Scenario Generation for Autonomous Driving using LLMs based on real-world Edge Data

Andreas Stephan, Robert Bosch GmbH

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Course Objectives

- Learn why scenario generation for autonomous driving is important
- Learn about scenario generation methods
- Hear about our current current project

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1

Motivation

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Robotaxis are coming

Robotaxis on the Rise: Waymo Plans Massive Fleet Expansion

(dpa) With around 1,500 robotaxis, the Google sister company completes over 250,000 rides with passengers per week. By the end of next year, more than 2,000 additional autonomous vehicles are to be added.

Waymo is still relying on Jaguar vehicles - in the future, vehicles from the Chinese manufacturer Zeekr will primarily be used. | Photo: Andrej Sokolow, dpa

Tesla: Robo-taxi service discreetly and limitedly starts in Austin

(dpa) For Tesla CEO Elon Musk, autonomous driving is the future of the struggling pioneer brand. An initial robotaxi service is starting with a few cars and accompanying personnel - and with simpler technology.

Sources:

- https://vision-mobility.de/en/news/robotaxis-on-the-rise-waymo-plans-massive-fleet-expansion-384270.html
- https://vision-mobility.de/en/news/tesla-robo-taxi-service-discreetly-and-limitedly-starts-in-austin-384752.html

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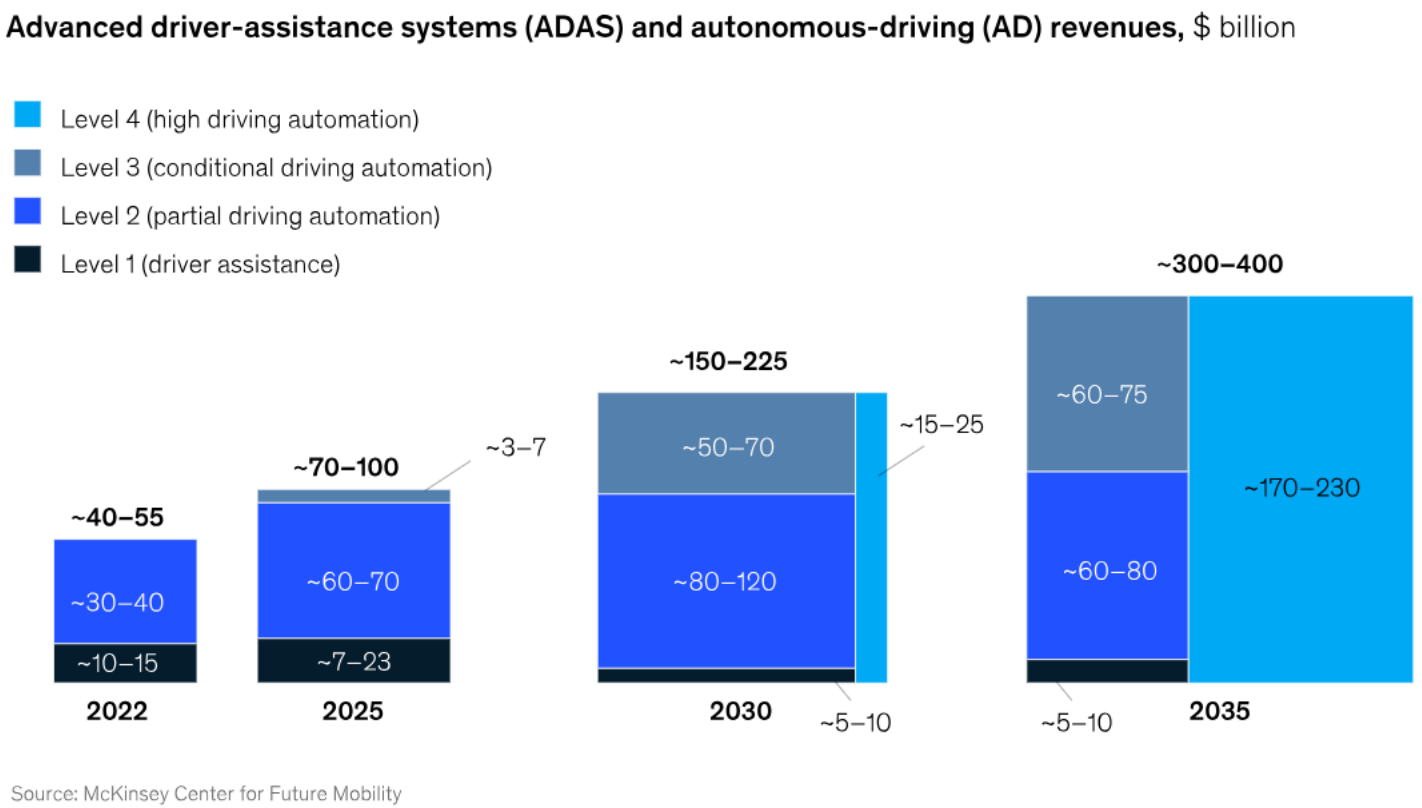
Market: McKinsey ADAS Growth estimation



