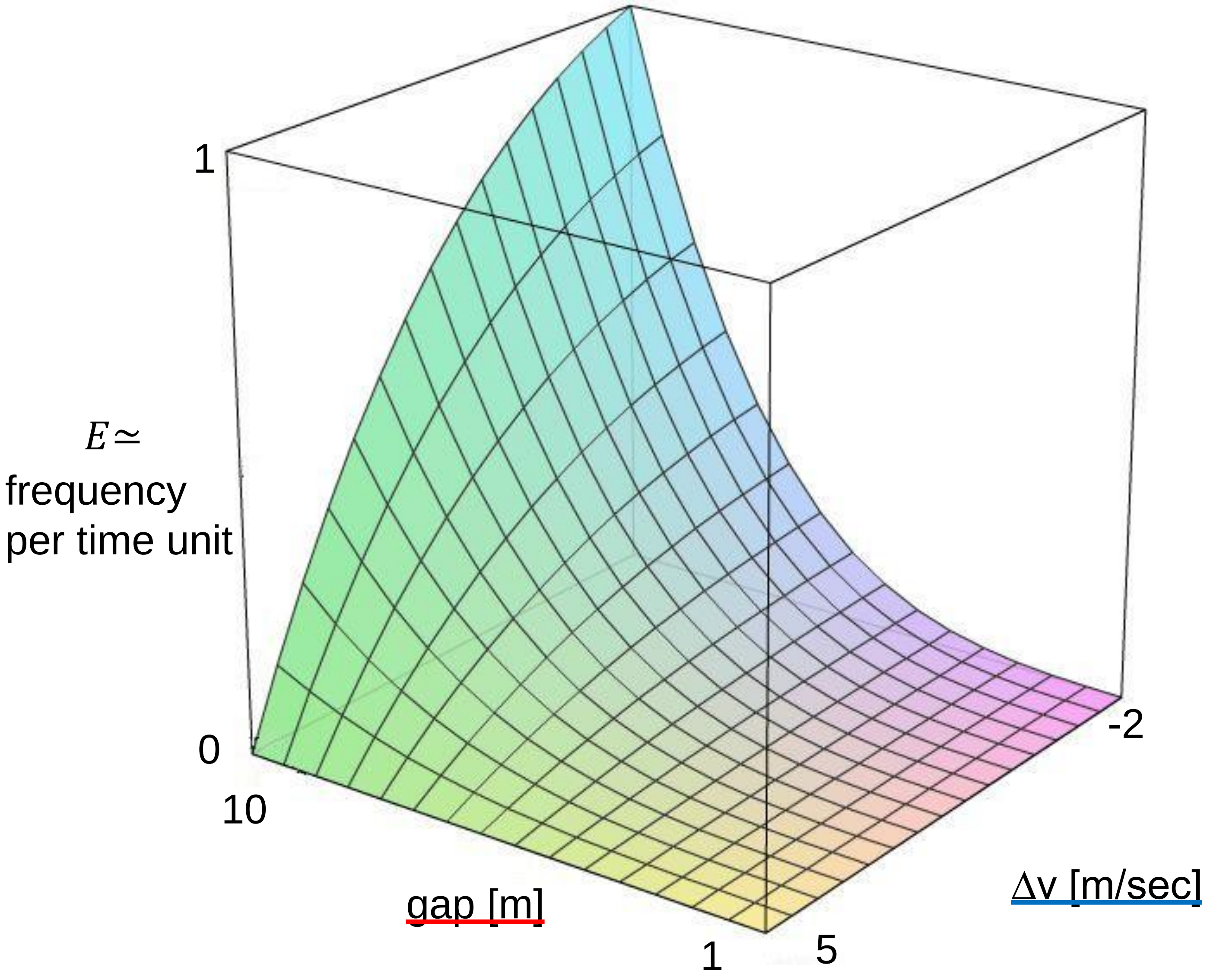
- Step 1:
  - Velocity [m/sec]: E , L: [22]; C-E: [1,45];
  - Position [m]: L-E: [33,100]; E-C: [0,30];
  - …
- Step 2: Cut-in starts (C crosses lane marking) Δt: [2,20]
  - Velocity [m/sec]: Δ L: [-7,+7]; Δ C: [-40,+4]; C-E: [-5,2]; C-L:[-9,12]
  - Position [m]: L-E: [25,110]; C-E: [3,12]; L-E: [15,100]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



