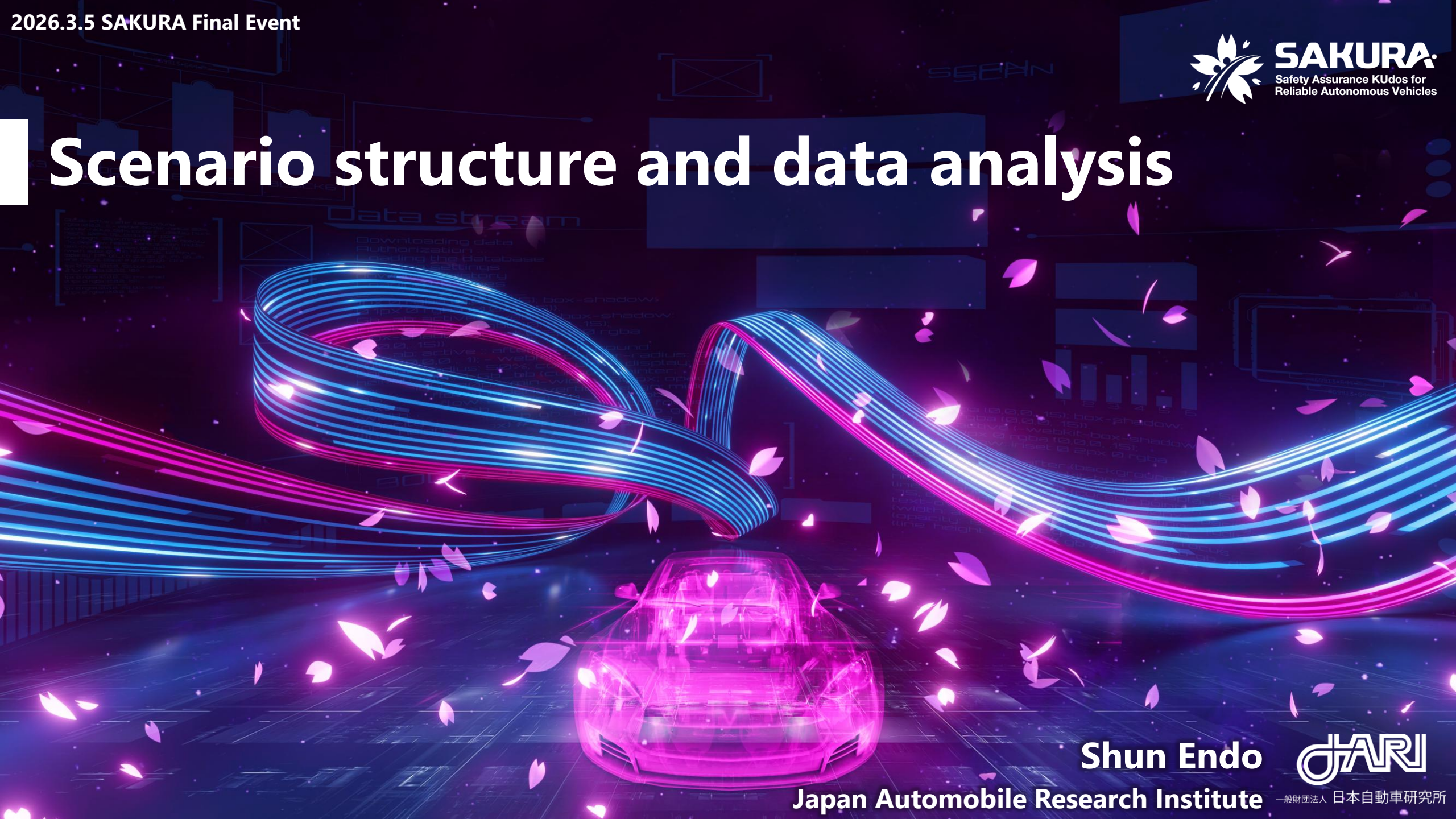
SAKURA
Safety Assurance KUdos for Reliable Autonomous Vehicles

# Scenario structure and data analysis



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# Outline

1. Background
2. Scenario structure
3. Data analysis
4. Conclusion

SAKURA
Safety Assurance KUdos for Reliable Autonomous Vehicles

# 1. Background

# International standards framework for autonomous vehicle safety

ADS : Automated Driving System
ODD: Operational Design Domain

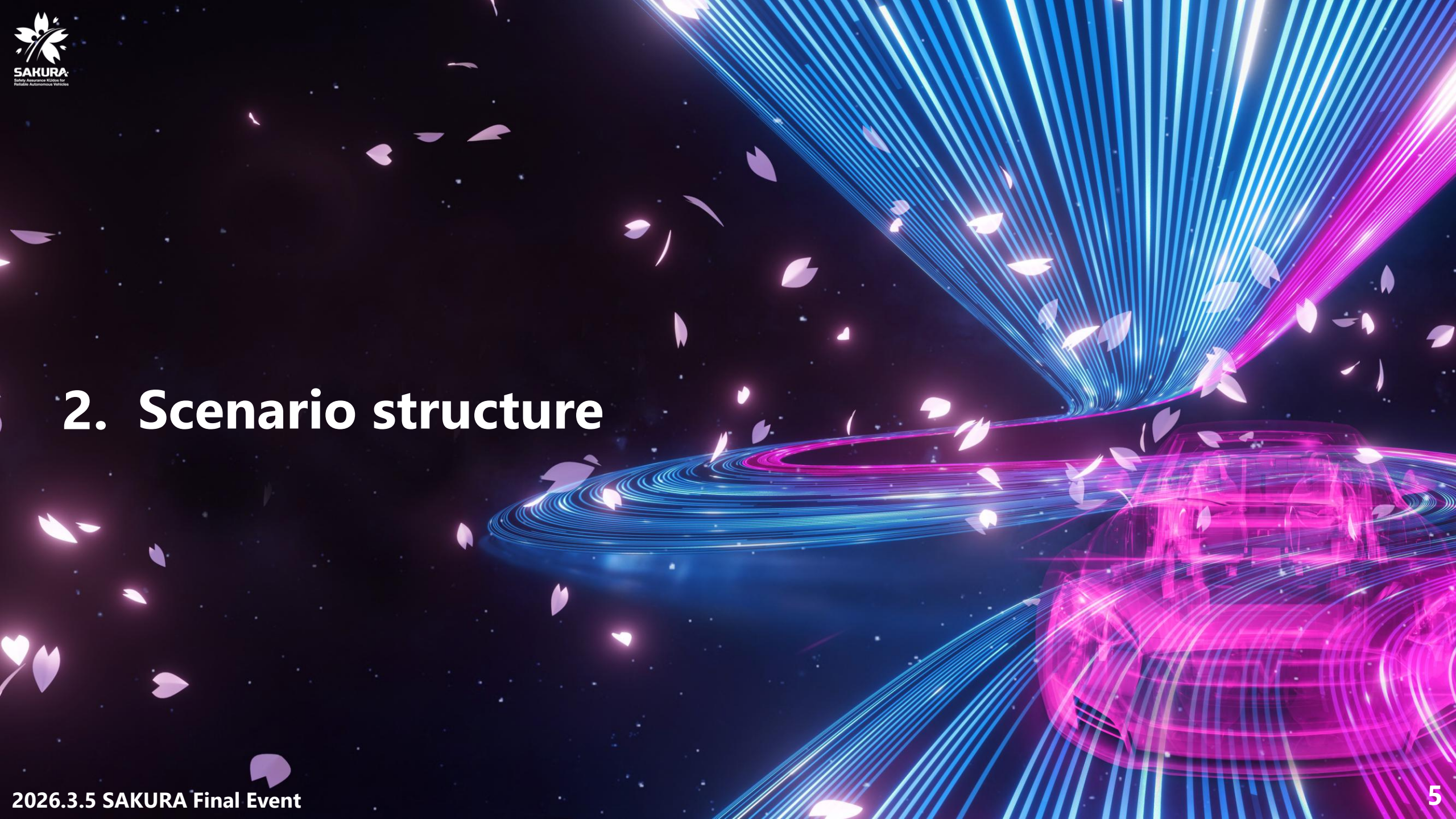
**WP29** Harmonization Forum GRVA
**ADS shall not, while engaged, cause:**

- **unreasonable risks** within their ODD.
- **reasonably foreseeable and preventable traffic accidents** within their ODD.