Source: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/autonomous-drivings-future-convenient-and-connected

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Scenario Generation: Why?

Autonomous driving systems are very **complex**

➔ needs to be tested thoroughly

Source: (*)

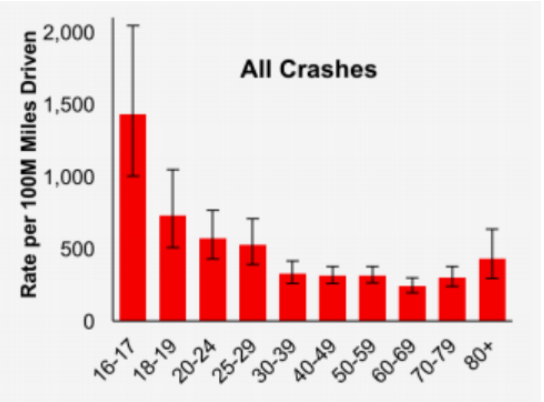
Simple ideas:

1. Let the autonomous system drive a large distance for testing
2. Record a large number of traffic scenarios

Problems

➔Safety-critical or interesting scenarios occur rarely [Ding et al., 2023 (*)]

➔Above ideas are expensive and are not sufficient to find all intersting scenarios



Source: (**)

(*) W. Ding, C. Xu, M. Arief, H. Lin, B. Li and D. Zhao, "A Survey on Safety-Critical Driving Scenario Generation—A Methodological Perspective," in *IEEE Transactions on Intelligent Transportation Systems, 2023*

(**) https://aaafoundation.org/rates-motor-vehicle-crashes-injuries-deaths-relation-driver-age-united-states-2014-2015

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Goals of Scenario Generation

➔Generate critical and interesting scenarios synthetically

Goals:

- **Safety Validation**
  - Across a large and diverse number of driving scenarios
- **Edge Case Identification**
  - Identify rare, critical cases not captured in a limited set of real-world driving
- **Accelerated Development**
  - Enable rapid iteration and testing in virtual environments
- **Cost Efficiency**
  - Significant cost reduction in comparison to physical testing