Risk Computation Illustration Scenario „Cut-in“: Exposure

Visualization of frequency of cut-in depending on

- Δv [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 Δv)
- gap [m]: gap between Cut-in and Ego vehicle:
    - The frequency *increases* with gap size
    - Usually, the gap is reasonably large

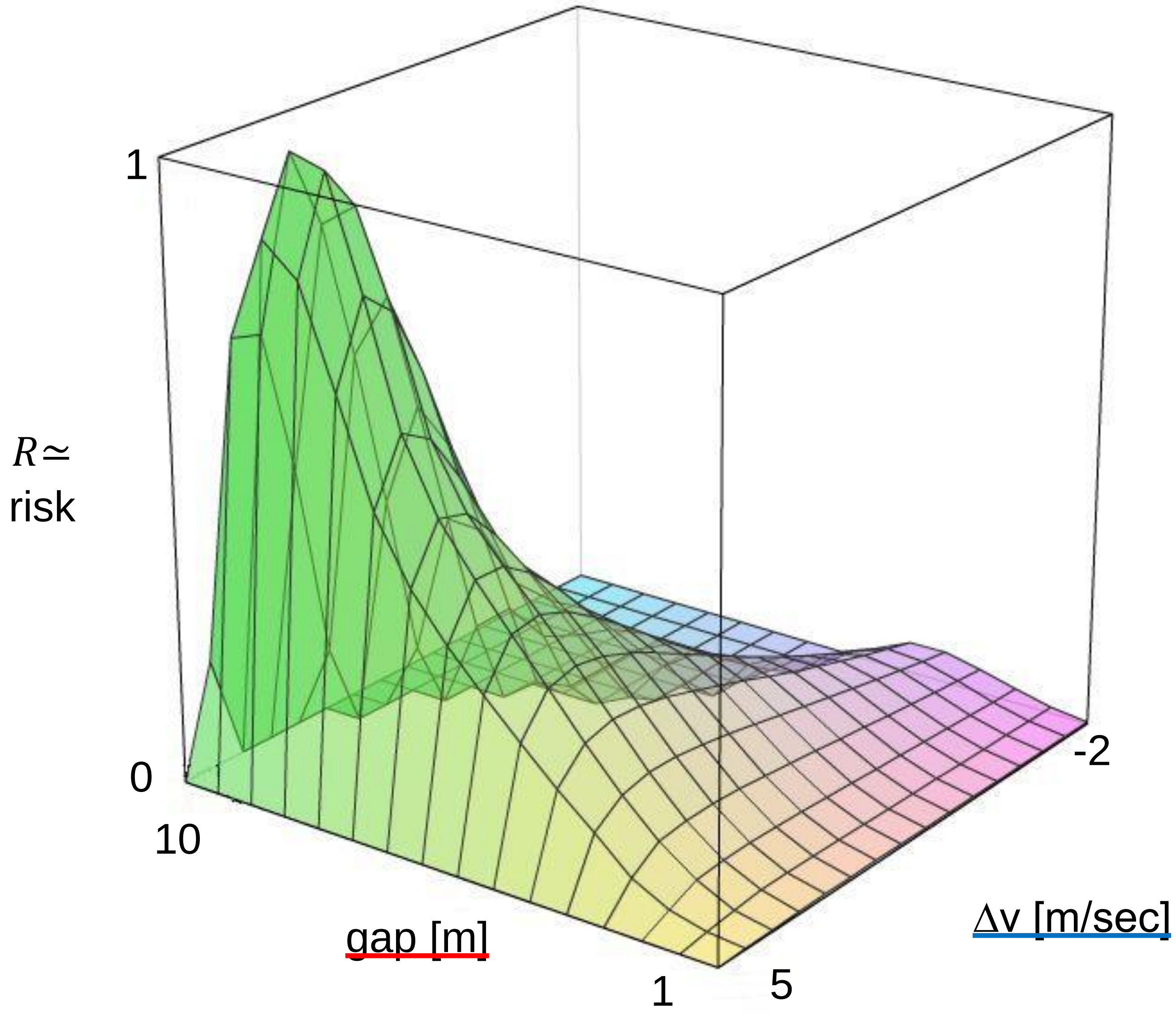


Risk Computation Illustration Scenario „Cut-in“: Risk

Visualization of risk* of cut-in

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