【Goal of SAKURA project】

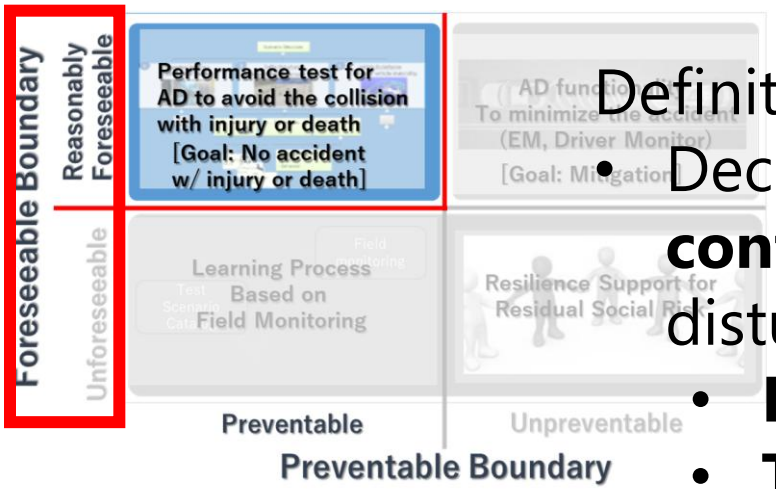
- Analysis of the reasonably foreseeable and preventable scope in traffic disturbance scenarios under ADS safety requirements.

**Focus on reasonably foreseeable and preventable domain**



# 2. Scenario structure

# Reasonably foreseeable boundary

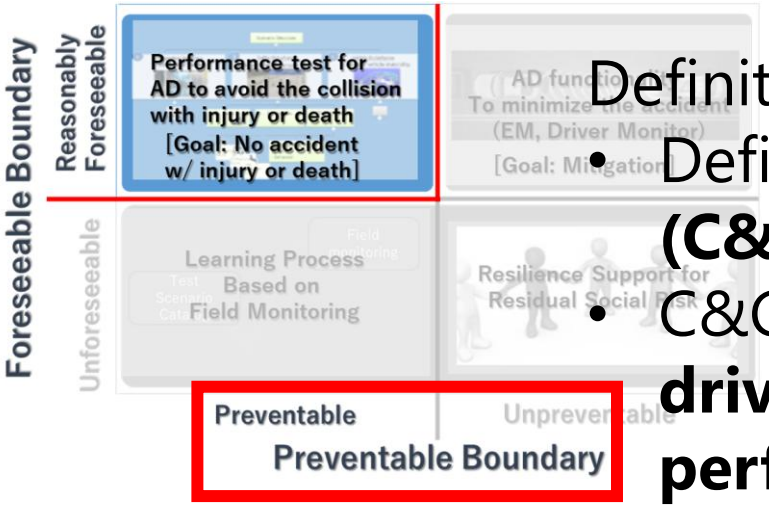



Definition of the **reasonably foreseeable boundary**

- Decompose the driving task into **perception**, **judgement**, and **control**, and define a structured taxonomy of scenarios involving disturbances:
  - **Perception disturbances**
  - **Traffic disturbances**
  - **Vehicle control disturbances**
- For each scenario, define representative parameters and determine their **reasonably foreseeable parameter ranges** based on real-world traffic data and other evidence

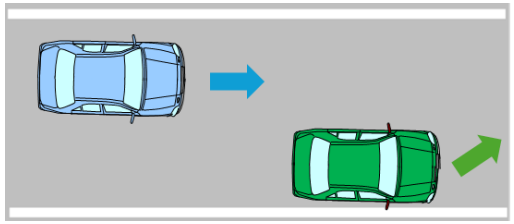
**Establishes the scope of reasonably foreseeable parameter ranges based on empirical evidence.**

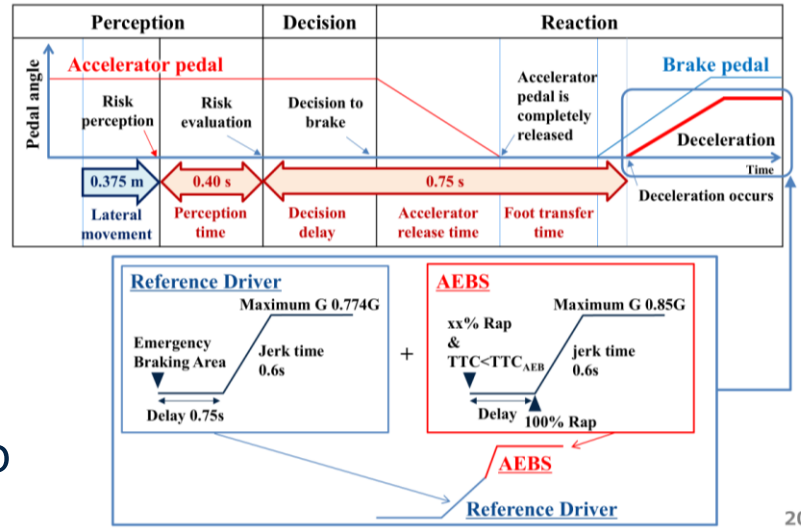
# Preventable boundary




Definition of the **preventable boundary**

- Define as the range of conditions that a **Competent and Careful (C&C) Human Driver** would be able to avoid.
- C&C driver represents a modeled driver with **a certain level of driving competence, statistically satisfying a defined performance threshold**.