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2

Background: Scenario Representation & Evaluation

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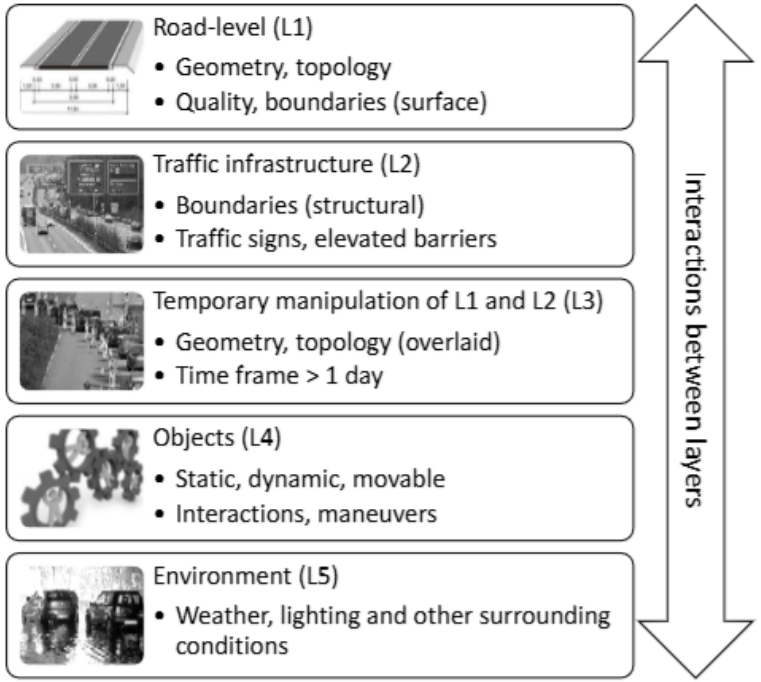
Example Scenario Representation Model



- Figure: Example which shows representation hierarchy organized by content
- Note: There exists a large variety of scenario representations
- Others representations include the level of abstraction
  - Highest level: Verbal description of goal of scenario
  - Lowest level: Exact description of all necessary parameters (e.g. those mentioned in Figure)

Figure. G. Bagschik, T. Menzel and M. Maurer, "Ontology based Scene Creation for the Development of Automated Vehicles," *IEEE Intelligent Vehicles Symposium, 2018*

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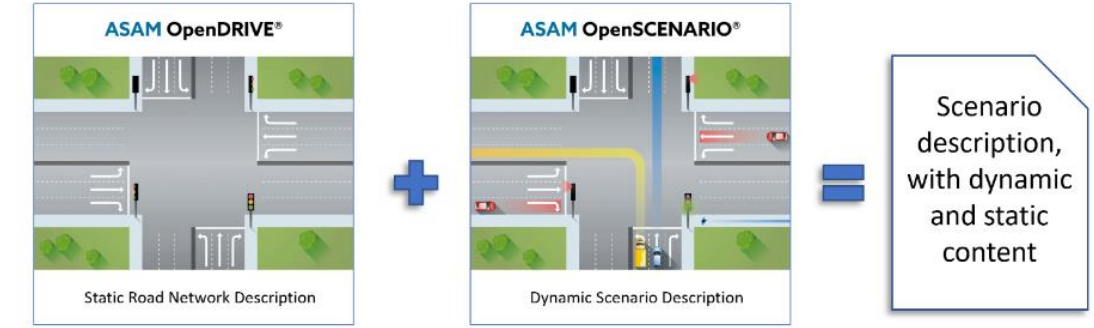
OpenDRIVE & OpenSCENARIO

- OpenDRIVE: Represent static content
- OpenSCENARIO: Represent dynamic content

Details:

- ➢ Uses XML as description language
- ➢ Many organizations drive standardization
- ➢ Compatible with software packages (e.g. Unreal Game Engine)