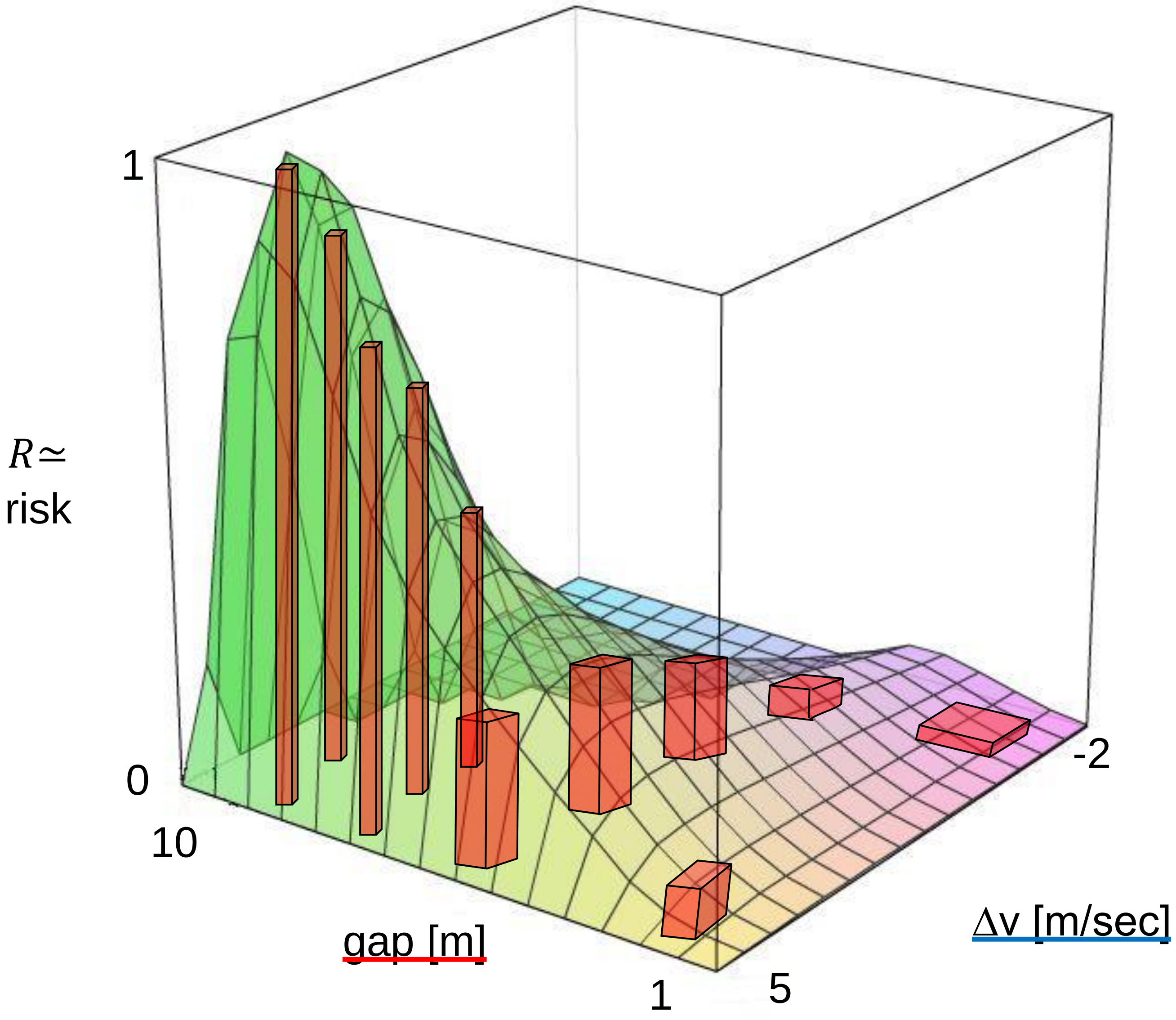
* The severity is assumed to be constant, here



Risk Computation Illustration Scenario „Cut-in“: Risk Integral

Computation by approximate discrete summation

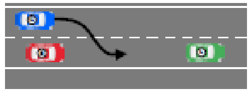
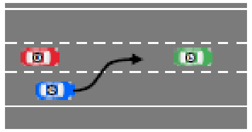
- Like Riemann integral approximation
- Each column represents the result of a test run (simulation / proving ground / field)
- Lower test density in regions with low accident probability



