Project Proposal: Safety Evaluation and STPA-Based Hazard Analysis of Autonomous Vehicles on Highways with Reduced Lane Widths

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Abstract

This project aims to evaluate the safety of autonomous vehicles (AVs) on highways with reduced lane widths by reproducing the results of D'Souza et al. (CoDIT 2024) [1], which use a dynamic bicycle model, Model Predictive Control (MPC), and a collision metric. The study is extended using a System-Theoretic Process Analysis (STPA) to identify hazards and unsafe control actions specific to narrow-lane overtaking. One STPA-derived hazardous scenario will then be integrated into the MATLAB simulation to assess its effect on collision risk. The work combines control modelling, simulation, and safety analysis to provide a more realistic evaluation of AV behavior under infrastructure constraints.

1 Introduction

Reducing highway lane widths has been proposed as a means to increase traffic capacity, based on the assumption that autonomous vehicles (AVs) can operate with higher precision than human drivers. The paper [1] investigates this idea using a dynamic bicycle model combined with Model Predictive Control (MPC) and a collision risk metric based on Virtual Boundaries (VBs).

However, the original study only considers nominal system behavior and does not incorporate hazardous scenarios, degraded sensing, or unsafe control actions. This project proposes to reproduce the baseline simulation from [1] and extend it through a focused STPA hazard analysis, followed by implementation of one hazard in MATLAB to assess its effect on collision risk.

2 Objectives

The proposed project consists of three main objectives:

- **Reproduce the original simulation model**: Implement the dynamic bicycle model and MPC based simulation presented in [1], simulate the overtaking scenario, vary lane widths from 4.0 to 3.0 m, and compute the Collision Metric.
- **Conduct a focused STPA analysis**: Identify system-level losses, hazards, safety constraints, and unsafe control actions (UCAs) associated with AV overtaking under reduced lane widths. As in the paper, V2V communication is assumed ideal.
- **Simulate one STPA hazard**: Integrate a selected hazardous scenario (e.g., steering delay, lateral perception bias, or incorrect lane-width estimation) into the MATLAB model, then compare its impact on the Collision Metric against the nominal case.

3 Methodology

3.1 Dynamic Bicycle Model and MPC

The project will not reproduce the exact dynamic bicycle model used in [1]; instead, it will implement a **similar dynamic bicycle model** available in the MATLAB *MPC Virtual Lab* [3]. This model is based on the same principles as the bicycle model referenced in Rajamani's *Vehicle Dynamics and Control* [2] and provides sufficient fidelity for reproducing the safety trends studied in the paper. The MPC controller will track the planned overtaking trajectory while enforcing steering and lane-keeping constraints:

- Steering angle: $\pm 30^\circ$
- Steering rate: $\pm 15^\circ$/s
- Lane boundaries defined by the selected lane width

3.2 Baseline Reproduction

The nominal simulation includes:

- AV_a: The vehicle maintains a nominal cruising speed but adaptively reduces its velocity when AV_b enters its Virtual Boundary safety margins,
- AV_b: MPC-controlled overtaking vehicle,
- Lane widths: 4.0, 3.75, 3.50, 3.25, 3.0 m.

The Collision Metric C is computed using the VB-based formulation provided in [1].

3.3 STPA Hazard Analysis

The STPA procedure includes:

- Defining system purpose, losses, and hazards related to reduced lane width;
- Building a simplified control structure containing MPC, steering actuator, vehicle dynamics, and perception feedback;
- Identifying 3 to 5 unsafe control actions (UCAs) relevant to lane-change and overtaking;
- Deriving causal scenarios and selecting one for implementation.

3.4 Hazard Integration

A selected hazard will be introduced into the simulation. Examples include:

- Steering actuation delay,
- Lateral position bias in perception,
- Incorrect controller assumption about lane width,
- Degraded sensor accuracy (e.g., noisy or biased lateral position measurement).

The impact on $C(t)$ and maximum collision risk will be compared to nominal results.

4 Expected Outcomes

- Successful reproduction of the collision-risk trends reported in [1].
- A concise STPA identifying narrow-lane-related hazards and UCAs.
- A simulation illustrating how a specific hazard affects safety in reduced-width scenarios.
- Insight into how infrastructure constraints amplify the impact of unsafe control actions.

5 Deliverables

- MATLAB/Simulink models (baseline and hazard-enhanced),
- Technical report including all STPA analysis (hazards, UCAs, causal scenarios),
- Presentation slides summarizing objectives, methodology, and results.

References

[1] J. D'Souza, K. Burnham, and J. Pickering, "An Investigation into the Safety of Autonomous Vehicles on Highways with Reduced Lane Widths," in *Proc. CoDIT*, 2024.

[2] R. Rajamani, *Vehicle Dynamics and Control*, Springer, 2011.

[3] MathWorks, "Model Predictive Control (MPC) Virtual Lab," MATLAB Central File Exchange, 2024. Available: `https://fr.mathworks.com/matlabcentral/fileexchange/158356-model-predictive-control-mpc-virtual-lab`