(*) Source:
https://www.asam.net/index.php?eID=dumpFile&t=f&f=4089&token=deea5d707e2d0edeeb4fccd544a973de4bc46a09




```
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                </link>
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            </lane>
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                </link>
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        <center>
            <lane id="0" type="none" level="false">
                <link>
                </link>
            </lane>
        </center>
        <right>
            <lane id="-1" type="driving" level="false">
                <link>
                </link>
                <width sOffset="0.0" a="4.0" b="0.0" c="0.0" d="0.0"/>
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    </laneSection>
</lanes>
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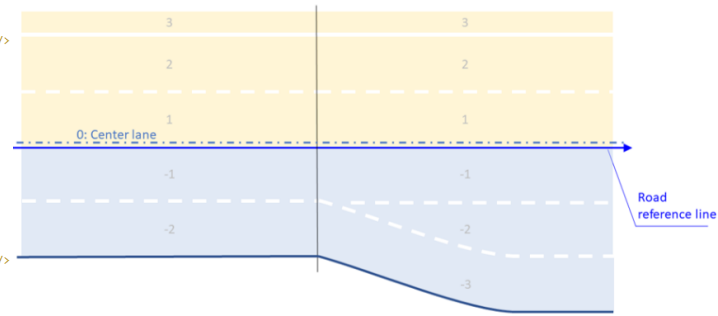

Figure: .xml example and road network (*)

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Criticality Evaluation of generated Scenarios

➢ **Temporal indicators** (*):

- Time to collision (TTC): Time until collision if vehicles continue present course at present rat rate
- Variants: Modified (MTTC), Time-to-accident (TTA)

➢ **Distance- and Deceleration-based indicators** (*):

- Proportion of Stopping Distance (PSD): Distance available to avoid collision
- Deceleration Rate to Avoid the Crash (DRAC): Breaking force needed to avoid collision

➔ Most measures relate criticality to collisions

(*) Mahmud, S. M. & Ferreira, Luis & Hoque, Md & Hojati, Ahmad „Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs“, IATSS Research 2017

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3

Scenario Generation Methods

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Knowlege-based Scenario Generation Methods

Intuition: Leverage expert domain knowledge to generate scenarios

Abstract algorithm

- **Step 1**: Set up constraints
  - Define a „world“: Formalize map, possible objects, possible traffic participants and their movements
- **Step 2**: Generate scenario
  - Option 1 - Optimization-based: Set up an optimization goal describing criticality of scenarios