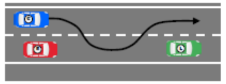
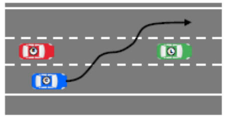
Test Specification and Test Definition

- The **test specification** consists of
  - The full set of logical scenarios
  - Annotated with frequencies (HAF)
    - Scenario overlap taken into account: Evolutions are counted only once

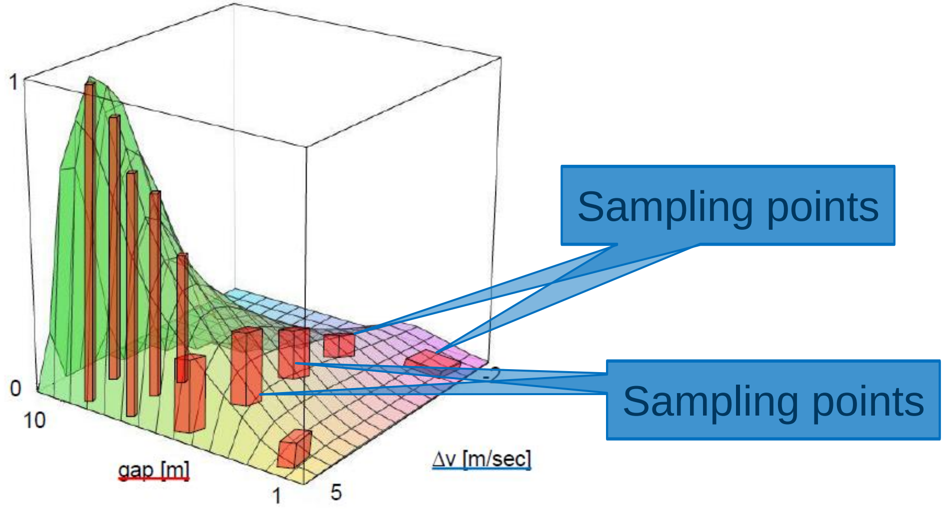
- The test cases of the **test definition** are dynamically constructed
  - Concrete scenarios sampling the risk function
  - Low risk: low density of sampling points
  - High risk: high density of sampling points

Cut-in (left, from behind)	0.04
Cut-in (left, front)	0.002
Cut-in (left, fall-back)	0.0003
Cut-in (right, from behind)	0.006
…	

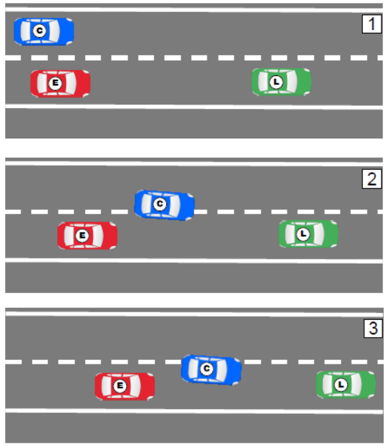



Cut-through (left, from behind)	0.002
Cut-through (left, front)	0.0005
Cut-through (left, fall-back)	0.00001
Cut-through (right, from behind)	0.0008
…	

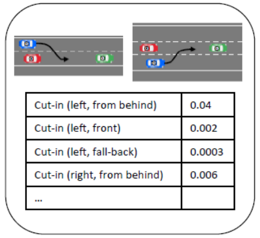


Summary

- **Test definition** based on Scenarios
  - Functional: high-level specification
  - Logical: precise specification
  - Concrete: test cases
- **Formalization** of test definition
  - Systematic derivation process
  - Supporting risk estimation by testing
- Usage for **safety case** along the lines of ISO 26262
  - More complex argumentation required for HAF homologation than foreseen in the standard



p 2: Cut-in starts (C crosses lane marking)
- Velocity [Δ m/sec]: L: [-7,+7]; C: [-50,+5]
- Position [m]: L-E: [25,110]; C-E: [1,60]; l
- …