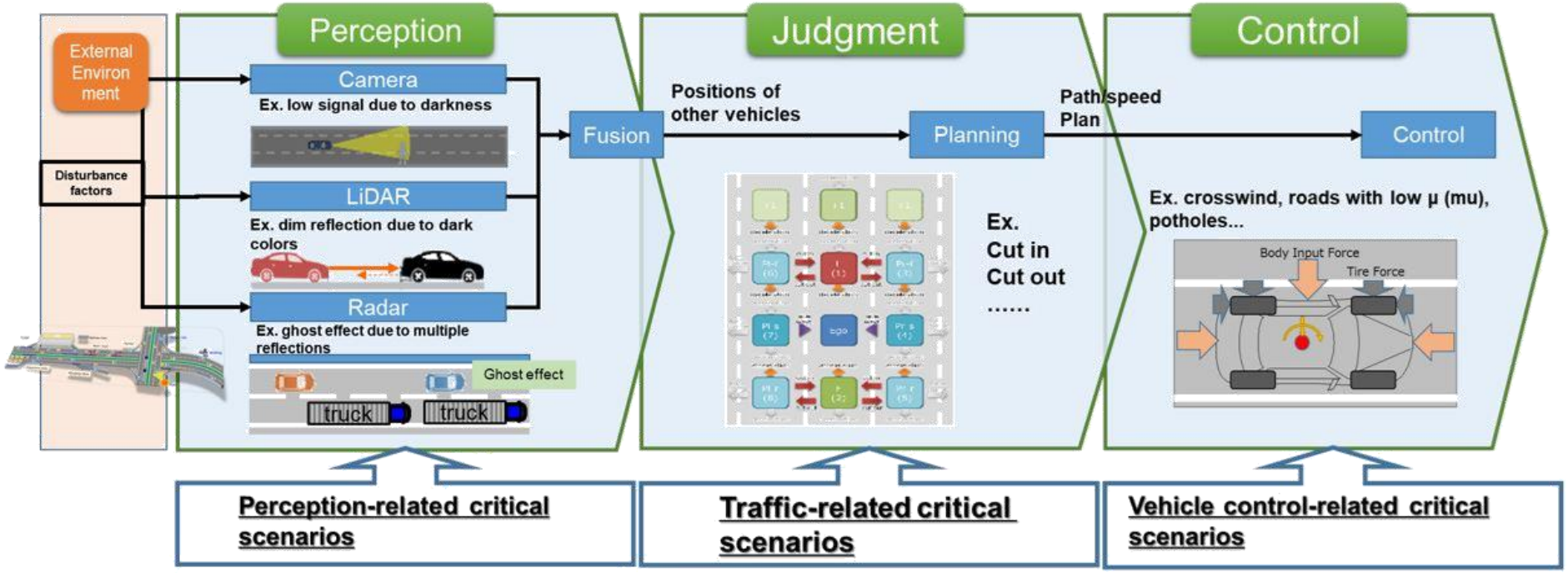

Model in cut-in scenario

20

**Establishes a human-based reference level for safety performance within the foreseeable scope.**

# Concept of safety evaluation scenarios

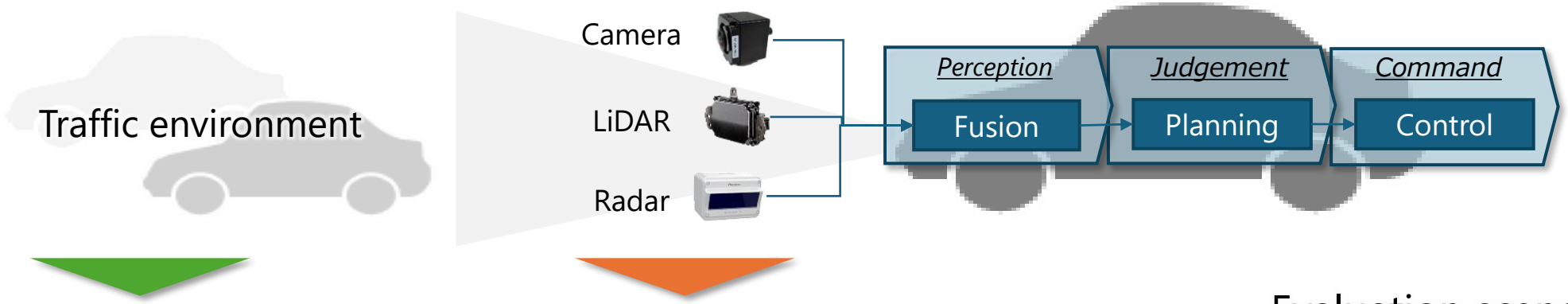
- **Decompose the dynamic driving task into three independent elements**
- Define critical conditions within each element
- Combine the three elements to construct evaluation scenarios
- This framework has been incorporated into the international standard ISO 34502



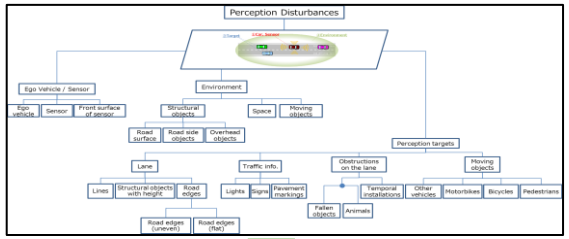

**Safety evaluation begins with the structured decomposition of perception, judgment, and control.**

# Perception disturbance scenarios

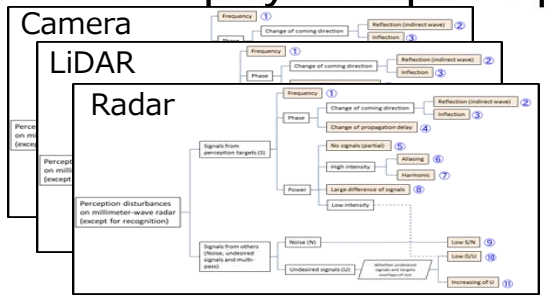
Perception disturbance scenarios consist of environmental factors and sensor physical principles.



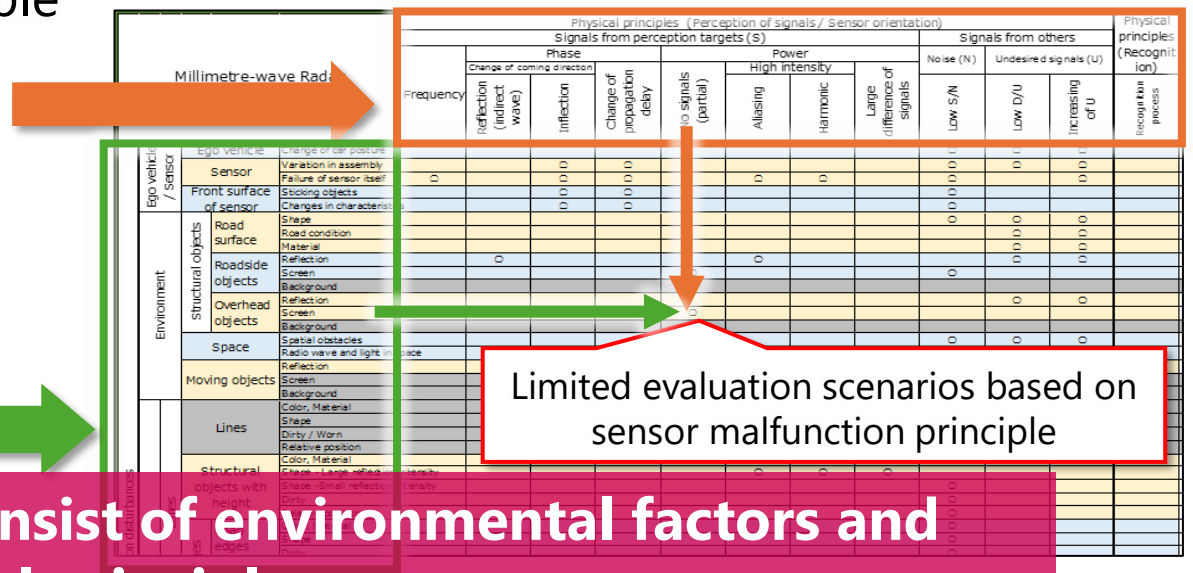

## Environmental factor




## Sensor physical principle




## Evaluation scenario



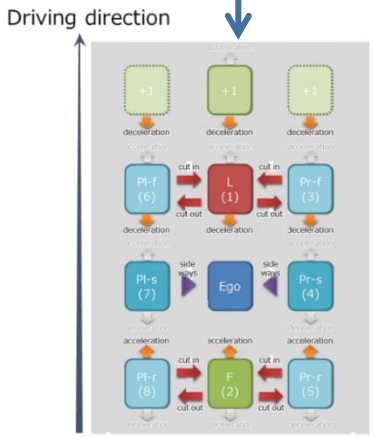

**Perception disturbance scenarios consist of environmental factors and sensor physical principles.**

# Traffic disturbance scenarios

Traffic disturbance scenarios organize and combine physical factors related to safety.

