SAKURA

Safety Assurance KUdos for Reliable Autonomous Vehicles

Generating Logical Scenarios from Naturalistic Driving Data for Testing Autonomous Vehicle at Intersections

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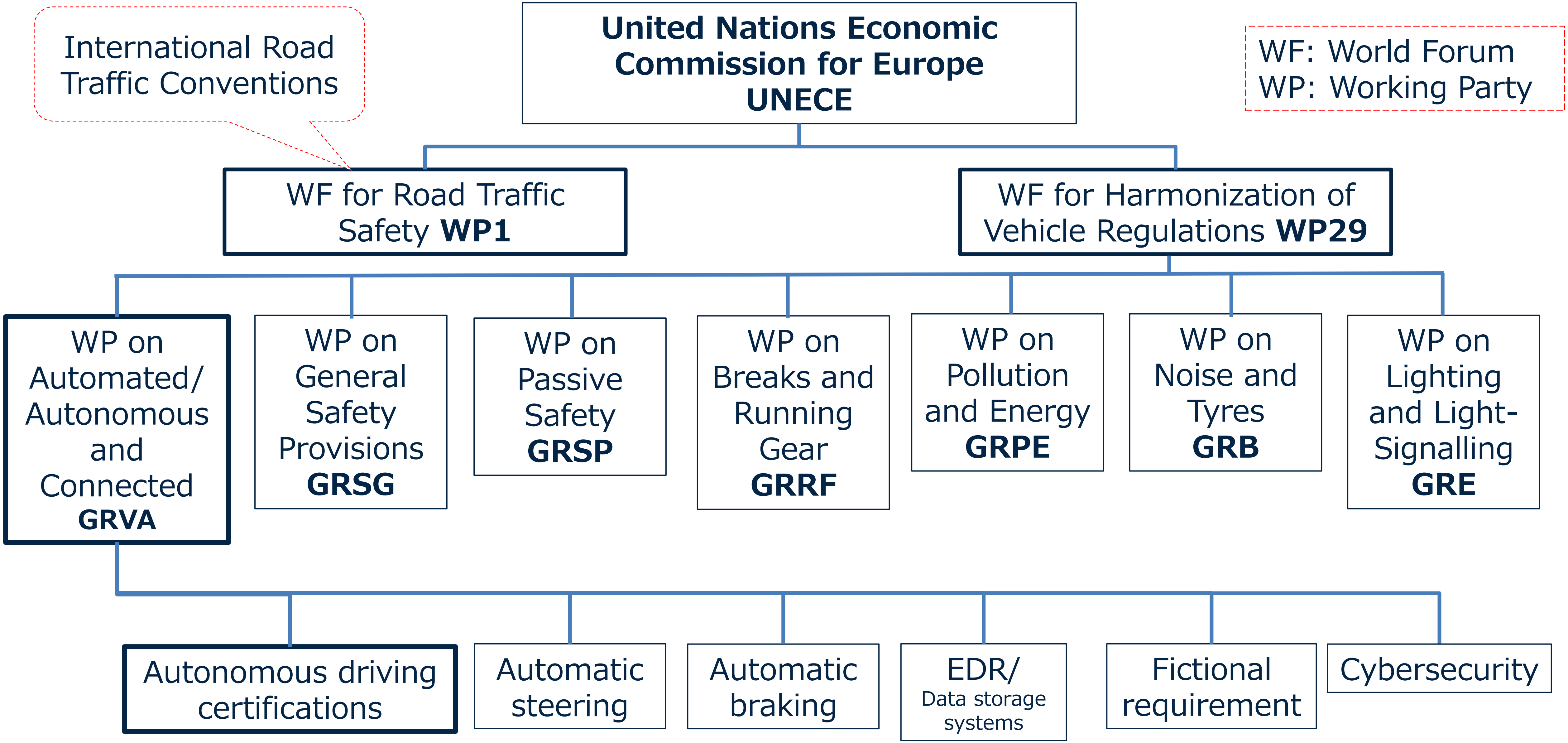
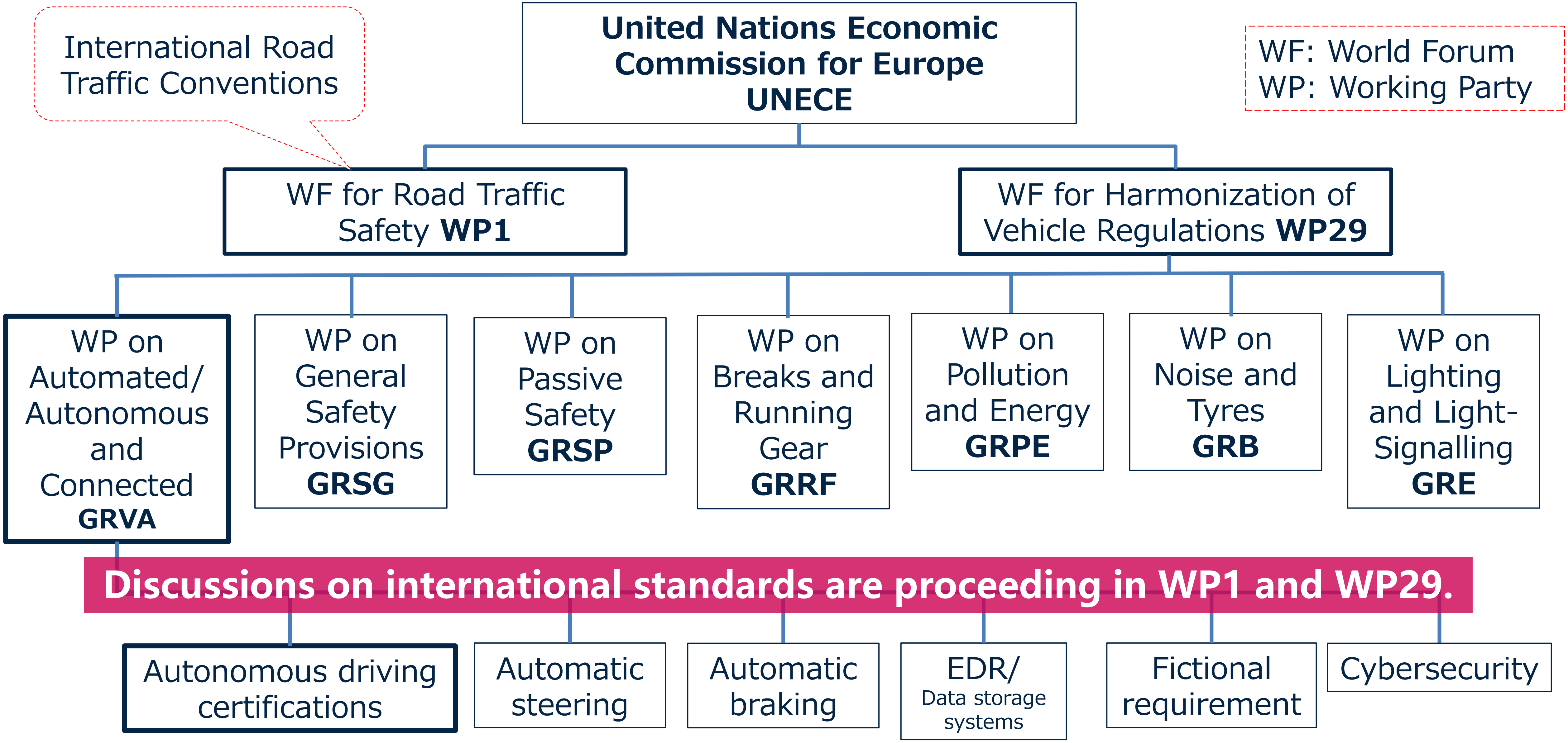
1. Introduction

International Standards Framework for Autonomous Vehicle Safety



https://unece.org/transport/road-transport/working-party-automatedautonomous-and-connected-vehicles-introduction

International Standards Framework for Autonomous Vehicle Safety



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International Standards Framework for Autonomous Vehicle Safety

ADS：Automated Driving System
ODD: Operational Design Domain

WP1 Road Traffic Safety Working Party

- Compliance with Road Traffic Laws

※As there is currently no internationally unified road traffic law, compliance with each country's road traffic laws is required.

WP29 Harmonization Forum GRVA

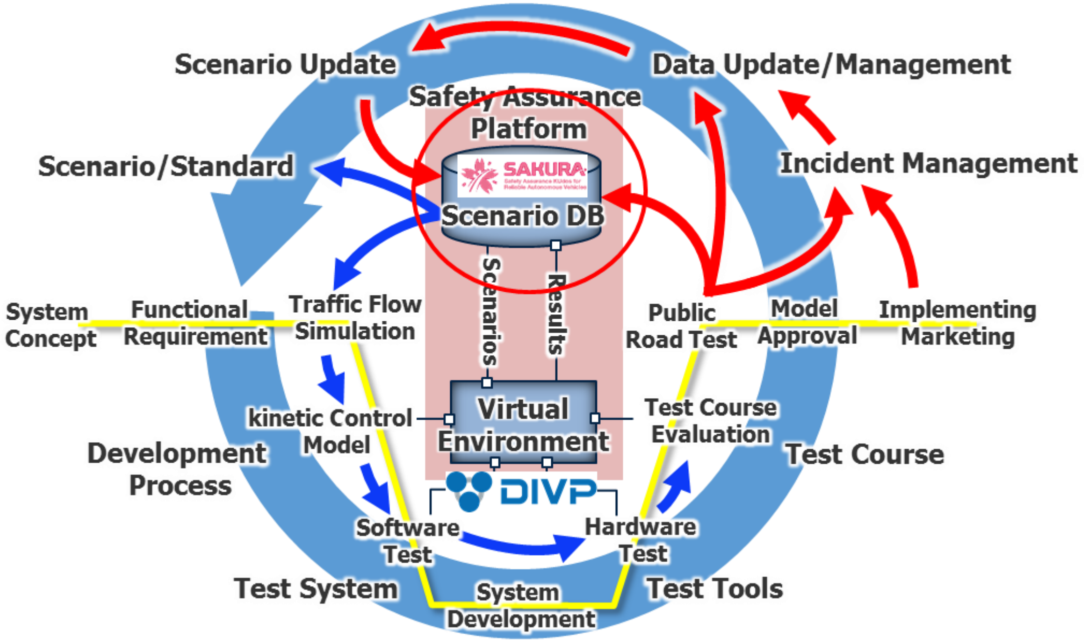
ADS shall not, while engaged, cause:

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

ADS, while engaged in their ODD, must be
Safe, Predictable & Preventable-Accident-Free

Overview of SAKURA project

- Project aims
  - **Establishing a continuous safety evaluation eco-system for safer ADS development**
  - Developing scenario-based safety assurance framework and platform
  - Coordinating standardization activities with JAMA and academia: ISO3450X



SAKURA project:
https://www.sakura-prj.go.jp/

SAKURA: developing safety evaluation methods

Aims

This study aims to

- **evaluate traffic data using the safety evaluation methodology developed by the SAKURA Project,**

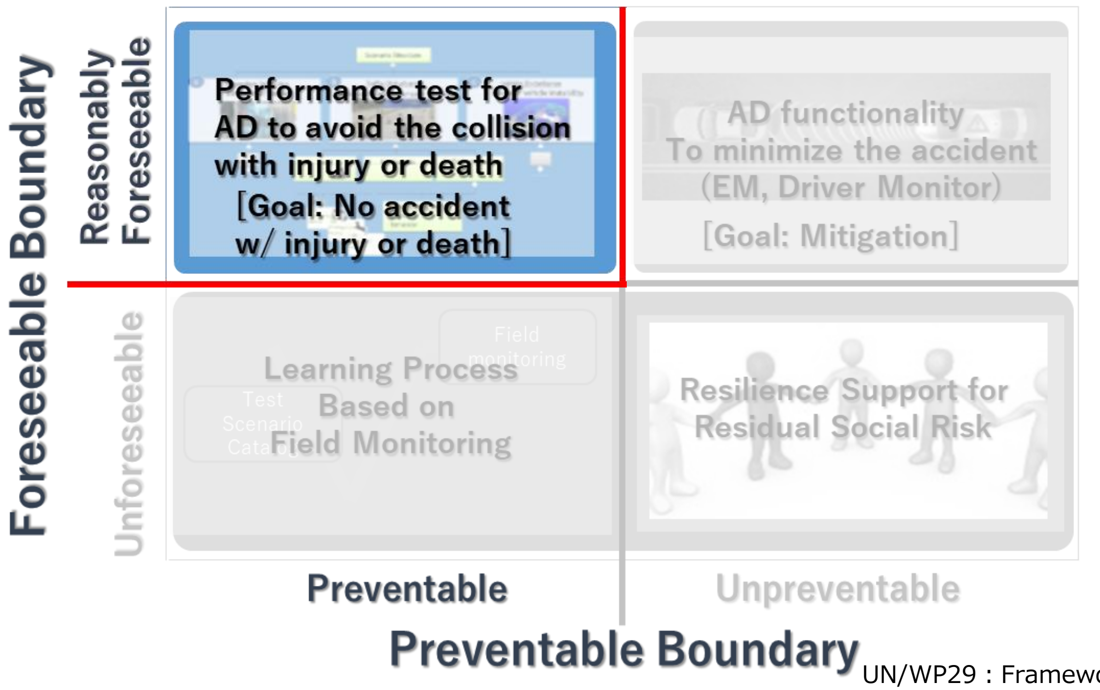
- **demonstrate steps of scenario parameterization (functional, logical, and concrete scenarios)**

2. Method

What safety is required for ADS?

According to UN-ECE WP29 framework document, safety principle is defined as follows

「*Automated vehicles shall not cause any non-tolerable risk, meaning that, under their operational domain, shall not cause any traffic accidents resulting in injury or death that are **reasonably foreseeable and preventable**」*



UN/WP29 : Framework document on automated/autonomous vehicles(2019)
JAMA : Automated Driving Safety Evaluation Framework (Ver.3)(2022)

Requirements : efficiently evaluation the reasonably foreseeable and preventable situation

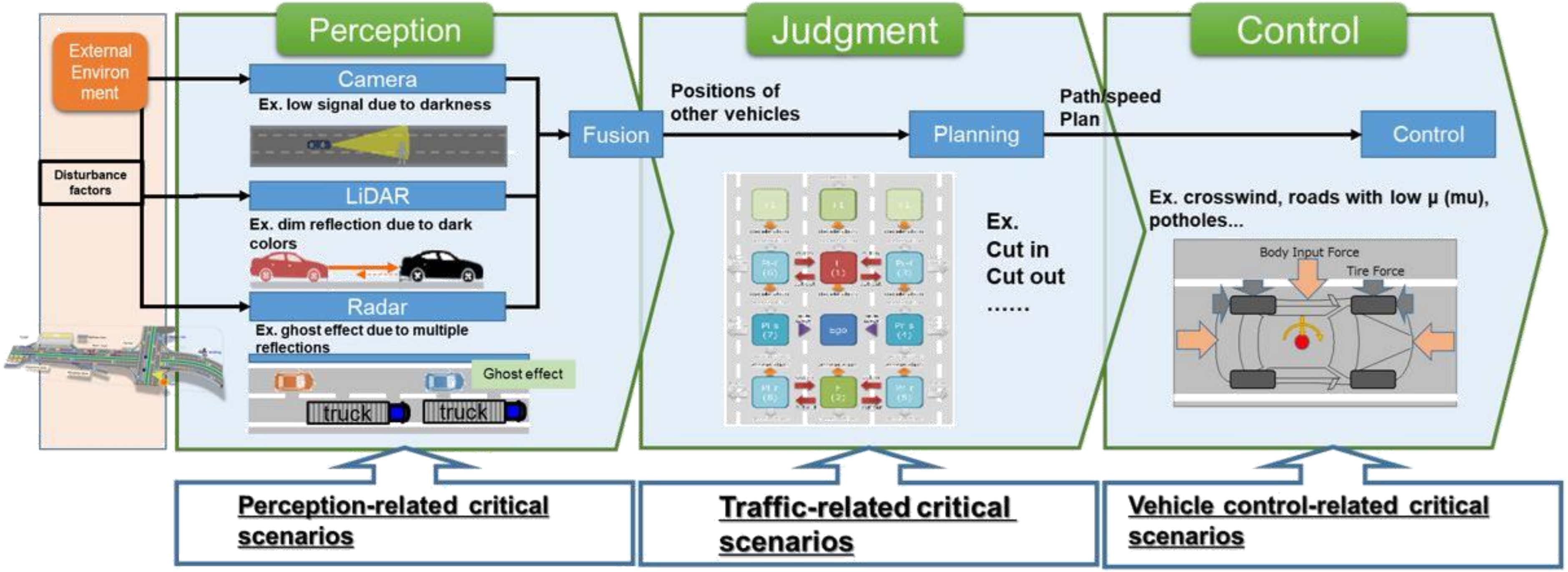
Scenario based safety evaluation

- Comprehensively extract scenes and identify the necessary parameters
- Create the scenario framework
  - **Functional Scenario** (FS): **qualitative**, described in natural language
  - **Logical Scenario** (LS): **quantify functional scenarios** by parameterizing and using data from real traffic or driving experiments
  - **Concrete Scenario** (CS): **define test parameters** using values from the parameter space

Three kind of scenarios

Concept of safety evaluation scenario

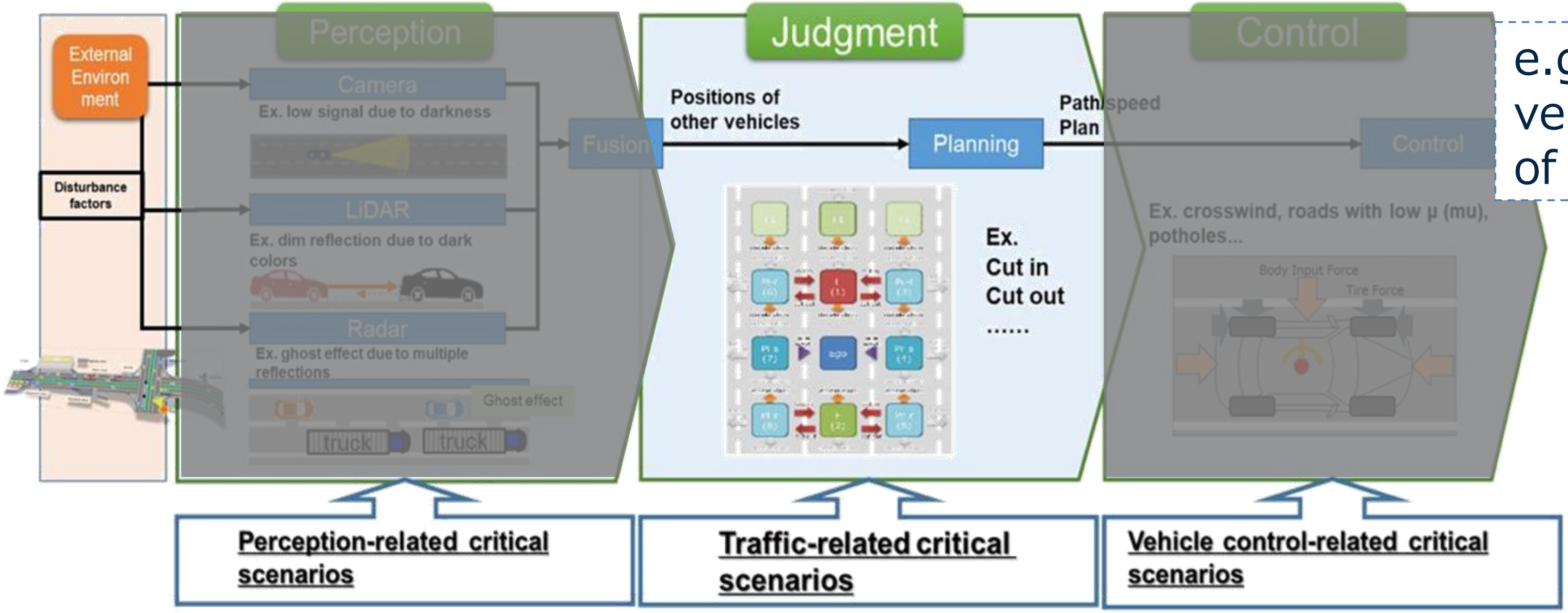
- Divide driving tasks into **3 independent tasks**
- Define critical situations (scenario source) for each task
- **Combination of 3 tasks are defined as "scenario" to be evaluated**
- This framework is reflected in ISO 34502



Each independent tasks can make FS, LS, and CS.