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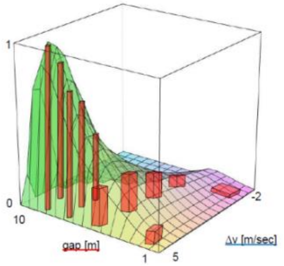
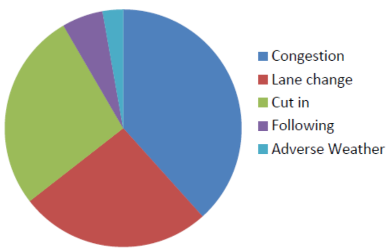
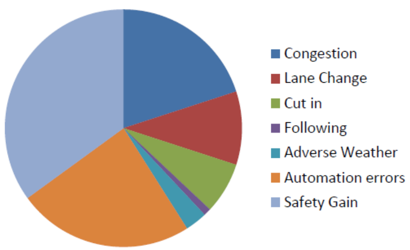
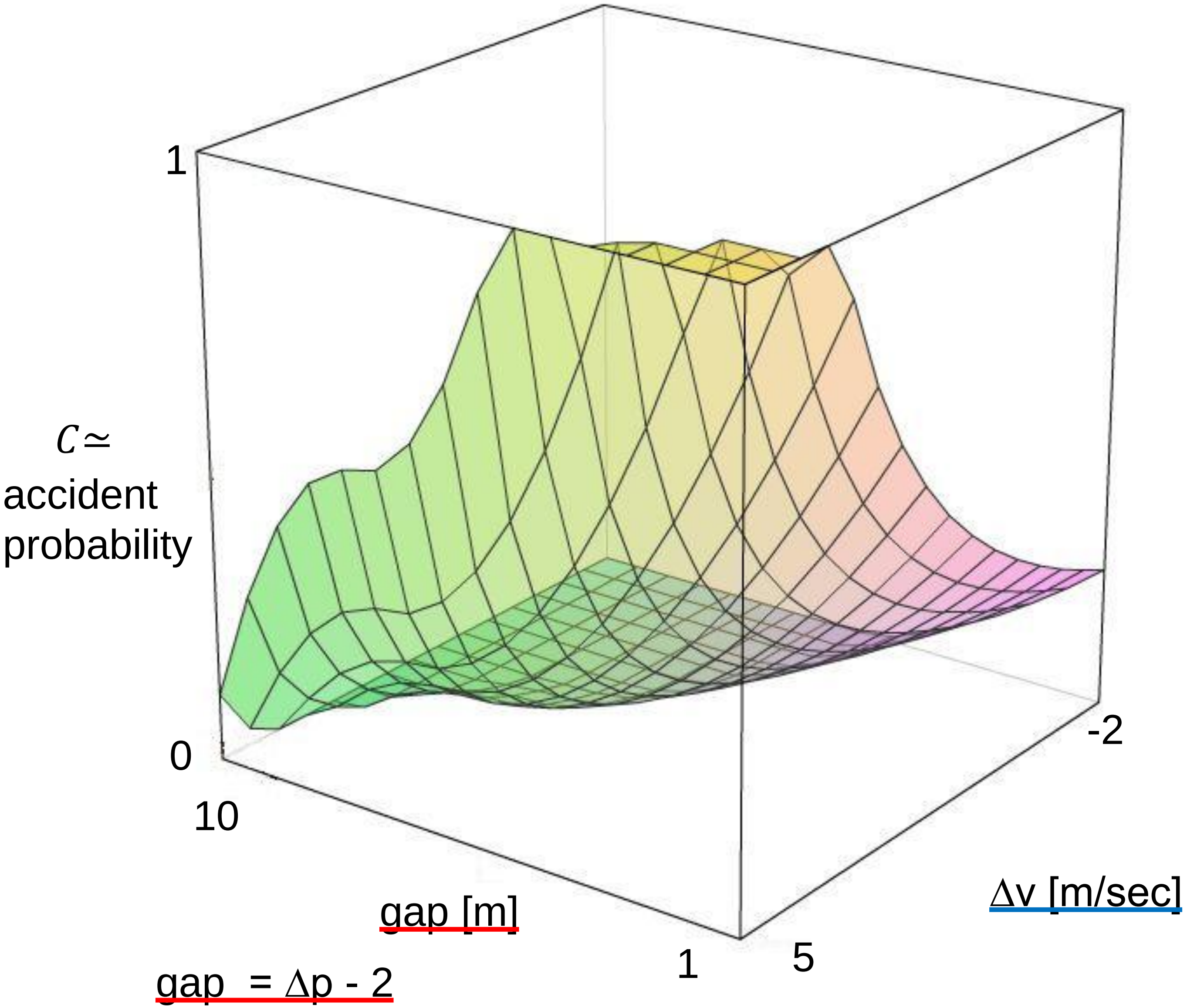