- Extract exhaustive and finite scenarios

| | | Ego-vehicle behavior | |
|---|---|---|---|
| | | Lane keep | Lane change |
| Road geometry | Main road | Free driving Following | Lane change Overtaking |
| | Merging zone | Being merged | Merging |
| | Departure zone | Being merged | Departure |




| Other road users position | vehicle position | Cut in | Cut out | Acceleration | Deceleration (Stop) |
|---|---|---|---|---|---|
| | | Othe road users behavior | | | |
| | 1.Lead(L) | | ✓※ | | ✓ |
| | 2.Following(F) | | ✓ | ✓ | |
| | 3.Parallel(Pr-f) | ✓ | | | ✓ |
| | 4. Parallel(Pr-s) | ✓ | | | |
| | 5. Parallel(Pr-r) | ✓ | | ✓ | |
| | 6. Parallel(Pl-f) | ✓ | | | ✓ |
| | 7. Parallel(Pl-s) | ✓ | | | |
| | 8. Parallel(Pl-r) | ✓ | | ✓ | |

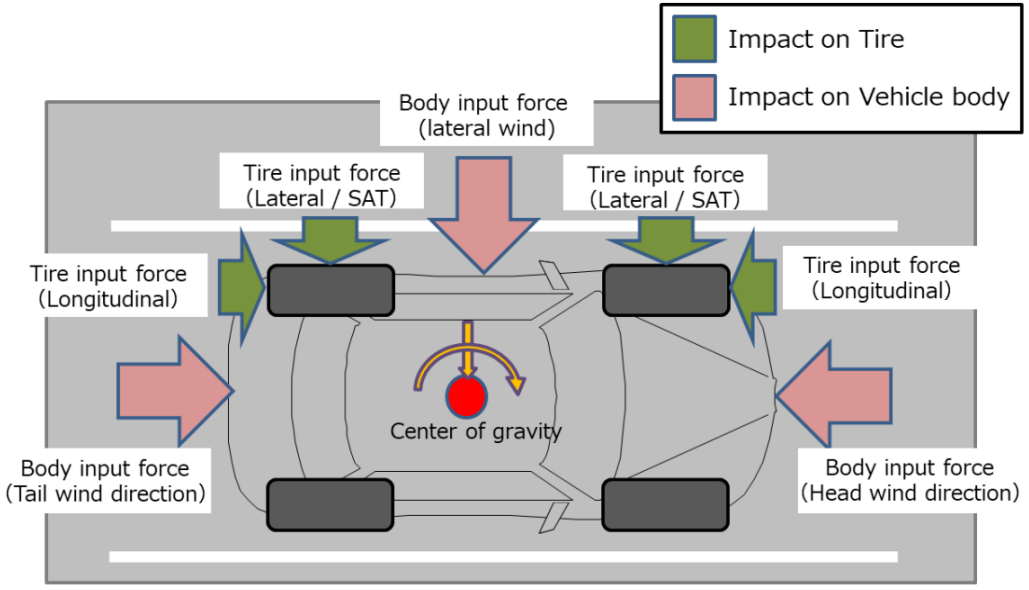
✓: have impacts, blank: no impact

Vehicle specific traffic-related critical scenario structure schematic

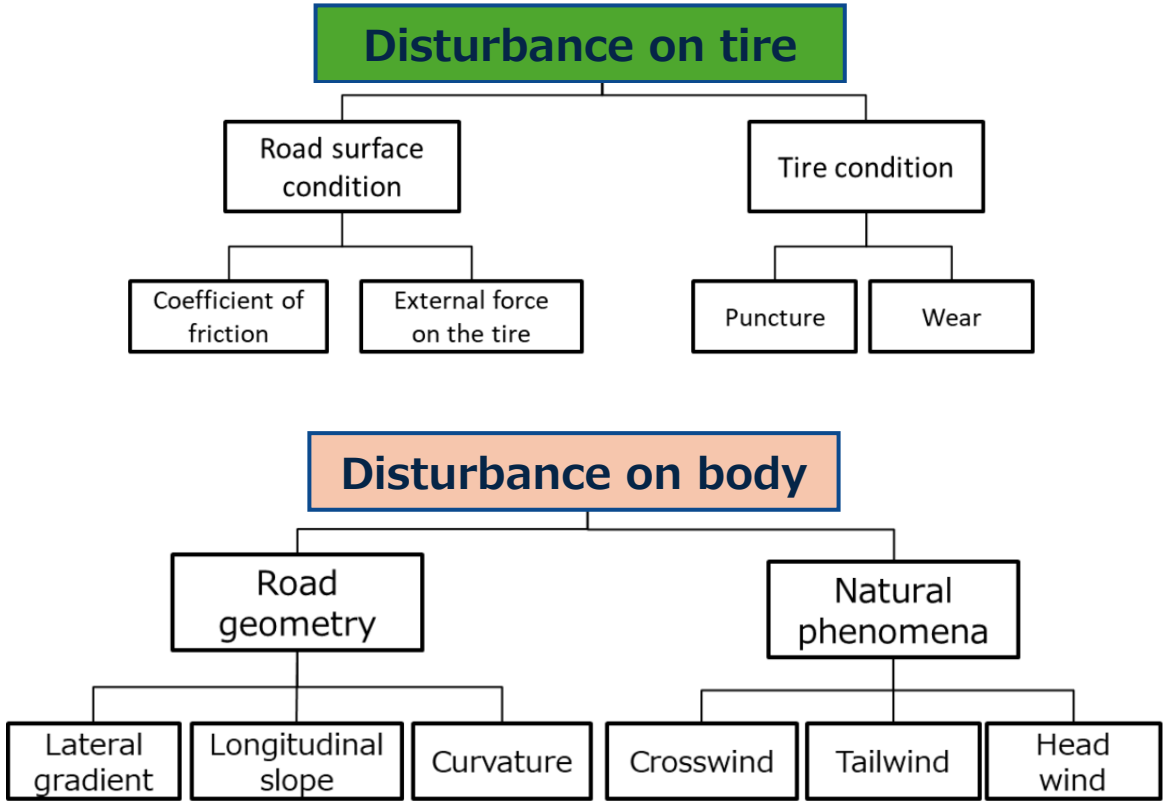
**Traffic disturbance scenarios consist of road geometry, vehicle positions, and vehicle behaviors.**

# Vehicle dynamics disturbance scenarios

Vehicle dynamics disturbance scenarios are divided into two main categories: tire-related and body-related disturbances.




Physical principle of vehicle dynamics



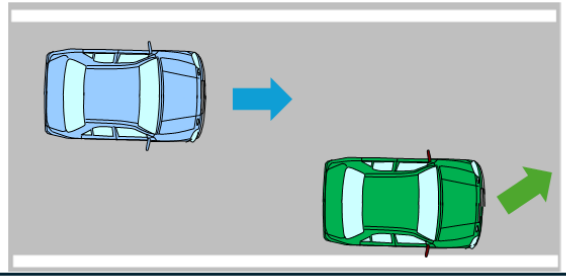

**The vehicle dynamics disturbance scenarios consist of tire factor and vehicle body factor.**

# Three layers of scenario abstraction

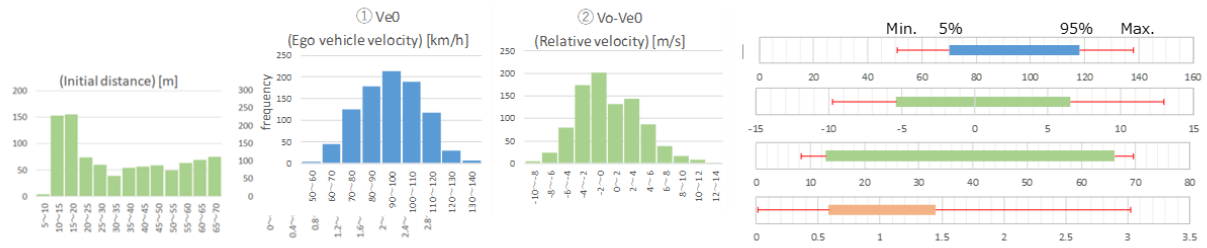
Each disturbance category follows the same three-layer abstraction: Functional Scenario (**FS**) → Logical Scenario (**LS**) →Concrete Scenario (**CS**).