Focus of this study

In this study, we focus on **judgment tasks to make FS and LS**.



e.g., the surrounding vehicle cuts in front of the test

e.g., The surrounding cut-in vehicle's velocity is around 40 km/h.

- **Traffic disturbance scenarios**
- **Combining physical factors related to safety**

Requirement for FS: vehicles positions, behaviors and road geometry

Generating FS for traffic disturbance scenarios

Traffic scenarios **combine physical factors related to safety.**

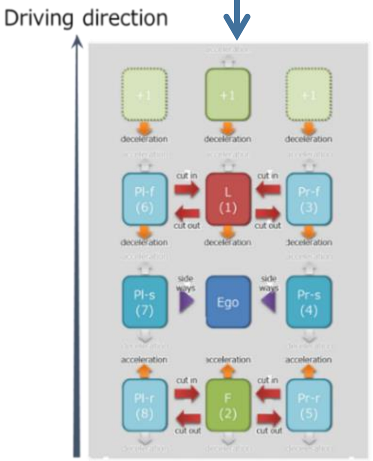
- Extract exhaustive and finite scenarios

General vehicle traffic disturbance scenarios

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

		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

behavior



Other road users position	Othe road users behavior			
vehicle position	Cut in	Cut out	Acceleration	Deceleration (Stop)
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)	✓		✓	

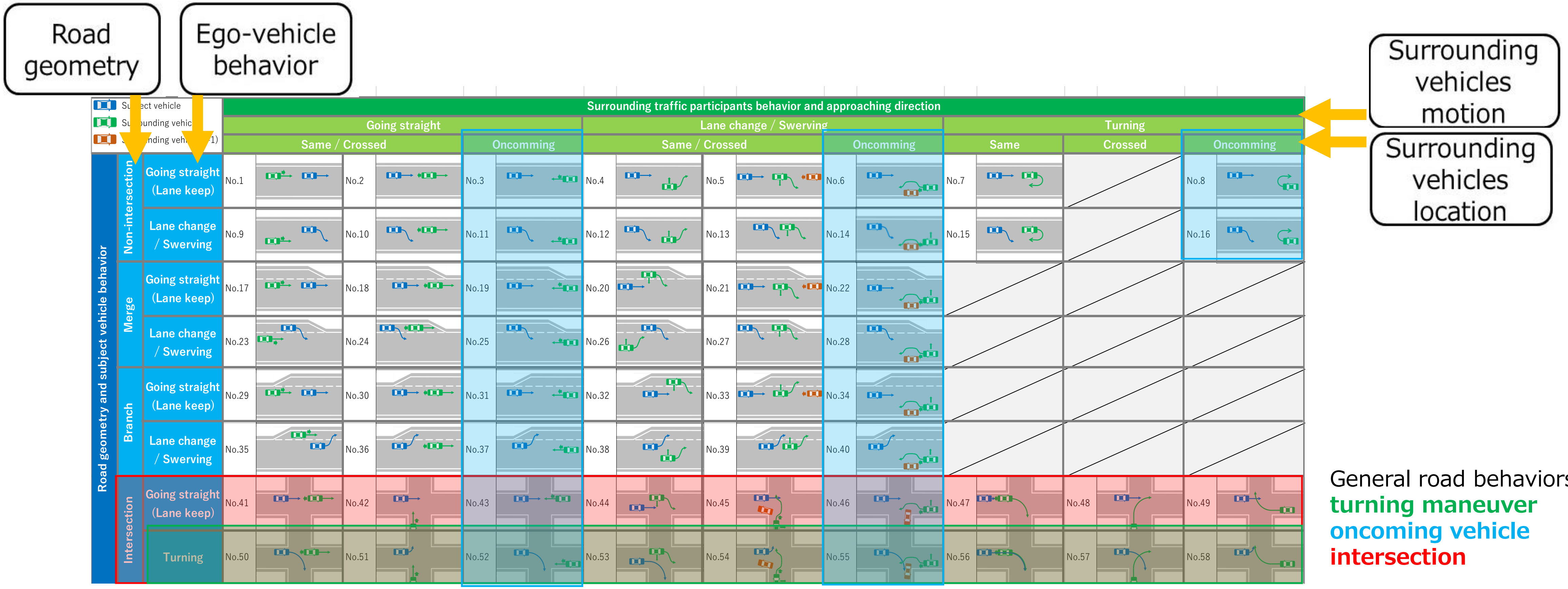
✓: have impacts, blank: no impact

Vehicle specific traffic-related critical scenario structure schematic

FS: By combining above road and vehicular factors

FS in urban environment

- All patterns on the public roads are covered
  - e.g. roundabout is considered as sub-categories of merging or branch
- Assign the necessary parameters for each behavior



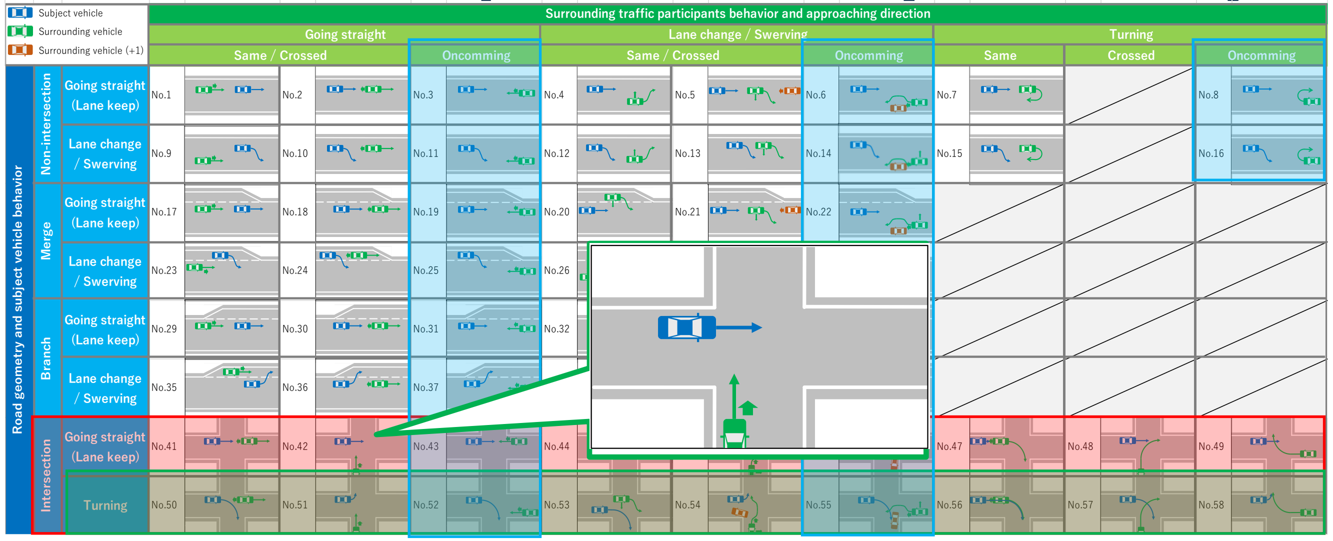
General road behaviors;
turning maneuver
oncoming vehicle
intersection

Urban 58 Scenarios

Next step: Create an LS by parameterizing FS

Logical Scenario parameterization

◆ Each FS is defined with parameters (variables)



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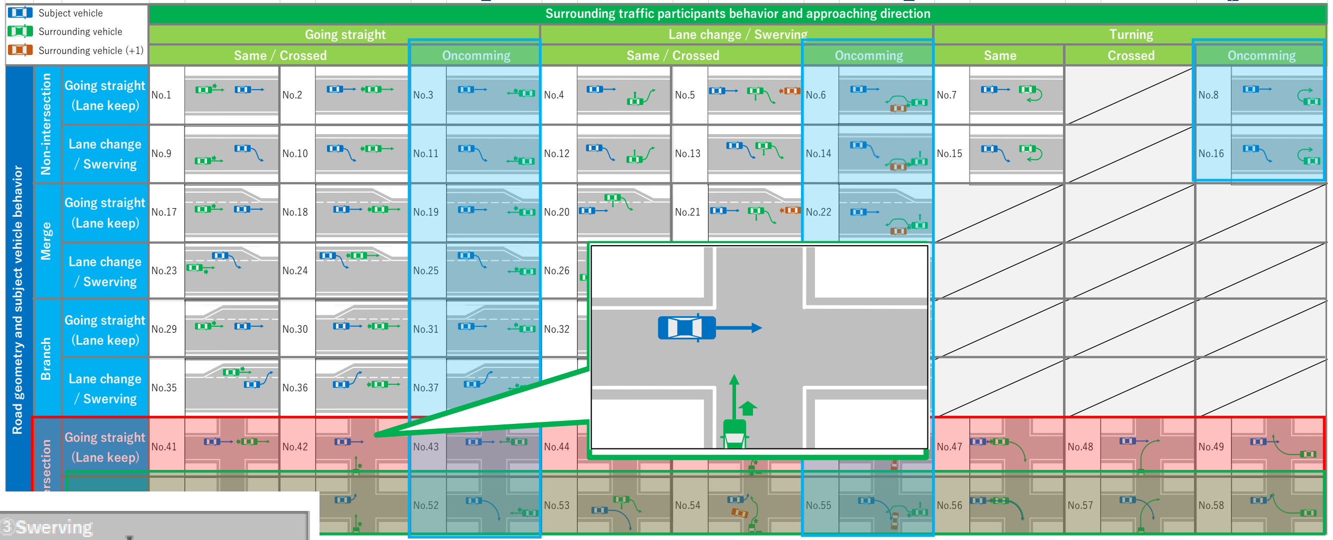
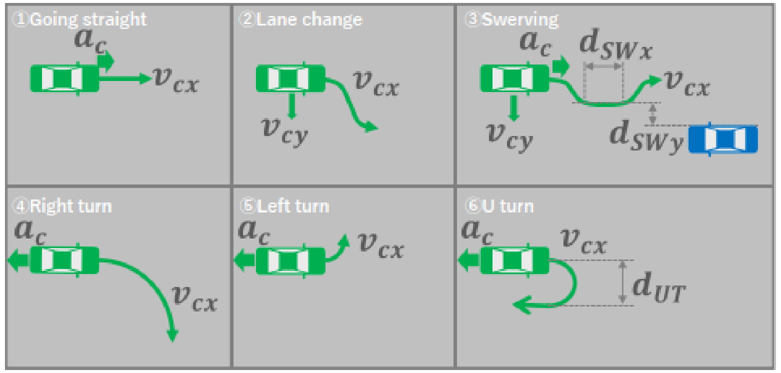
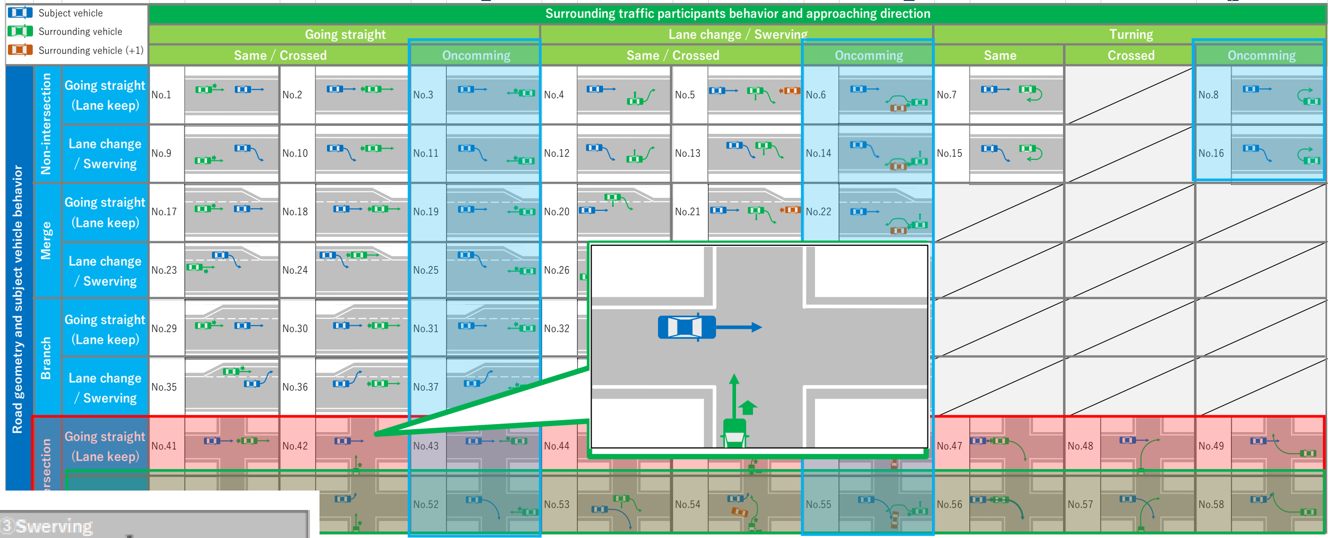