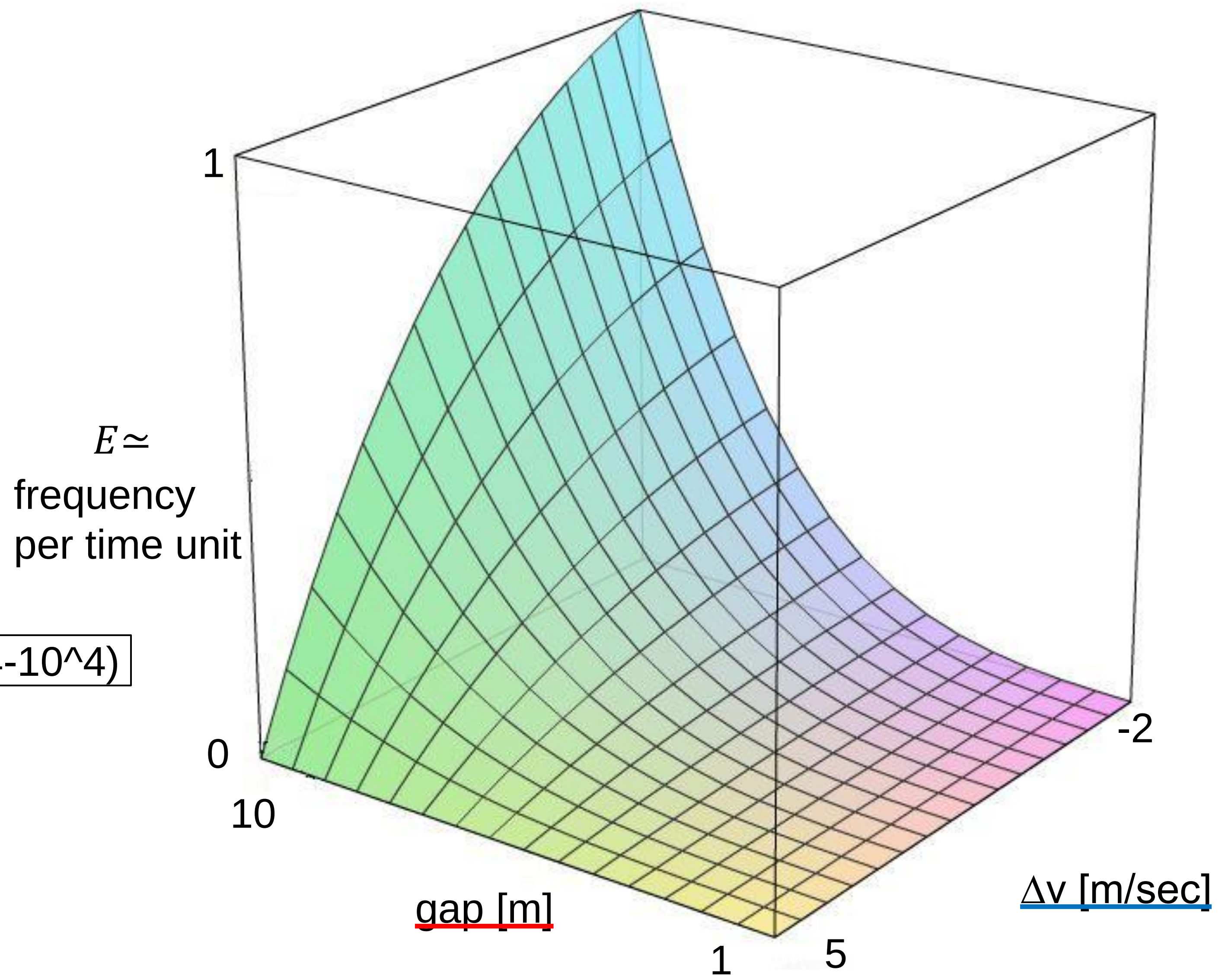
Risk Computation Illustration
Scenario „Cut-in“:
Accident Probability

(max(min(Δv*abs(Δv)/(2*gap) + 3/gap,5),0.5)-0.5)