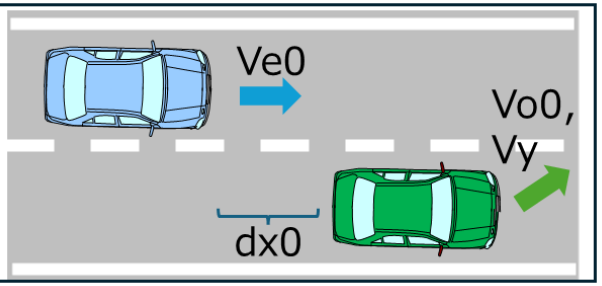
**FS**

Road geometry ✖ Ego-vehicle behavior ✖ Surrounding vehicles location ✖ Surrounding vehicles motion

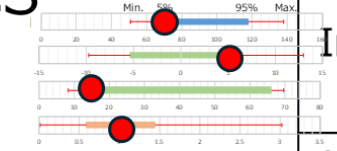


**LS**

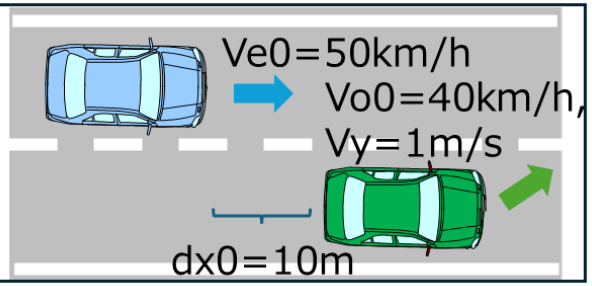



**CS**




| | | |
|---|---|---|
| Initial condition | Initial velocity | Ve0 = X1 km/h |
| | | Vo0 = X2 km/h |
| | Initial distance | dx0 = Y1 m |
| Vehicle motion | Lateral motion | Vy = Z m/s |

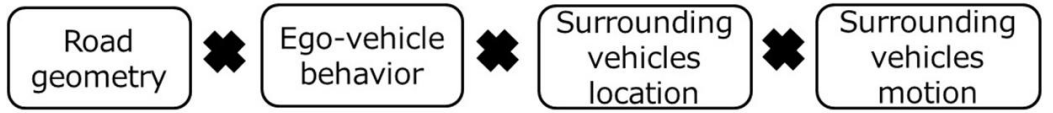


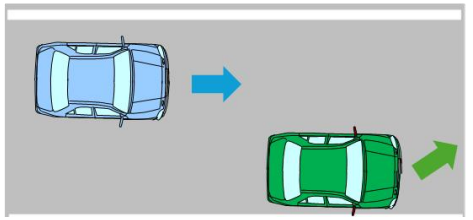

Example of scenario structure in traffic disturbance scenarios

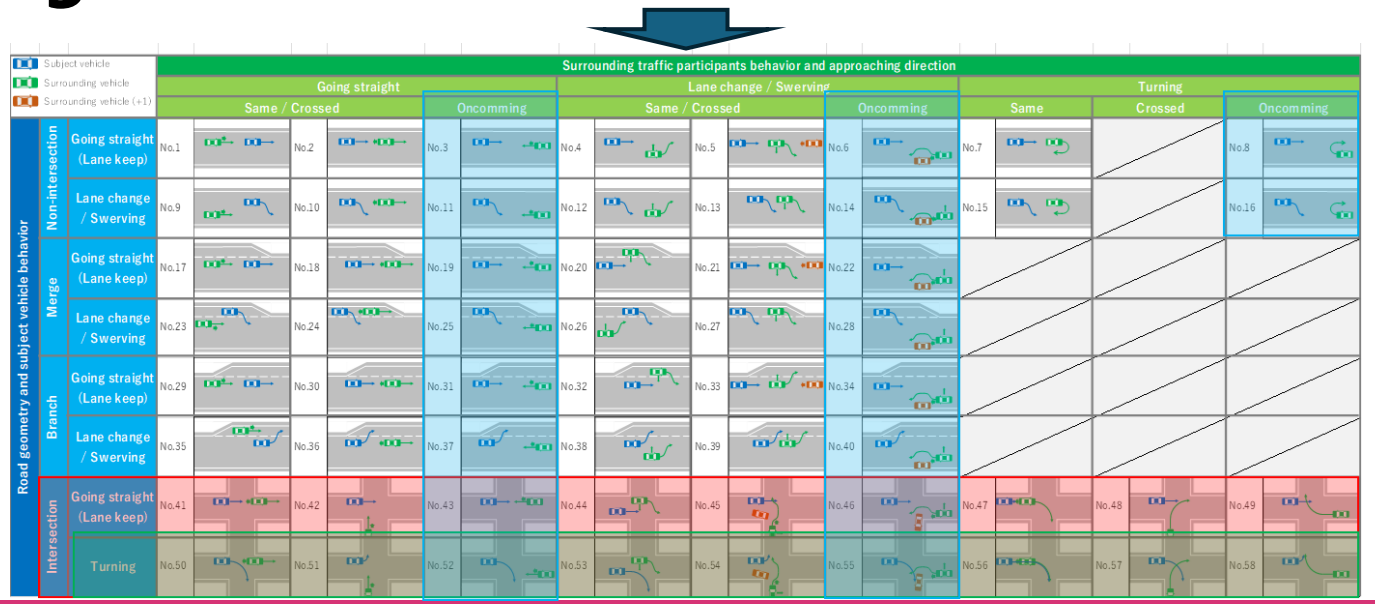
# Functional scenario(FS): Qualitative structure



- Defines the highest-level qualitative scenario structure
- Decomposes scenarios into fundamental elements:
  - **Road geometry**
  - **Ego vehicle behavior**
  - **Surrounding vehicle location**
  - **Surrounding vehicle motion**






58 FS for general vehicles

General road behaviors;
turning maneuver
oncoming vehicle
intersection

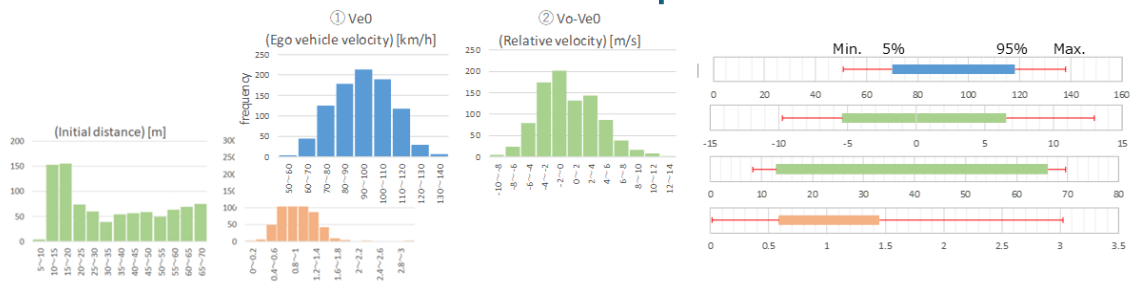
**FS provides a comprehensive qualitative coverage of real-world driving situations.**

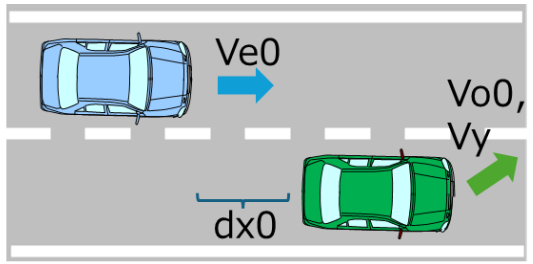
# Logical scenario (LS): Quantified parameter space



- Derived from structured FS
- **Assigns quantitative parameter ranges to each scenario**
- Defined using a data-driven approach