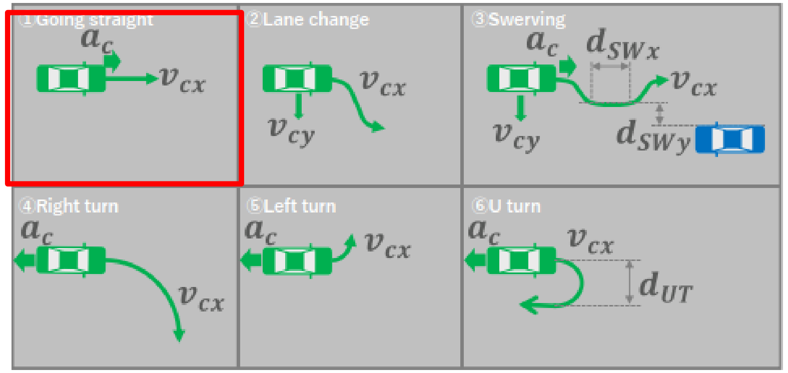


Movement of other vehicles

Logical Scenario parameterization

◆ Each FS is defined with parameters (variables)





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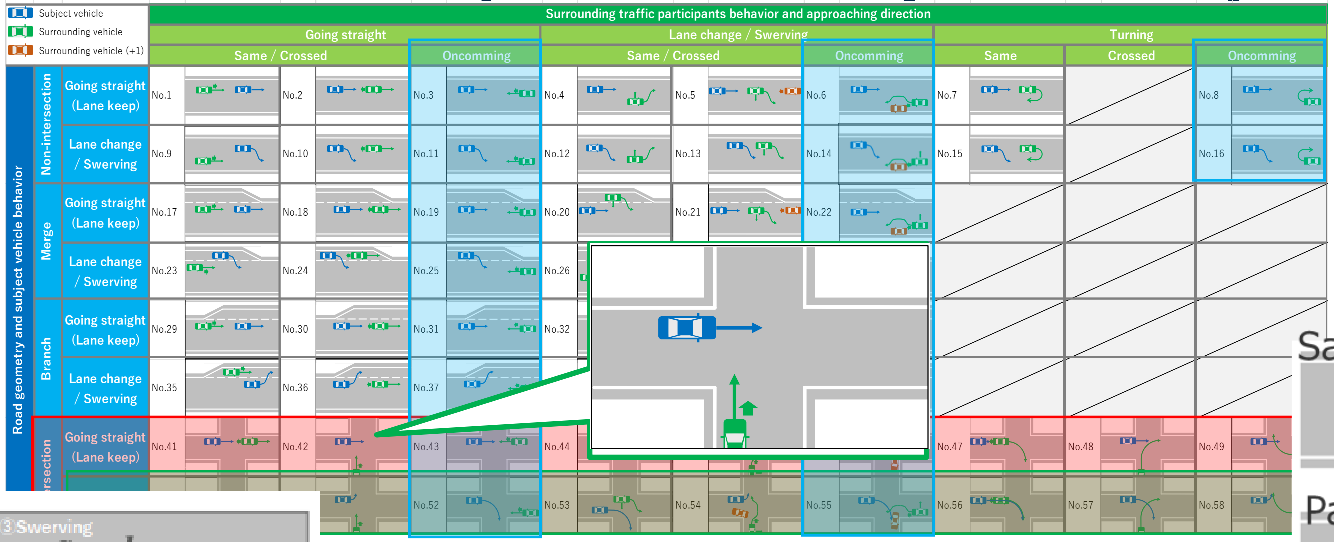

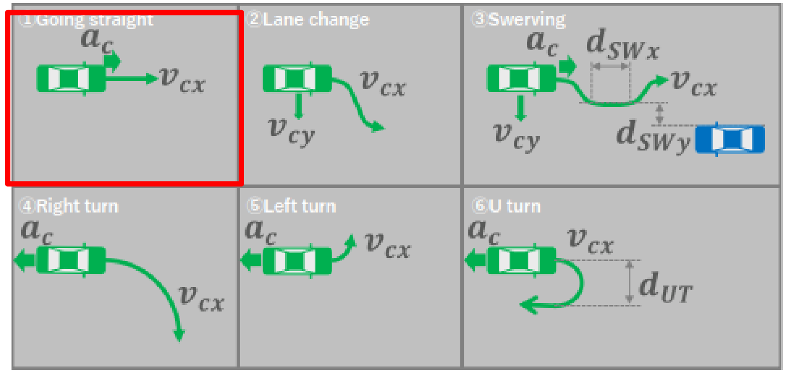

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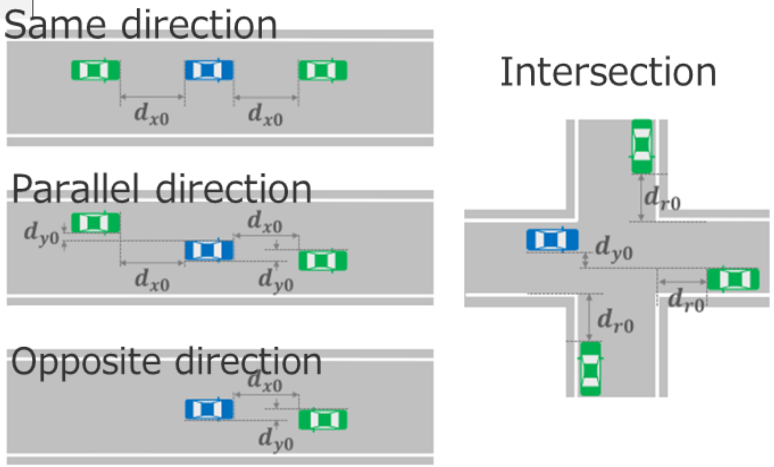
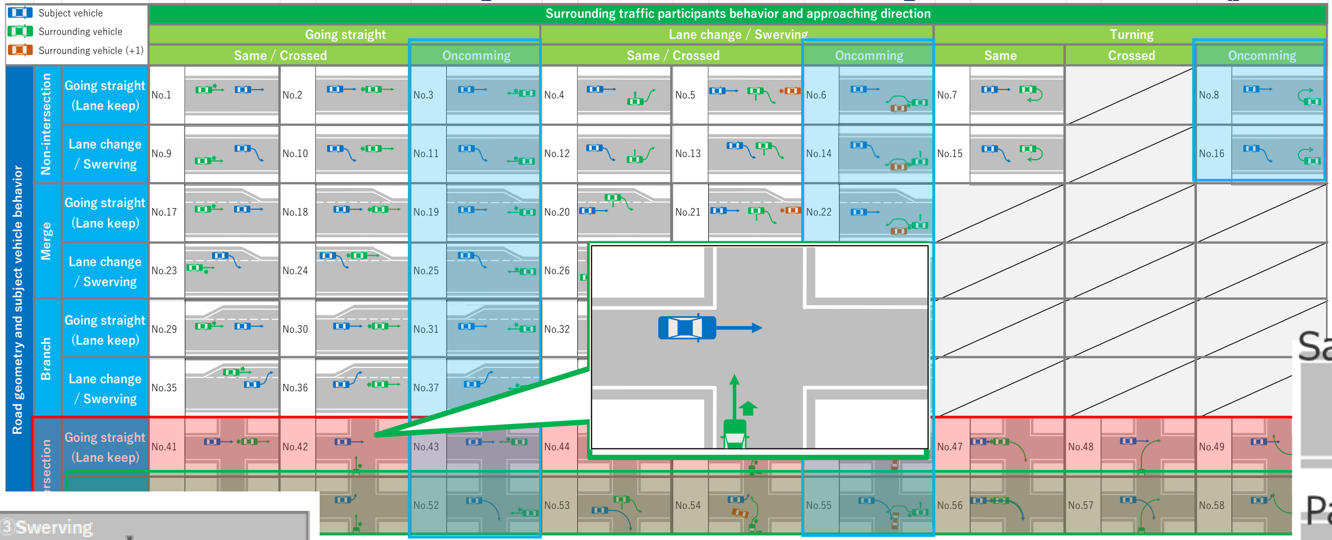
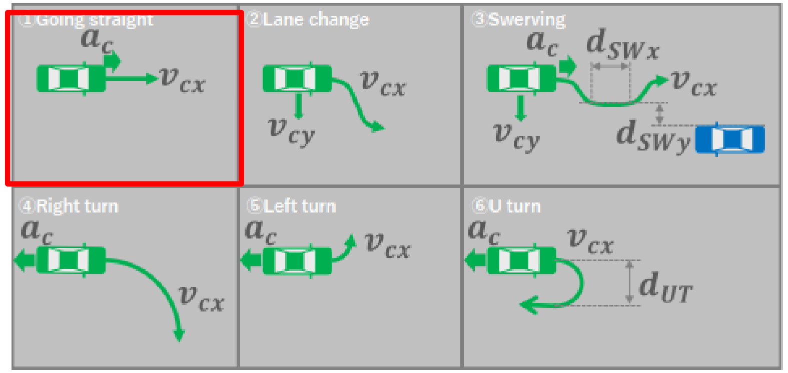