  - Option 2 - Statistical: Leverage domain knowledge to define how to sample critical scenarios

Problems

1. The real world is complex and engineers & researchers imagination is limited
2. The process of defining and integrating domain knowledge is difficult and expensive

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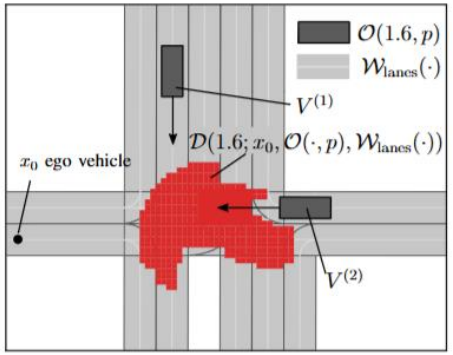
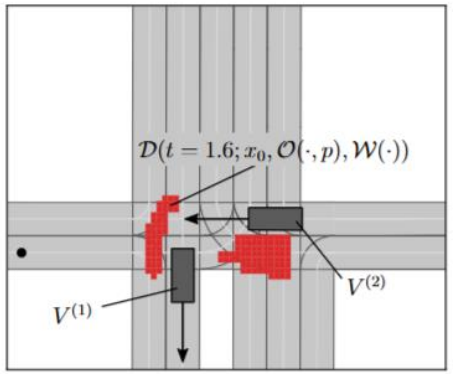
Example: Optimization-based Scenario Generation



(a) Initial scenario at time t=0



(b) Optimized scenario at t=end

Example method by Klischat et al., 2019 (*)

Intuition: Use driveable area as proxy for criticality

- Driveable area: For a given starting state, due to steering and speed, limited area is reachable
- Intuition: If there is less opportunities to drive, scenario is more difficult

Algorithm

- Define initial state (see (a))
- Define optimization problem minimizing driveable area while allowing for collision avoidance
- Use evolutionary algorithms to optimize the problem (see (b))

(*) M. Klischat and M. Althoff, "Generating Critical Test Scenarios for Automated Vehicles with Evolutionary Algorithms," *2019 IEEE Intelligent Vehicles Symposium*

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Data-driven Scenario Generation Methods

Intuition: Use available data to automatically learn to generate scenarios

Benefits: Less reliance on human engineering, and scalability

Problem: Available data might be limited or wrongly distributed (e.g. most data gathered in city A)

Idea 1: Use recorded traffic data

➢ Learn scenario distribution similar to actual data (and possible side goals such as criticality)

Idea 2: Use simulation runs of the ADAS system

➢ Adversarial scenario generation: Optimize for scenarios such that ADAS system fails

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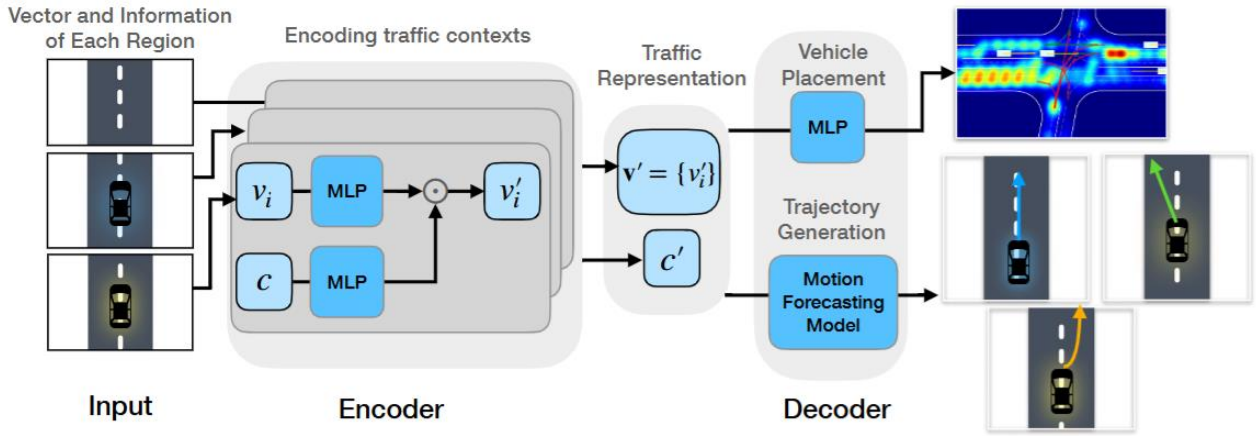
TrafficGen: Learning to Generate Traffic Scenarios (*)

Idea: Leverage existing scenario data to generate new scenarios



Source: (*)

- **Preprocessing**: Split map into regions
- **Training**: Mask out map regions in input; model has to predict them
- **Autoregressive** (step-by-step) model: In each prediction step 1 vehicle is added