Parameter: velocity, distance,…



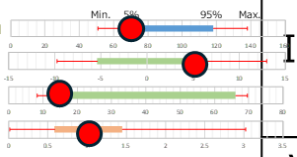




**LS transforms qualitative structures into data-driven, quantitative parameter spaces.**

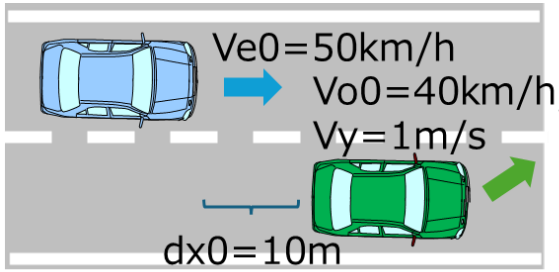
# Concrete scenario (CS): Executable evaluation conditions

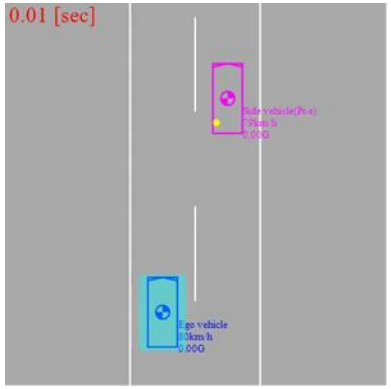
FS
LS
CS

- Defined within the quantified parameter ranges of LS
- **Represents specific evaluation conditions used for testing and validation**
- Can be established using driver models or system performance models

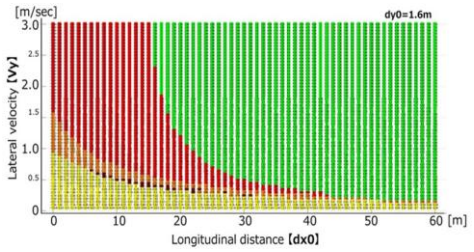


| | | |
|---|---|---|
| Initial condition | Initial velocity | Ve0 = X1 km/h |
| | | Vo0 = X2 km/h |
| | Initial distance | dx0 = Y1 m |
| Vehicle motion | Lateral motion | Vy = Z m/s |




**Collision occurrence**

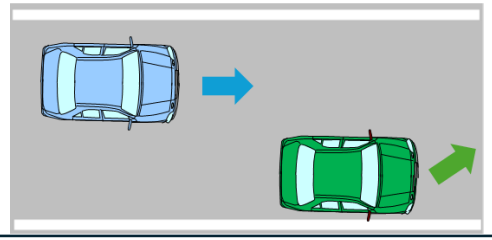


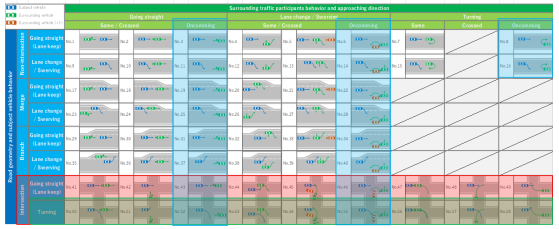

**CS converts quantified scenario spaces into executable safety evaluation cases.**

# Integrated three-layer scenario framework

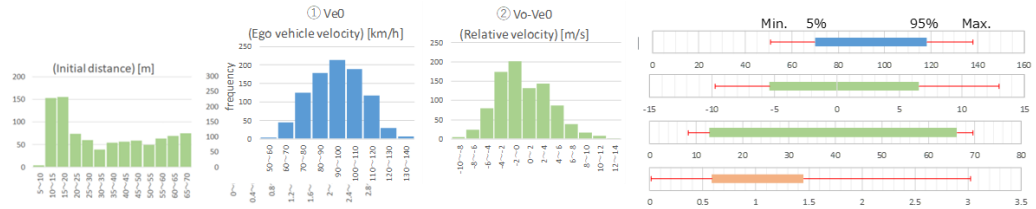
**FS**

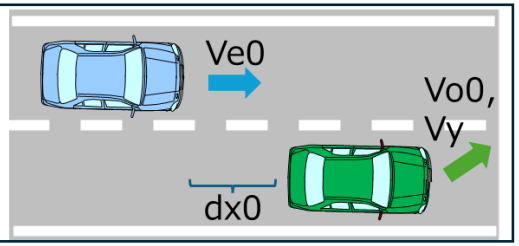
Road geometry ✖ Ego-vehicle behavior ✖ Surrounding vehicles location ✖ Surrounding vehicles motion

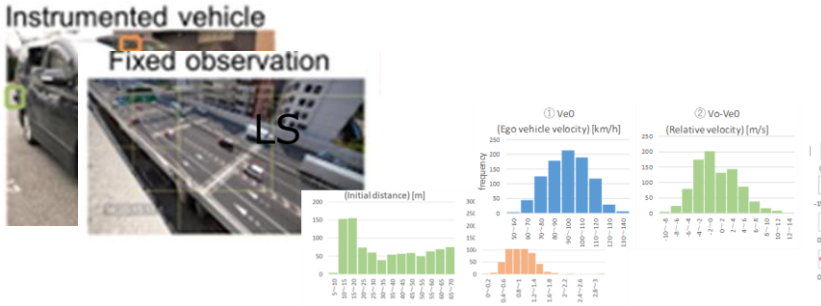




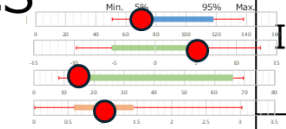
**LS**




**CS**

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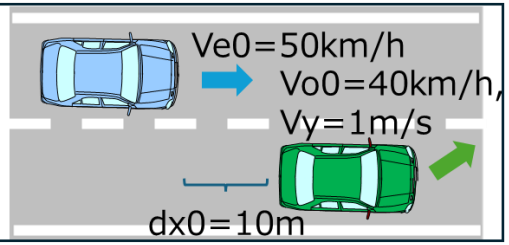
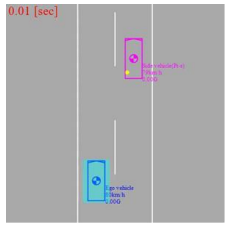
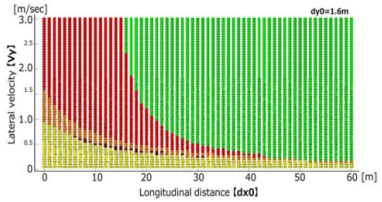


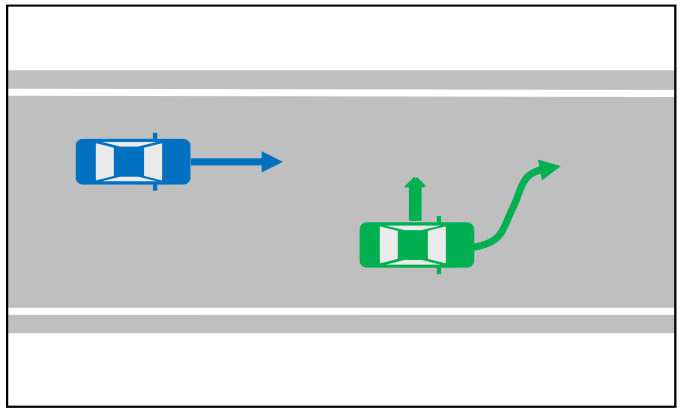

**From qualitative structure to data-driven parameters to executable safety evaluation.**

# 3. Data analysis

# Case study: cut-in logical scenario

- Numerous Logical Scenarios can be derived from functional scenarios
- Each scenario involves a wide parameter space
- As a representative example, we focus on **cut-in scenarios** on highways