Relative positions between vehicles

Logical Scenario parameterization

◆ Each FS is defined with parameters (variables)





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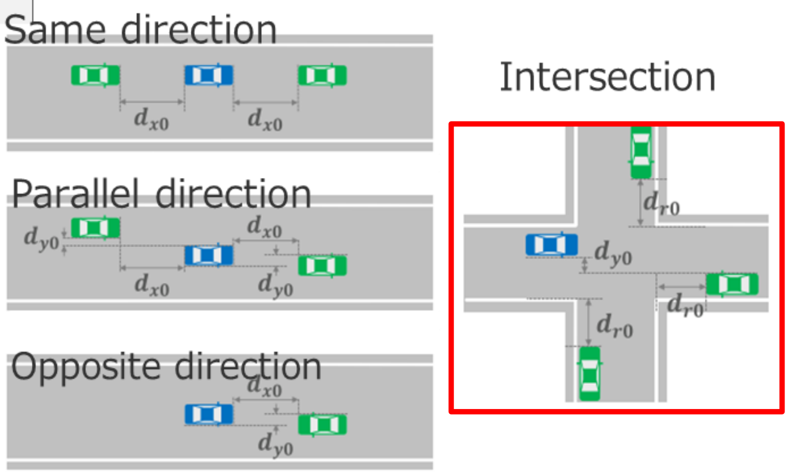
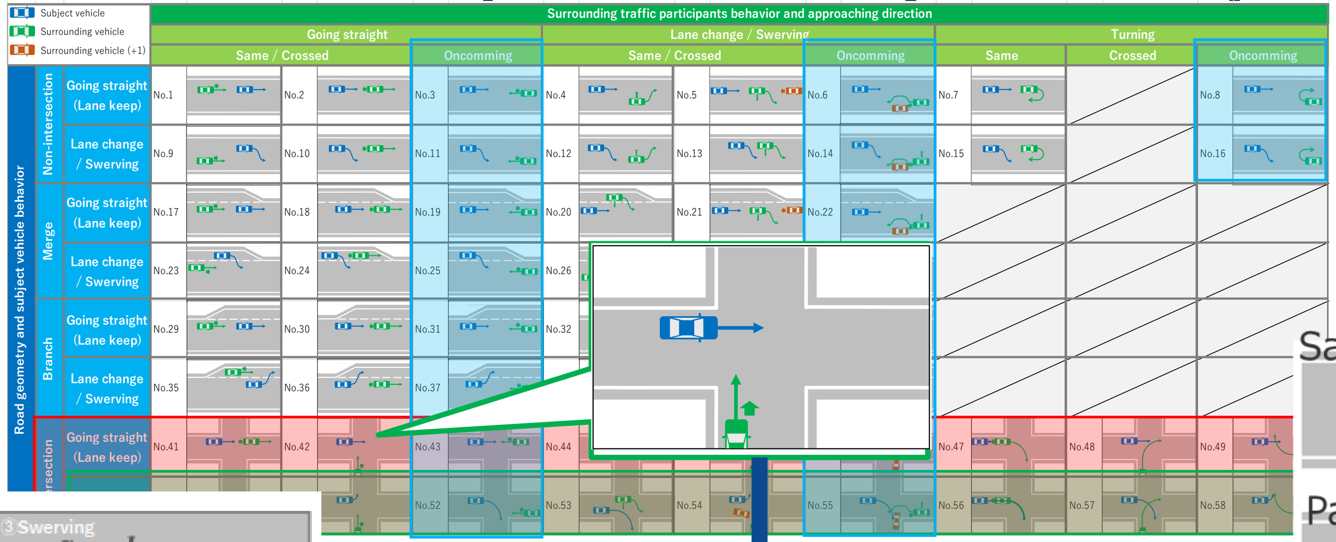
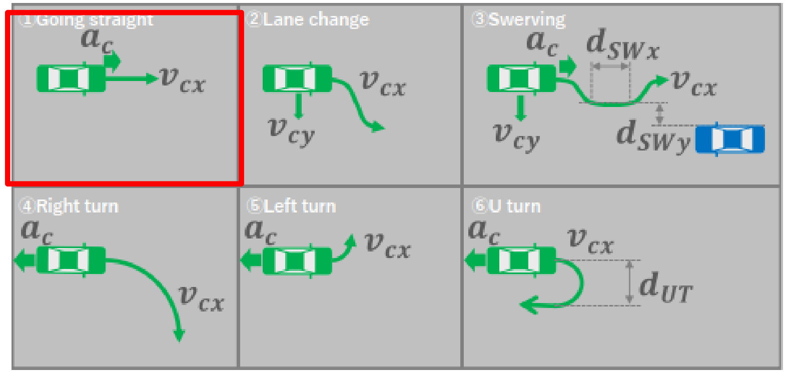


Relative positions between vehicles

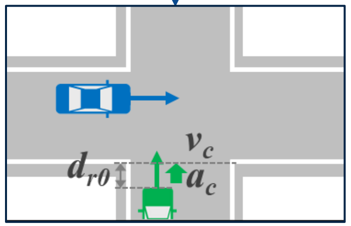
Logical Scenario parameterization

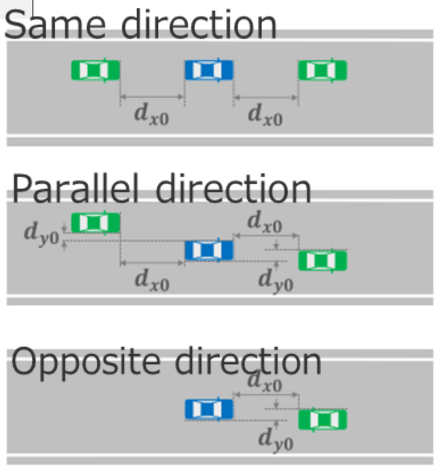
◆ Each FS is defined with parameters (variables)

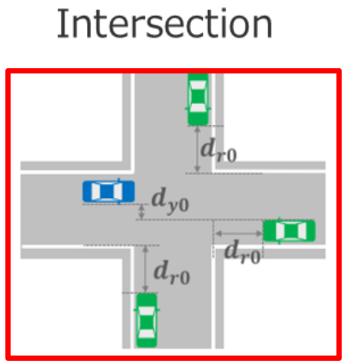




Movement of other vehicles







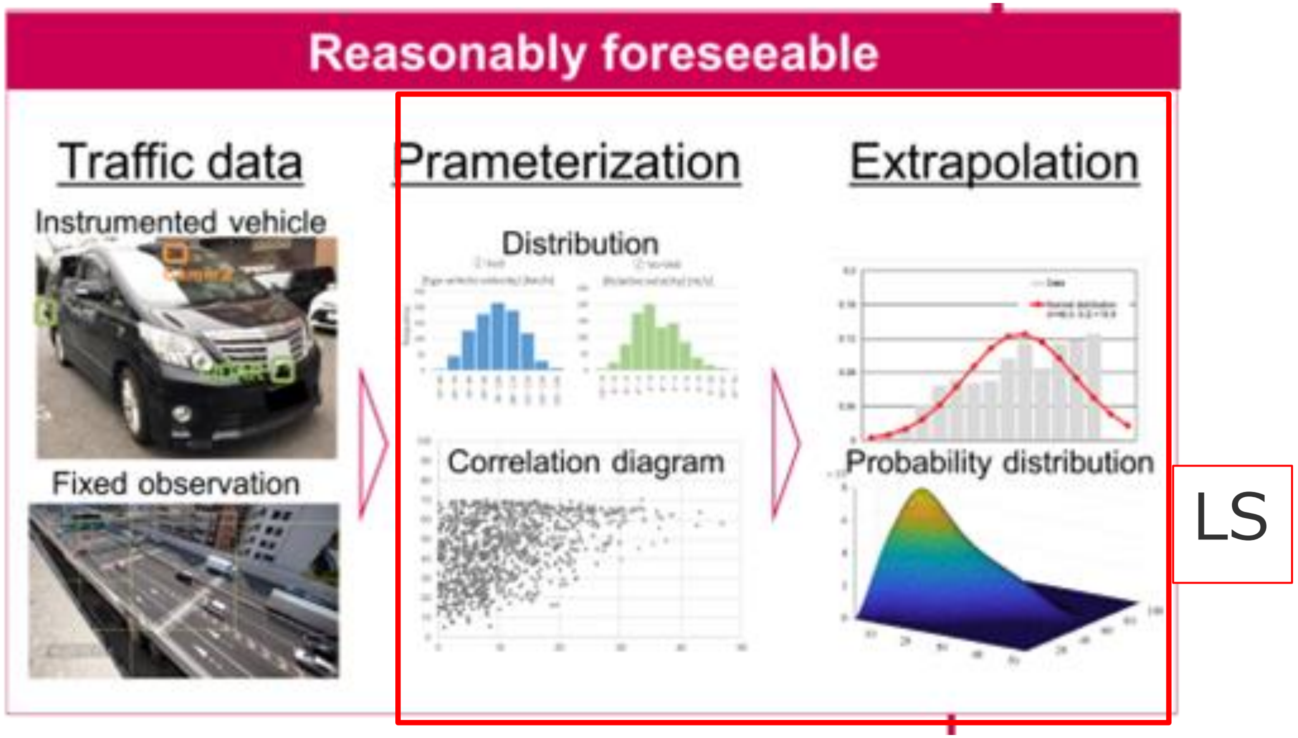
Relative positions between vehicles

This scenario's Parameters:
Velocity, Acceleration, and Distance(to the intersection)