- **Sampling**: Given an initial scenario, model augments it by adding more vehicles

(*) L. Feng, Q. Li, Z. Peng, S. Tan and B. Zhou, "TrafficGen: Learning to Generate Diverse and Realistic Traffic Scenarios“,
IEEE International Conference on Robotics and Automation (ICRA), 2023

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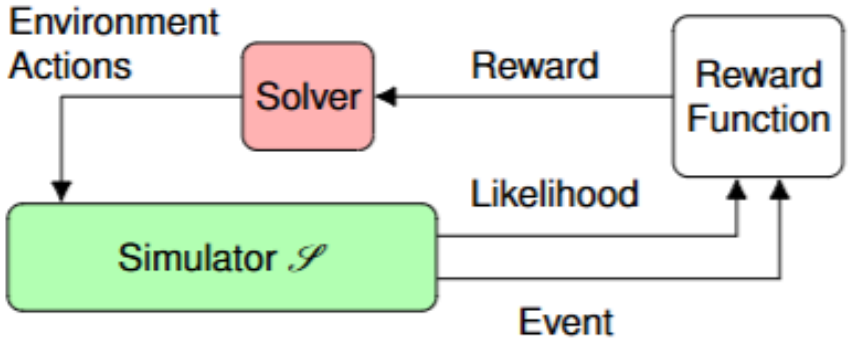
Adaptive stress testing (Koren et al. (*))

Intuition

➔Optimize a scenario such that the (ADAS) system under test fails



Source: (*)

Components

- Simulator (ADAS system): Output next step (e.g. break)
- Reward Function: 0 reward for found collision, negative reward for no collision
- Solver: Neural Network predicts actions of traffic participants (e.g. speed, direction)

➔ Optimize for non-negative reward using Deep Reinforcement Learning

(*) Koren et al., "Adaptive Stress Testing for Autonomous Vehicles„, *IEEE Intelligent Vehicles Symposium (IV)*, 2018

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LLMs for Scenario Generation

Problems of data driven methods

- Recorded data is limited
- Leveraging limitations of current ADAS system results in unrealistic testing

LLMs can access „natural“ format of language

➔This allows access to wide range of existing data

Examples:

- ➢ Crash reports
- ➢ In formalized scenario generation languages
- ➢ Legal specifications
- ➢ ….

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ChatScene: LLM-based Scenario Generation

Intuition: Use knowledge available in existing scenario specifications

- **Step 1**: Populate database, connecting descriptions to scenario description code snippets.
  - ➢ Description: „Ego is driving straight when car in front suddenly breakes“; Code snippet: see Figure
- **Step 2**: Leverage LLM to make up a new scenario
  - ➢ Prompt: „Provide one safety-critical scenario.“
- **Step 3**: Leverage LLM to generate texts relating to database.
  - ➢ Prompt: „{Few-shots snippets} Extract behaviour, geometry …“
  - ➢ Output: „Ego is driving straight when car in front suddenly breakes“;
- **Step 4**: Plug in code-snippets from Step 1

Scenic code:

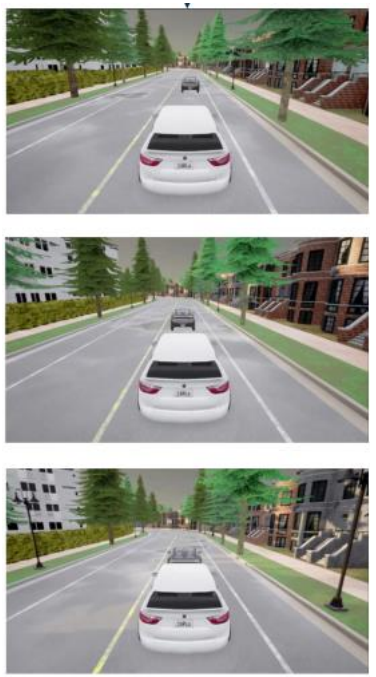
```
### Default Setting ###
…
model scenic.simulators.carla.model
EGO_MODEL = "vehicle.lincoln.mkz_2017”

