Generating Safety-Critical Driving Scenarios for the Design of the CAV Proving-Ground - using domain knowledge, causality, and large language models

Ding Zhao (PI) (https://orcid.org/0000-0002-9400-8446)

FINAL REPORT

September 18, 2024

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, under [grant number 69A3552344811] from the U.S. Department of Transportation's University Transportation Centers Program. The U.S. Government assumes no liability for the contents or use thereof.

Problem

Autonomous vehicles (AVs) and connected autonomous vehicles (CAVs) have witnessed significant achievements recently, and the usage of artificial intelligence (AI) has empowered this field. However, a paramount challenge is the safety evaluation of the AI-based system. While traditional autonomous driving systems, for example, rule-based systems, could be thoroughly evaluated by manually designed testing scenarios, AI-based systems are hard to evaluate and it is challenging to collect sufficient critical scenarios to conduct the evaluation. Consequently, realistic critical scenario generation algorithms have been investigated by academia and industrial companies.

The goal of this project is to study the critical scenario generation, design a testing framework, and use the generated scenarios to help the design of autonomous vehicle proving ground infrastructure aiming at the connected and autonomous vehicles evaluation. These scenarios should reflect the critical factors and risky driving conditions in the real world. Therefore, this objective encompasses the utilization of real-world datasets and the reasoning ability of large language models (LLMs). Specifically, the primary goals include:

1. Building a simulation environment. This simulation environment is capable of replaying the generated critical scenario and the evaluation of self-driving algorithms.
2. Develop a critical scenario generation algorithm, incorporating the reasoning ability of LLM and domain-specific knowledge of driving and road conditions. Utilize the LLMs to analyze the initiating critical factors and the responsibility for the crashing.
3. Use the proposed algorithm to establish a dataset that reflects realistic critical scenarios and verify the value of the dataset with comprehensive testing.
4. Summarize the road conditions and key factors associated with critical scenarios and the information that is valuable for proving ground design.
5. Establish a testing framework for connected and autonomous vehicle evaluation.

Methodology and findings

For the first task, we implemented a simulation interface based on ESMINI [1], which achieved highly efficient parallel running over 3000 scenarios. The simulation will be used together with state collection, customized action, algorithm training, and evaluation.

For the second task, we have achieved the critical scenario generation based on vision language models (VLMs). Previously we completed the literature review on VLM-based critical scenario generation in autonomous driving tasks [2]. We used the National Highway Traffic Safety Administration (NHTSA) crash dataset [3] from the Crash Investigation Sampling System as the source of realistic critical scenarios, which includes textual description, structured numerical data, and image representation. We proposed and implemented a novel method that translates the crash dataset into standard scenario representation, which can be incorporated into popular simulation environments. Specifically, we utilized the VLM to identify the key road conditions and road users' behavior to reconstruct the crash scenario in the OpenScenario format. To improve the reconstructed scenario of this data-driven scenario generation method, proposed a framework that leverages the reasoning ability of VLM and LLM and proposed to incorporate domain knowledge in both textual and numerical manners. The proposed algorithm has the potential to translate the police crash record into a structured format with a simple description and make the real-world crash data accessible for the training and evaluation of self-driving algorithms. Specifically, we proposed a 3-level pipeline to achieve this goal. In the first stage, we used VLM to identify the key road conditions, for example, a highway interchange, or a 5-way intersection, and generate a standard format road description, which is further represented in the OpenDrive format. In the second stage, we used VLM to analyze the behavior of road users and generate trigger and action pairs to reconstruct the crash scenario. In this stage, a detailed description is first generated by VLM based on the image, numerical, and textual description of the crash. Then this description is used as a reference for trigger and action selection and parameter generation. By combining the trigger and action types and parameters, our method can create an OpenScenario format critical scenario based on the real-world crash record. To enhance the quality of the scenario, we further incorporated domain knowledge, causal analysis powered by LLM [4], and prior knowledge of traffic rules [5].

For the third task, we have created a realistic critical scenario dataset by applying the algorithm implemented in task 1 to generate the realistic critical scenarios into OpenScenario format. The generated scenarios are not the exact reconstruction of the crash record in the standard format, but critical scenarios with the key factors that lead to the given crash record. We verified the quality of the reconstructed critical scenario dataset by training self-driving algorithms using non-critical scenarios and the generated critical scenarios. The value of our dataset is shown by the performance improvement under critical scenarios of the self-driving algorithm trained with the generated dataset.

For the fourth task, we have summarized the major types of road conditions and traffic conditions that are associated with higher risks of crashes. This is achieved by data analysis of the NHTSA crash dataset and the reasoning ability of VLM. The road network summary has the potential to provide guidance of the proving ground road design, while the traffic condition summary has the potential to guide test critical scenario design.

For the fifth task, we designed a two-fold evaluation framework. First, the evaluation of the self-driving algorithm will be conducted under selected 100 testing critical scenarios, including unprotected turn, car following, multi-event crash, and other typical scenarios. The performance is summarized as the evaluation result. Second, we are building a virtual town in the simulation environment, which allows a large number of agents controlled by respective self-driving algorithms. The performance of the algorithms will be summarized regarding the collision rate and other indices after accumulating a certain running time or mileage in the simulation environment.

To summarize, we have built the simulation environment, developed a novel realistic and critical scenario generation algorithm, created a critical scenario dataset, and established the testing framework in a simulation environment. We also built a town in the simulation environment which allows thorough evaluation of connected and autonomous driving algorithms under comprehensive critical scenarios.

Conclusions

We proposed a novel framework to create realistic critical scenarios based on real-world crash records. Our method has the potential to translate various kinds of real-world traffic records into a standard structured format. Our contribution summary: 1) we proposed and implemented a method to generate critical scenarios based on unstructured data and created a dataset, and 2) based on the dataset, we established a testing framework in the simulation environment.

References

[1] https://github.com/esmini/esmini
[2] Tan, Shuhan, et al. "Language conditioned traffic generation." Conference on Robot Learning 2023
[3] https://crashviewer.nhtsa.dot.gov/
[4] Ding, Wenhao, et al. "Causalaf: Causal autoregressive flow for safety-critical driving scenario generation." Conference on robot learning. PMLR, 2023.
[5] Ding, Wenhao, et al. "Semantically adversarial driving scenario generation with explicit knowledge integration." arXiv preprint arXiv:2106.04066 1 (2021).