Next step: identify parameters range using quantitative values

Parameter Ranges

◆ Evaluating parameterized scenarios by using traffic data collected by:
- Instrumented vehicle data
- Fixed camera observation data
- Unmanned Aerial vehicles
- Rule and Lows



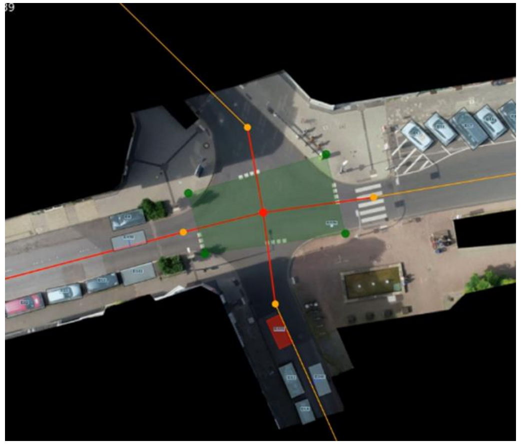
LS can be created using data and can be used for evaluation.

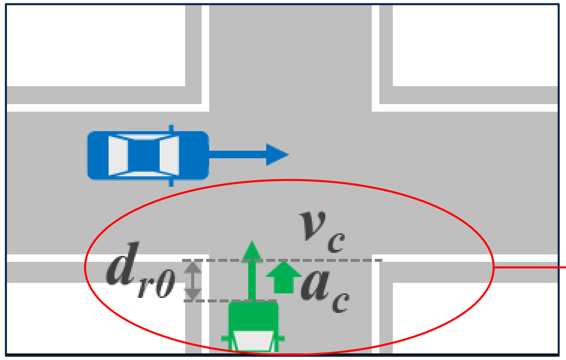
Overview of real traffic-based data analysis

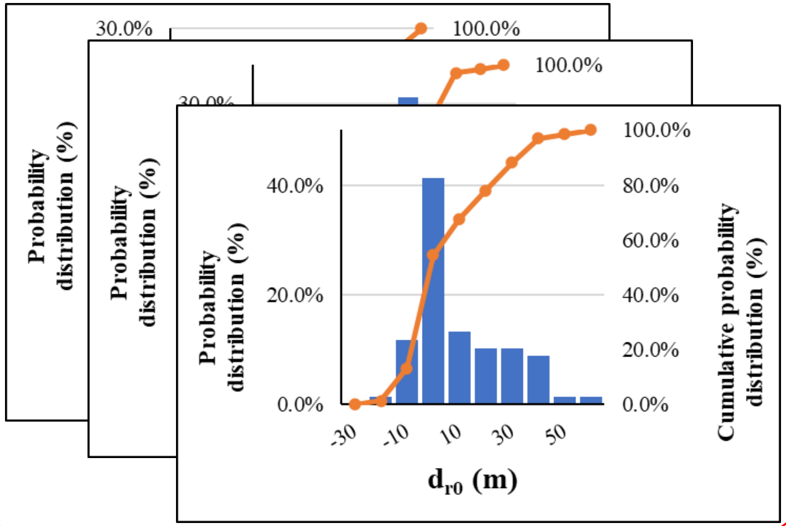
Creating **LS** based on naturalistic driving data(NDD) following the **scenario-based safety evaluation approach**

- Focusing on intersection scenario
  - high-risk areas (25% of crashes are side-impact)
- Expanding the method applied in highway scenarios (Nakamura et. al 2022)

Intersection scenario







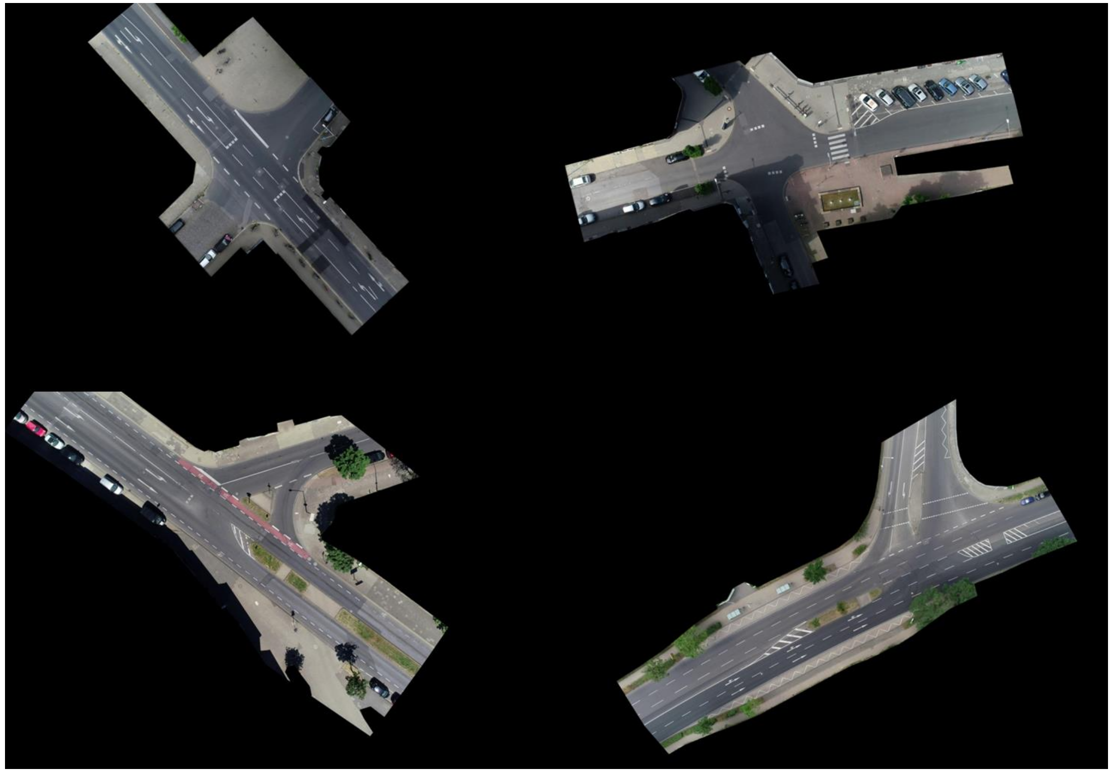
Parameterize

Calculating and evaluating

Analyzing the intersection scenario using the SAKURA method

Dataset

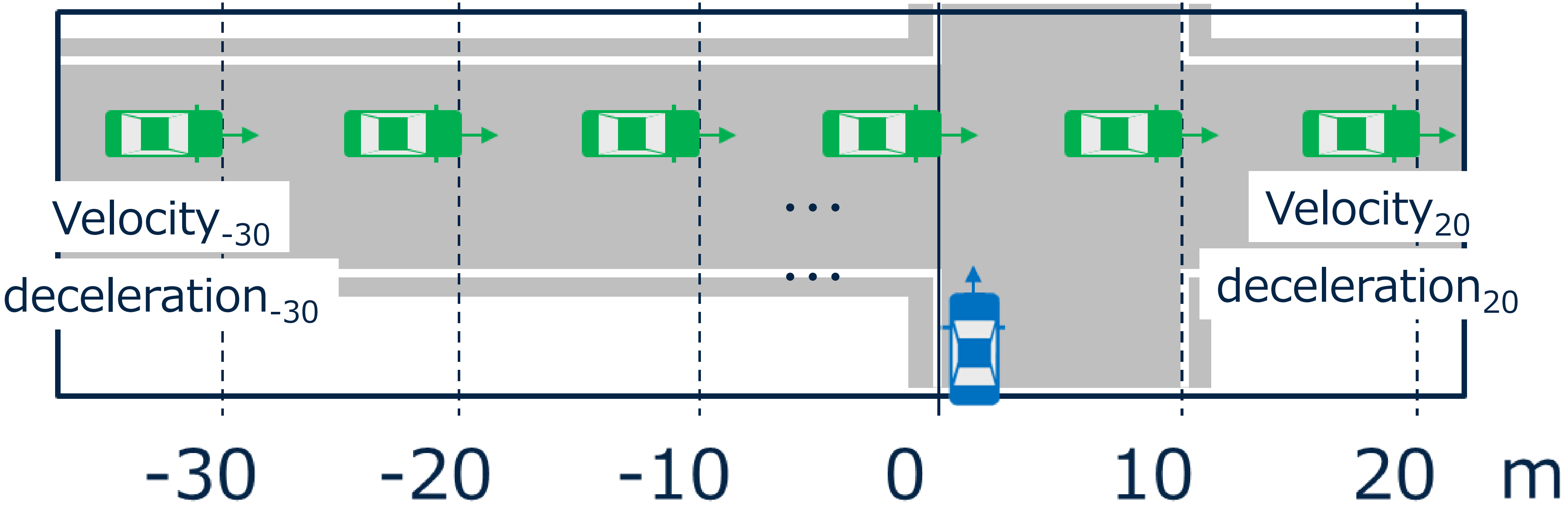
- Intersection Drone Dataset (inD), RWTH Aachen University
- 4 unsignalized intersections (2 crossroads, 2 T-junctions)
- Speed limit: 50 km/h
- High-resolution vehicle trajectories captured by drones



Using German urban road data

Scenario Extraction

- Two vehicles entering an intersection simultaneously
- Test vehicle vs. conflicting vehicle (focus on accelerating cases)
- 212 valid interaction cases analyzed