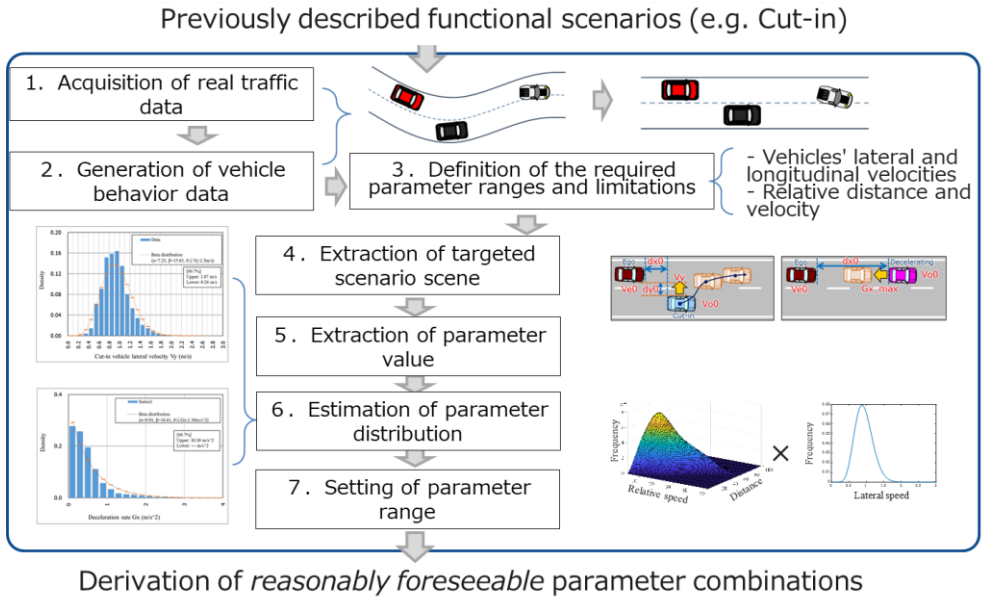
**Objective**:
Demonstrate how reasonably foreseeable parameter ranges can be defined for a specific logical scenario.



**Cut-in is presented as a representative example of Logical Scenario analysis.**

# Methodology for defining reasonably foreseeable cut-in ranges

- **Extract cut-in events from real-world traffic data**
- **Define Logical Scenarios using key parameters**
- Basic range observation
- Additional analyses to identify reasonably foreseeable bounds:
  - Distribution modeling
  - Correlation analysis
  - Occurrence frequency estimation

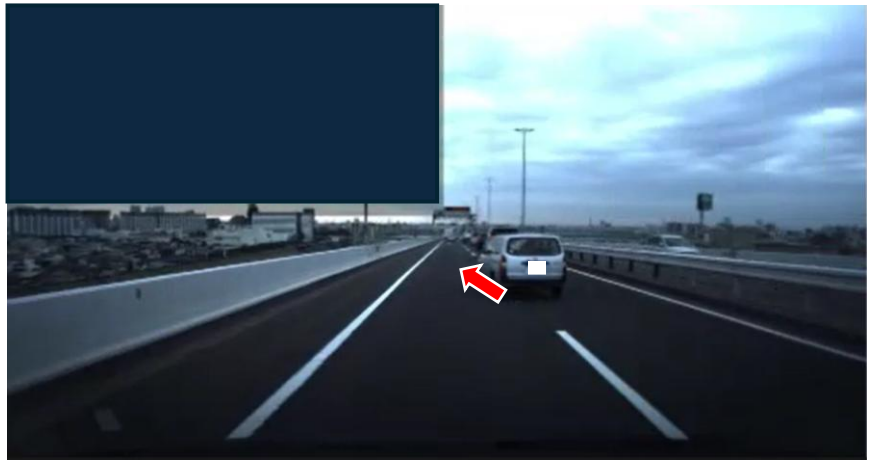



H. Nakamura et al.,(2022).

**Reasonably foreseeable ranges are derived through statistical modeling.**

# Real-world highway traffic data

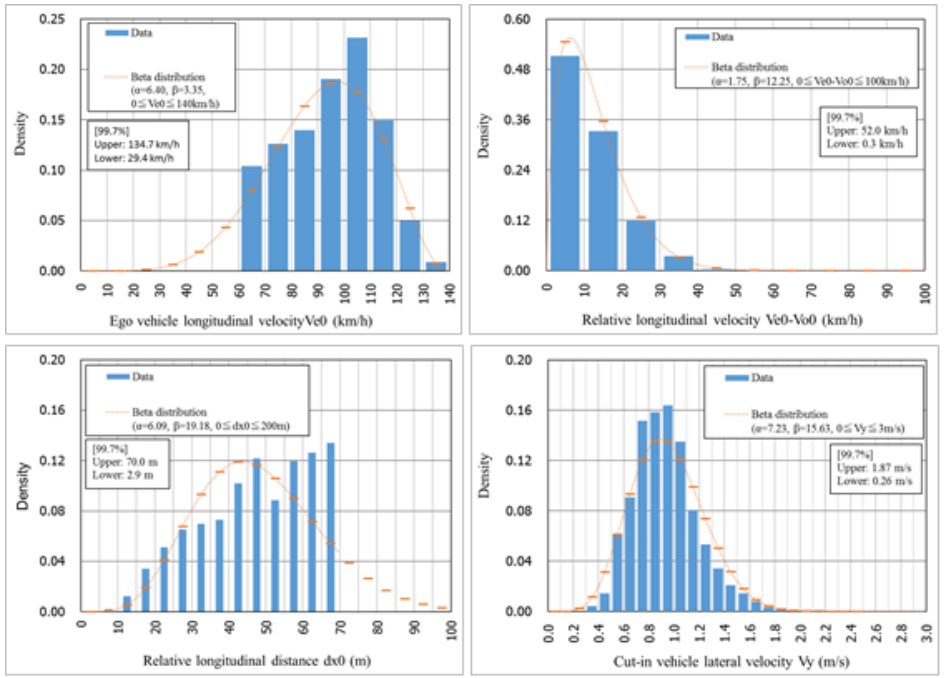
- Data collected on **Japanese limited-access highways** (2017–2020)
- Sources:
  - Instrumented vehicles (professional/regular drivers)
  - Fixed roadway cameras
- Focus on speed range ≥ 60 km/h
- Extracted:
  - **903 cut-in scenarios**
- Straight road sections only
- Weather and road curvature effects excluded



**Logical Scenarios are grounded in large-scale real traffic observations.**

# Cut-in logical scenario: Observed parameter characteristics

- **Observed parameter ranges** (≥ 60 km/h):
  - $Ve_0$: 60–138 km/h
  - Relative velocity: 0–50 km/h
  - $dx_0$: 8–70 m
  - Vy: 0.2–2 m/s




- **Distribution insights**:
  - Cut-ins most frequent around 100–110 km/h
  - Drivers prefer small relative velocity (<10 km/h)
  - Larger longitudinal distance associated with higher relative speed
  - Majority of maneuvers show low urgency (TTC typically > 7.5 s)

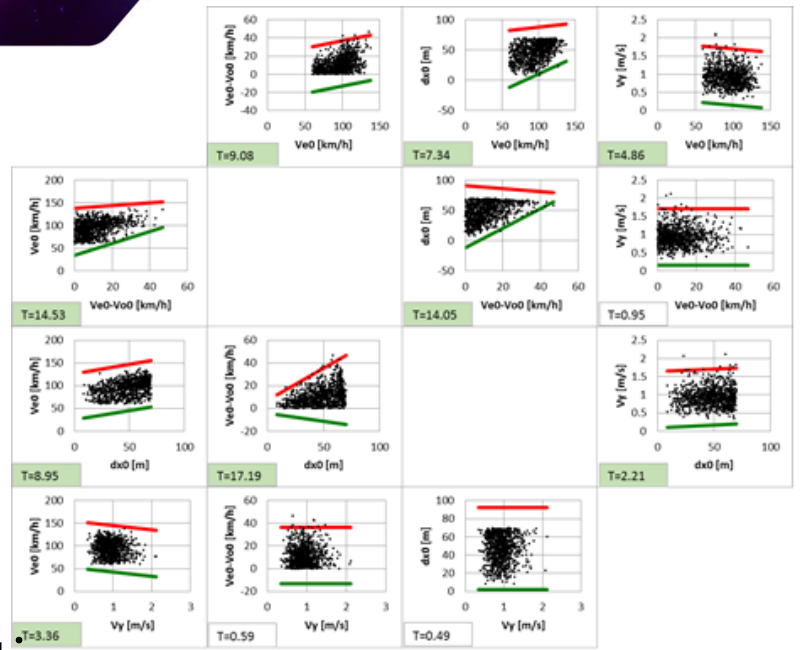
**Observed cut-in maneuvers occupy a bounded and non-critical parameter region.**