### BEHAVIORS ###
behavior EgoBehavior():
   do FollowLaneBehavior(EgoSpeed)

behavior AdvBehavior(AdvSpeed):
   try:
      do FollowLaneBehavior(AdvSpeed)
   interrupt when withinDistanceToAnyObjs
         (self, AdvBreakingThreshold):
      take SetBrakeAction(1.0)

### GEOMETRY ###
lane = Uniform(*network.lanes)

### SPAWN POSITIONS ###
SpawnPt = OrientedPoint on lane.centerline
…
```



Source: (*)

(*) J. Zhang, C. Xu and B. Li, "ChatScene: Knowledge-Enabled Safety-Critical Scenario Generation for Autonomous Vehicles“, *IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 2024*

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Thoughts on Scenario Generation Method

- There is a vast variety of other scenario generation methods
- All shown approaches have their own strengths and weaknesses

- Modern and deployed scenario generation pipelines consider a mixture of said approaches
  - You should use available domain knowledge
  - You should use available gathered data

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Case Study: Regulation-based Scenario Generation

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Description

Goals

- Use real-word edge data (mostly cameras)
- Create virtual world (using game engine)
- Generate new scenarios for virtual world
- Evaluate ADAS (Autonomous driving systems) on those scenes in virtual world

Novel approach

- Use traffic rules to analyze what type of situations are tested in a given camera scene
- Use LLMs to integrate the capability of LLMs to work work with traffic rules

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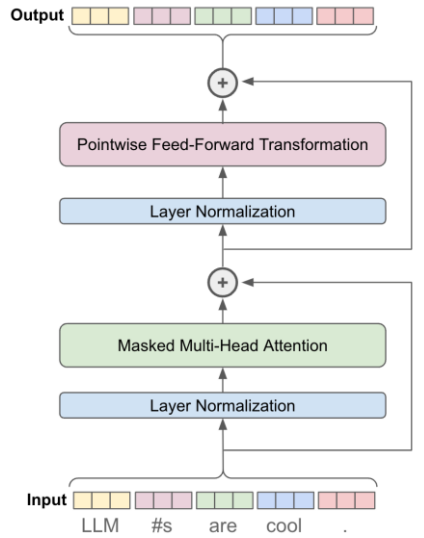
Background: Vision-LLMs

- **Standard LLM:**
  - Input: Text
  - Text gets transformed into tokens (pure happiness -> pure_ happi ness_)
  - Each token is represented as vectors and then fed into transformer



((https://cameronrwolfe.substack.com/p/decoder-only-transformers-the-workhorse)

- **Vision-LLM:**
  - Input: Text + Interleaved Images
  - Patches (parts of images), are transformed into vector representations using vision encoders
  - A projection is trained such that vision vectors are in same vectorspace as text vectors

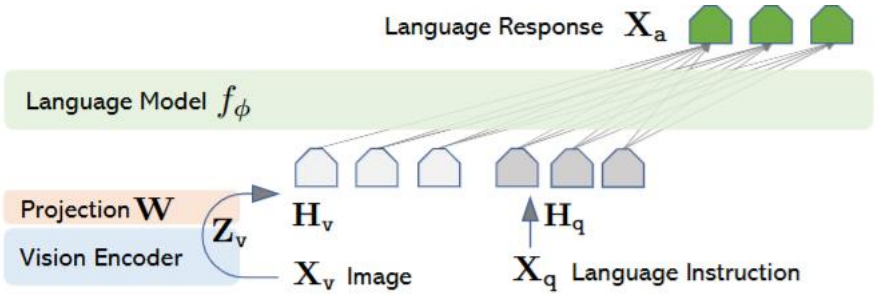


Figure. LLaVA: Large Language and Vision Assistant
(Liu, H., Li, C., Wu, Q., & Lee, Y., Visual Instruction Tuning. *Neurips, 2023)*

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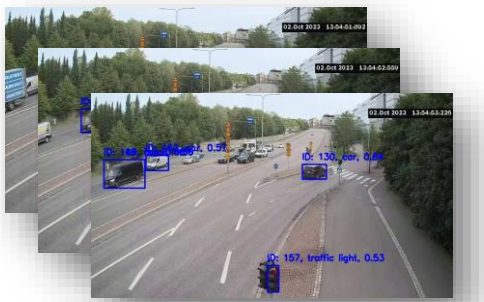
Overview Architecture

Traffic Rules

§ 1. Cars have to stop at crosswalks
§ 1. Cars have to stop at crosswalks
§ 1. Cars have to stop at crosswalks if a predestrian crosses.
§ 2. Vehicles must come to a complete stop at red traffic lights.
§ 3. Vehicles must come to a complete stop at stop signs.
§ 4 …

Scenarios



1. Law Ingestion Module