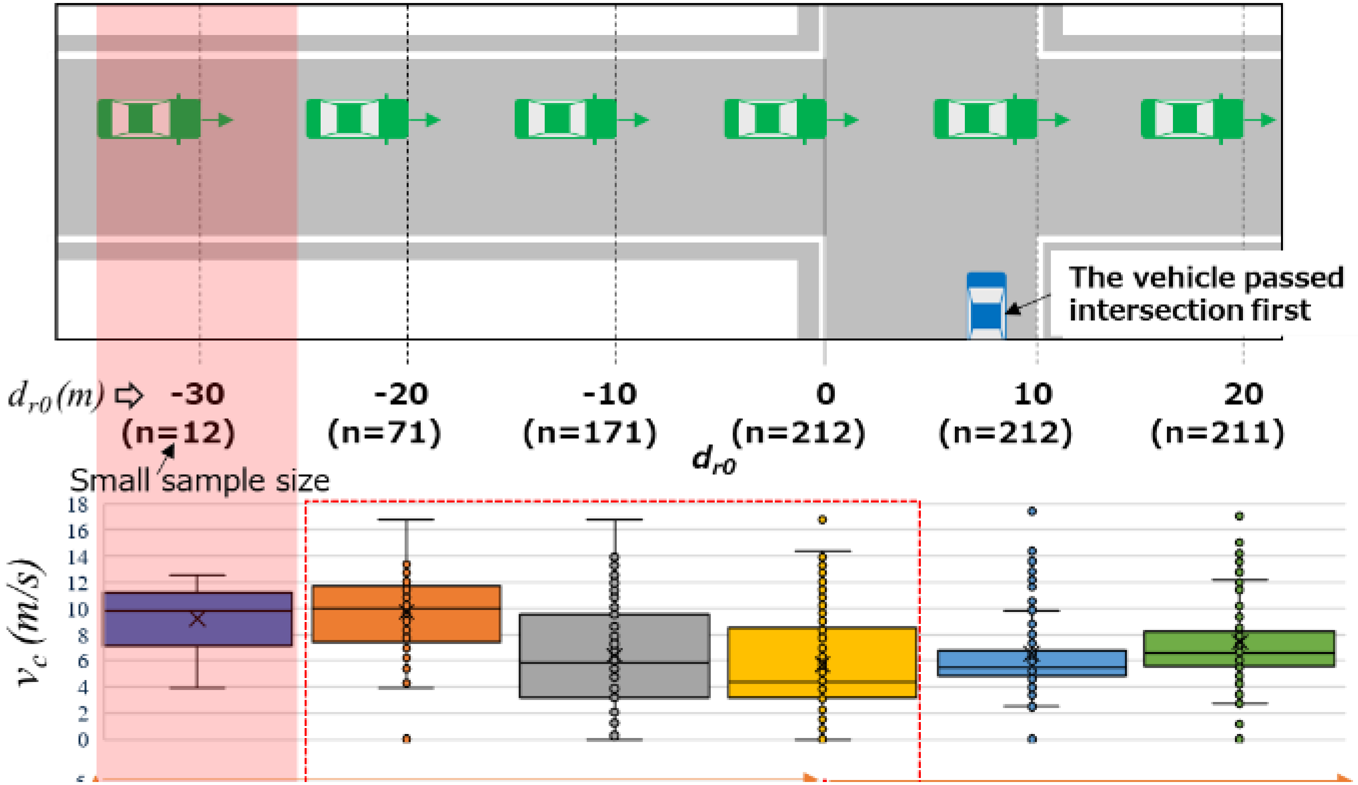
Extract the interaction between two vehicles at an intersection.

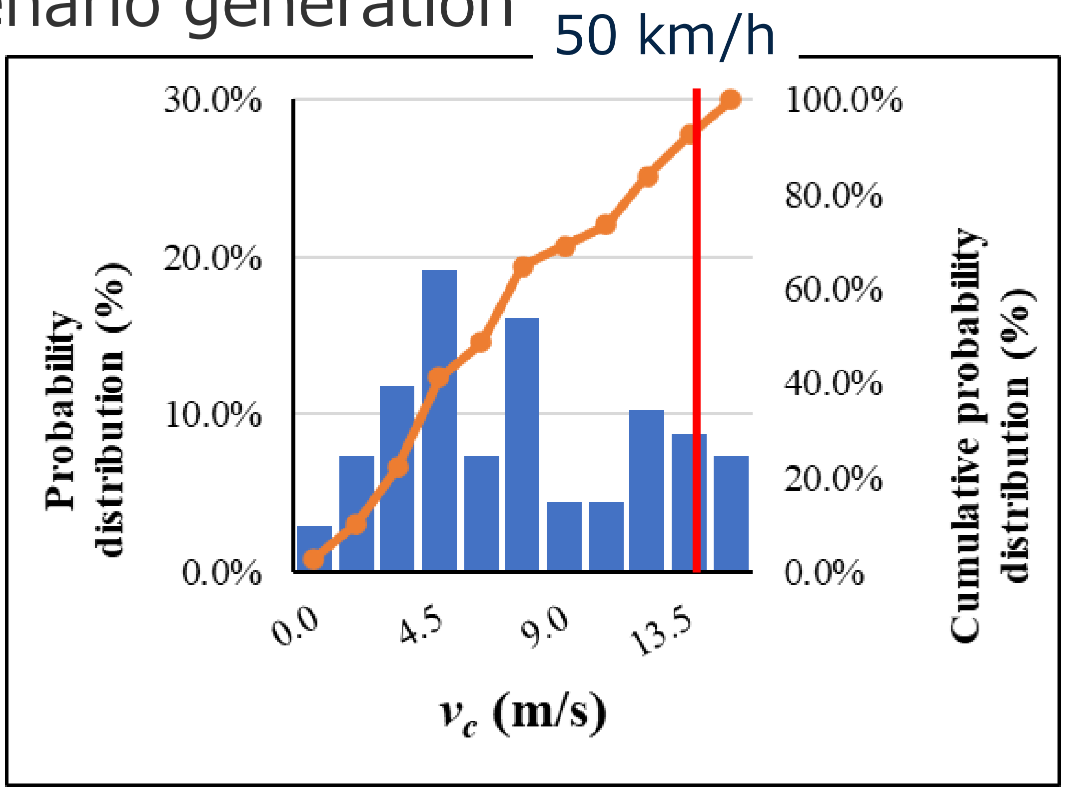
3. Result

Parameter ranges: Velocity

Velocity: up to ~48.8 km/h (95th percentile)

- ◆Vehicles approach intersections close to **the 50 km/h speed limit**
- ◆**Decrease from 30 m to 0 m before the intersection**
- ◆The use of high-speed edge cases in scenario generation