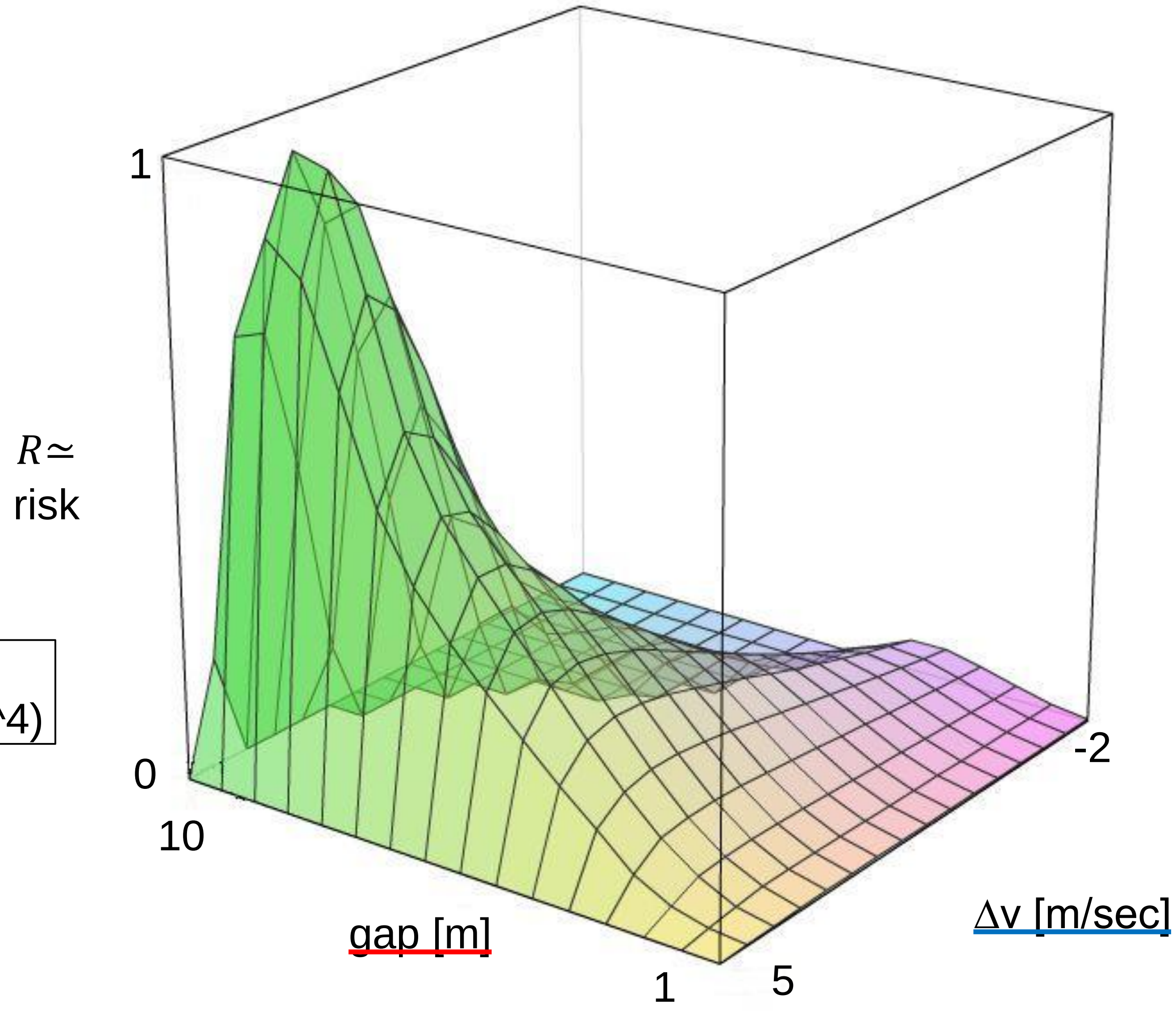


Risk Computation Illustration Scenario „Cut-in“: Exposure

$(((\Delta v-6)^4)/4096)^* ((19^4-(abs(gap-20)^4)))/(19^4-10^4)$



Risk Computation Illustration Scenario „Cut-in“: Risk



(max(min(Δv*abs(Δv)/(2*gap) + 3/gap,5),0.5)-0.5) *
(((Δv-6)^4)/4096)* ((19^4-(abs(gap-20)^4)))/(19^4-10^4)