```
[
  {
     "law_id": 1,
     "applicable concepts": ["car", "pedestrian", "crosswalk"]
     "description": "A typical testing case for …"
    …
  }
  …
]
```

2. Scenario Analysis Module

The scenario is during daylight and shows a car that turns right and drives over a crosswalk …

3. Law Retrieval Module

§ 1 & § 2 are retrieved.

4. Law Application Module

§ 1. is applicable but not tested (no pedestrian)
§ 2. is tested (traffic light is red)

5. Coverage Quantification Module

§ 1: 0 times tested
§ 2: 100 times tested
§ 3: 50 times tested

6. Scenario Modification Module

Add a pedestrian to the crosswalk to test whether ego car 130 adheres to § 1.

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Challenges

- **Challenge 1: Scenarios are complex objects.**
  - Example: Adding a car requires to define its trajectory in the form of a sequence of (latitude, longitude) tuples. E.g., using 60fps, up to 180 tuples need to be generated ➔ LLMs struggle to generate such complex data objects
  - Solution: Use tools to translate from high-level modifications (e.g. „add a pedestrian“) to low-level scenario descriptions

- **Challenge 2: Laws are complex objects**
  - Not all laws are relevant to test ADAS systems, e.g. „The seatbelt should be fastened.“
  - Not all laws are equally important: Safety-critical laws are more important
  - Court cases show that traffic rules are not always unambiguous

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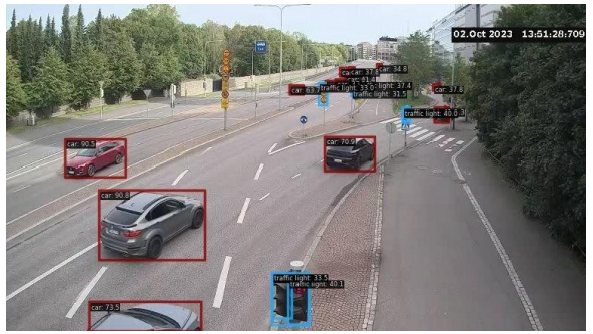
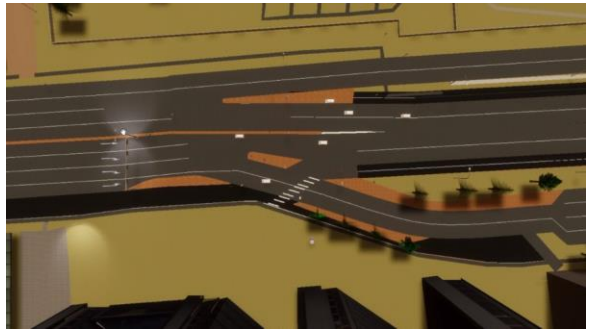
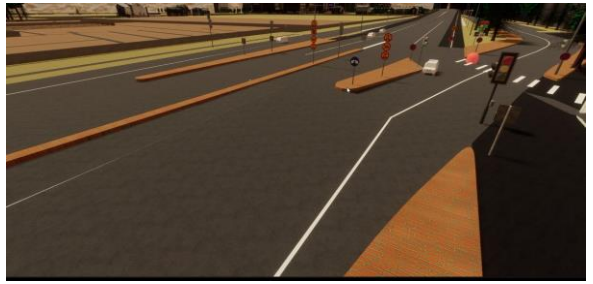
Example view



➔ Driving scene from camera perspective



➔ Top-down view of virtual environment



➔ Added pedestrian (in red)

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5

Conclusion

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Takeaways

- **Critical scenarios are rare**

➔ Scenario generation is an essential tool to overcome sparsity of critical scenarios

- There exists a vast literature of scenario generation
  - ➢ Different methods have unique strengths and weaknesses
  - ➢ Realistic pipelines leverage multiple methods

- LLMs provide new opportunities, allowing to integrate language-based knowledge into the scenario generation process

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Literature Suggestions

[1] W. Ding, C. Xu, M. Arief, H. Lin, B. Li and D. Zhao, "A Survey on Safety-Critical Driving Scenario Generation—A Methodological Perspective„, in *IEEE Transactions on Intelligent Transportation System, 2023*

[2] C. Cui *et al*., "A Survey on Multimodal Large Language Models for Autonomous Driving“, *IEEE/CVF Winter Conference on Applications of Computer Vision Workshops (WACVW), 2024*

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Questions?

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