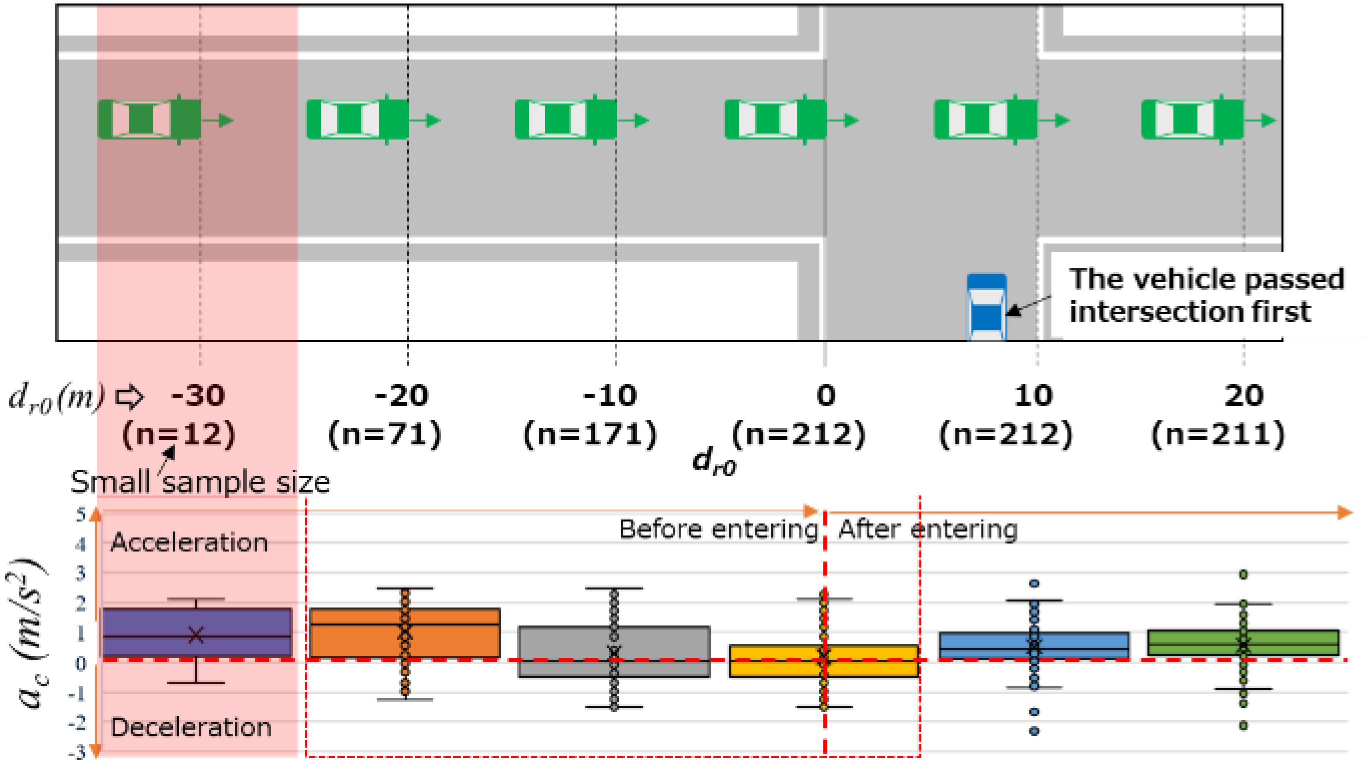


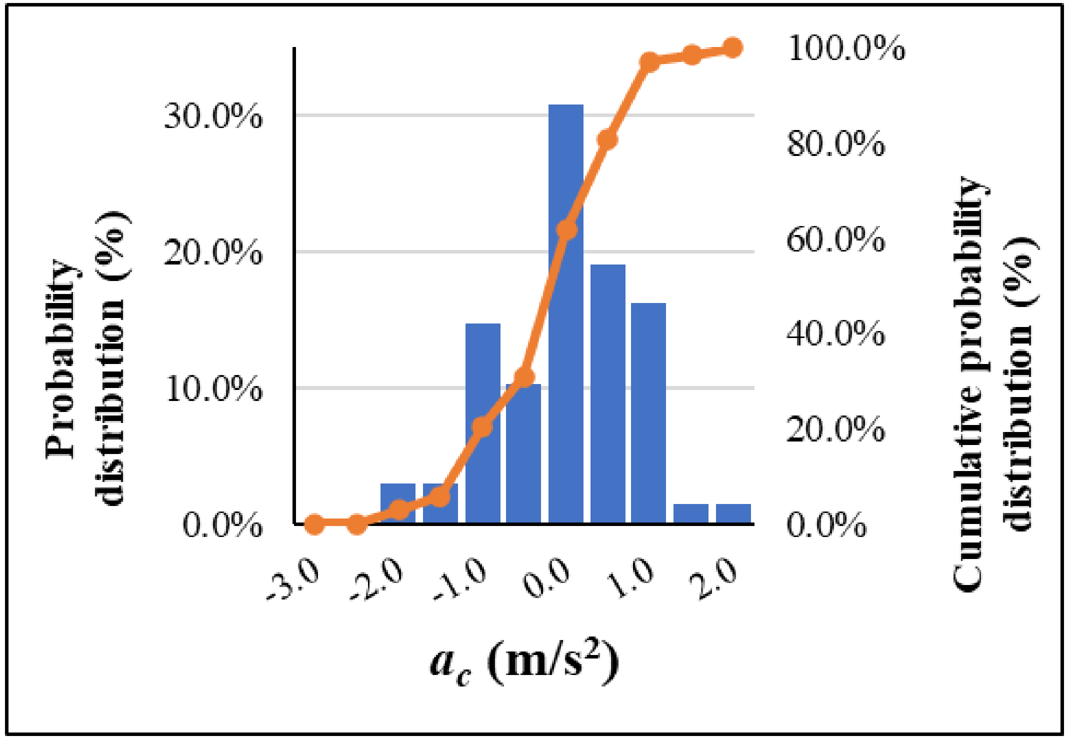
Approaching intersections at speeds close to the speed limit (50 km/h)

Parameter ranges: Deceleration

Deceleration: up to 2.19 m/s² (95th percentile)

- ◆**Centered near 0 m/s², with most values between -2.0 and 2.0 m/s²**
- ◆Deceleration typically begins around 20 meters before the intersection

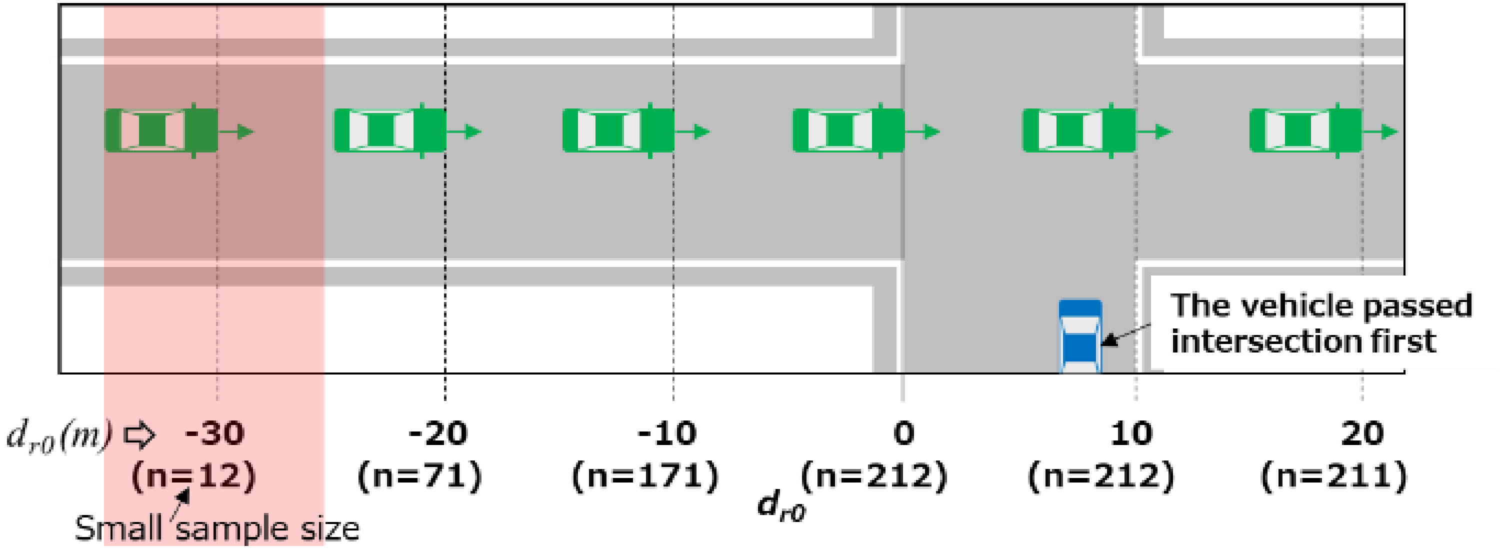


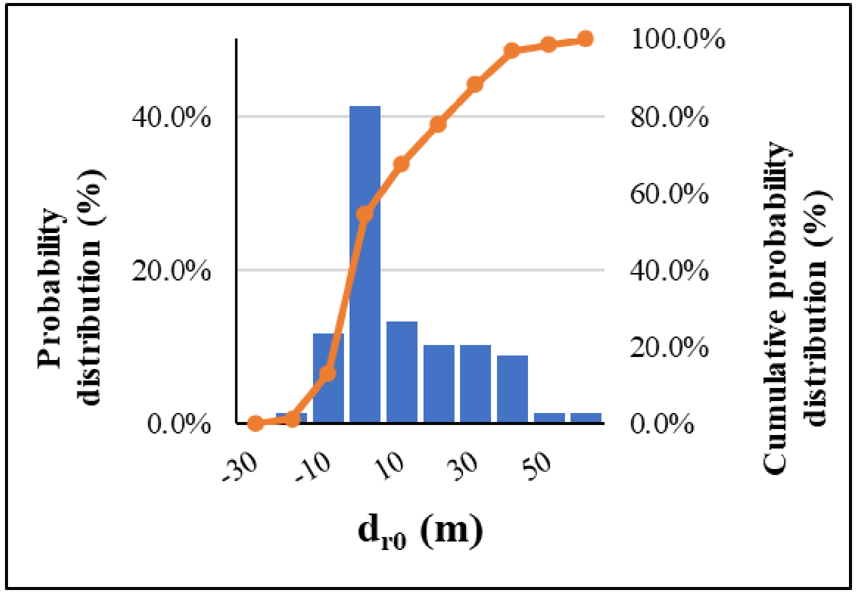


Many vehicles slightly decelerate

Parameter ranges: Distance

- Most vehicles were located within ±10 m of the intersection entrance
- Most vehicle interactions occur within this narrow band





The peak is near the intersection entrance

Summary of Results

Velocity

- Approaching speeds often near the limit
- 95th percentile ≈ **48.8 km/h**

Acceleration

- Mostly light deceleration
- Some cases of acceleration
- 95th percentile ≈ **+2.19 m/s²**

Distance

- Most conflicts within ±10 m
- Critical zone for ADS evaluation

"These results provide data-driven parameter ranges for constructing realistic and safety-relevant Logical Scenarios."

4. Discussion and Conclusion

Discussion

- **The critical percentile values of the distribution functions are crucial for safety assessment.**
- Most vehicle conflicts occurred within ±10 meters of the intersection entry point

→**ADS be validated in this specific range**

Interaction zones

%ile	d_{r0}=-30		d_{r0}=-20		d_{r0}=-10		d_{r0}=0		d_{r0}=10		d_{r0}=20	
	n=12		n=71		n=171		n=212		n=212		n=211	
	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c
100	12.55	2.11	16.77	2.46	16.77	2.46	16.77	2.46	17.42	2.62	17.02	2.94
95	12.42	2.03	13.33	2.19	12.80	1.99	12.63	1.97	12.97	1.76	12.93	1.47
75	11.16	1.64	11.60	1.77	9.53	1.14	8.44	0.53	6.79	0.97	8.19	1.06
50	9.84	0.84	9.99	1.29	6.08	0.08	4.33	0.02	5.56	0.45	6.58	0.60
25	7.26	0.23	8.00	0.21	3.15	-0.47	3.15	-0.50	4.82	0.12	5.58	0.26
5	4.74	-0.31	5.59	-0.54	2.07	-1.41	1.25	-1.41	3.44	-0.64	4.24	-0.59
0	3.93	-0.68	3.93	-1.24	0.29	-1.50	0.00	-1.50	0.20	-2.31	1.14	-2.14

Discussion

- **Majority of vehicles slightly decelerated before entering the intersection.**
- The 95th percentile acceleration reached 2.19 m/s²

→**Variability in acceleration is critical for ADS validation."**

Aggressively behavior

%ile	d_{r0}=-30		d_{r0}=-20		d_{r0}=-10		d_{r0}=0		d_{r0}=10		d_{r0}=20	
	n=12		n=71		n=171		n=212		n=212		n=211	
	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c	v_c	a_c
100	12.55	2.11	16.77	2.46	16.77	2.46	16.77	2.46	17.42	2.62	17.02	2.94
95	12.42	2.03	13.33	2.19	12.80	1.99	12.63	1.97	12.97	1.76	12.93	1.47
75	11.16	1.64	11.60	1.77	9.53	1.14	8.44	0.53	6.79	0.97	8.19	1.06
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0	3.93	-0.68	3.93	-1.24	0.29	-1.50	0.00	-1.50	0.20	-2.31	1.14	-2.14

Conclusion

- The proposed methodology identified critical parameter ranges for conflicting vehicles at unsignalized intersections using naturalistic driving data.

- The extracted parameter distributions provide realistic and high-risk behavior boundaries essential for scenario-based testing of ADS.

- The implicit yielding behavior observed highlights the need to model interdependent vehicle dynamics in logical scenarios.

- This data-driven framework enables the generation of physically consistent, safety-relevant test conditions for ADS validation.

Thank you for your attention

Any questions?

Acknowledgement
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SAKURA

FINAL EVENT

SAVE THE DATE

5 March 2026

Tokyo | Japan

SAKURA
Safety Assurance KUdos for Reliable Autonomous Vehicles