# Cut-in logical scenario: Structural and probabilistic modeling

## Parameter correlations

- Strong correlations among $Ve_0$, Vrel, and $dx_0$
- Higher speed → larger distance and relative velocity
- Vy largely behavior-dependent and weakly correlated

→ Effective parameter space is structured, not arbitrary

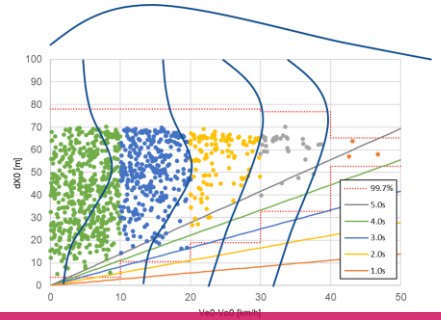


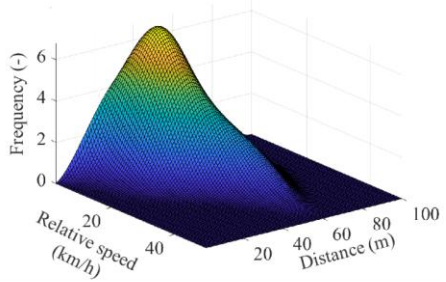

## Occurrence modeling

Joint occurrence frequency derived from correlated distributions

$$Pcut-in = p1(Vrel, dx0) \times p2(Vy)$$

→ Enables probabilistic characterization of Logical Scenarios

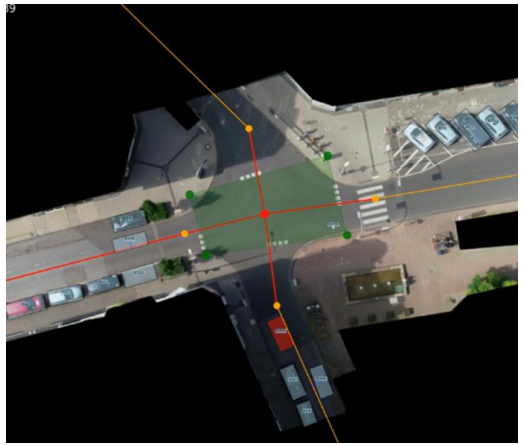


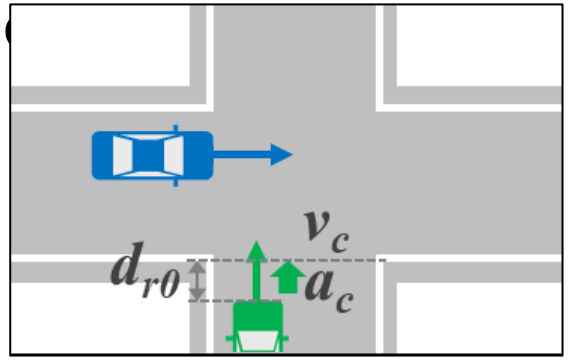


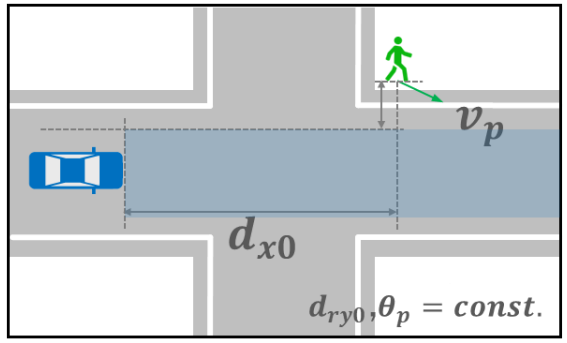

**Cut-in Logical Scenarios form a structured and statistically quantifiable parameter space.**

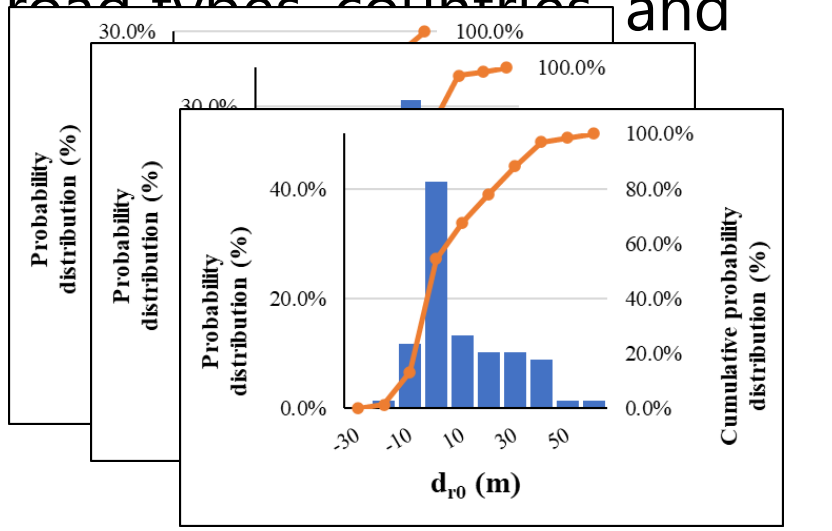
# Extension to urban scenarios using international data

The proposed methodology was also applied to international urban traffic datasets.
The Logical Scenario framework is transferable across road types, countries, and different types of road us

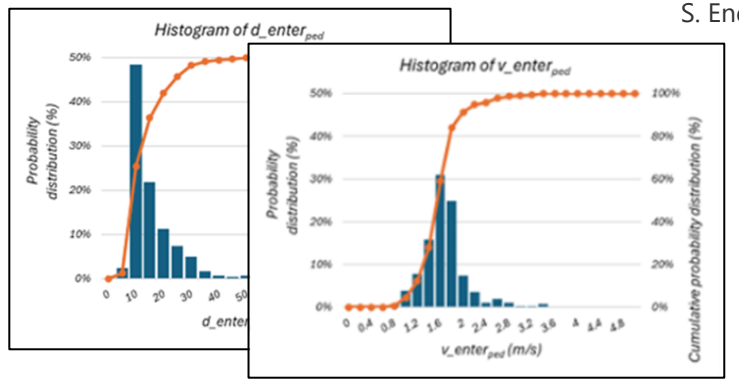





S. Endo et al. , (2025).




SAKURA project (2024).

**Logical Scenarios define a quantifiable and transferable parameter space across different environments and road users.**

# 4. Conclusion

# Conclusion and future perspective

## Summary

- A structured three-layer scenario framework (FS–LS–CS) enables systematic and data-driven safety evaluation
- Logical Scenarios define a quantifiable and transferable parameter space across environments and road users

## JARI's Contribution

- JARI has developed a comprehensive safety assessment process through the SAKURA Project

## Future Direction

- Expanding the safety assessment framework to address emerging technologies, including AI-based systems

# *Thank you for your attention.*

METI
Ministry of Economy, Trade and Industry

**Acknowledgement**
The Ministry of Economy, Trade, and Industry of Japan funded this research through the SAKURA project.