Reachability-based confidence-aware probabilistic collision detection in highway driving

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SAFE-UP

MFTS, Dresden, Dec 2022

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Background

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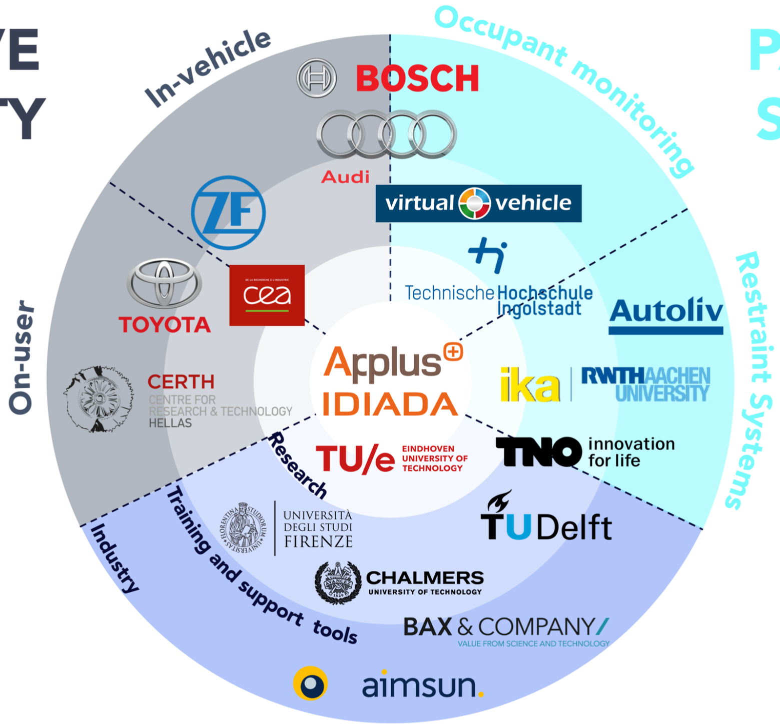
ACTIVE SAFETY

PASSIVE SAFETY



FUTURE SCENARIOS

SAFE-UP aims to proactively address the upcoming safety challenges based on 3 key pillars: i) future safety-critical scenarios ii) new safety technologies and iii) novel safety assessment methodologies.

TUD related subtasks:
Safety-critical scenario identification

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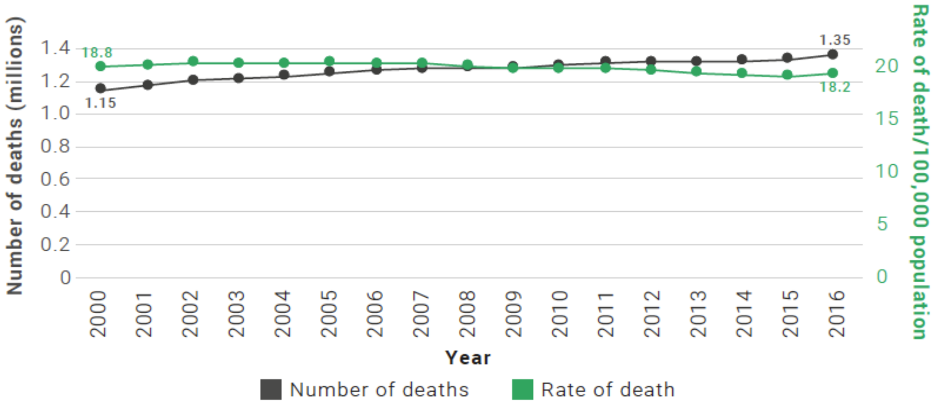
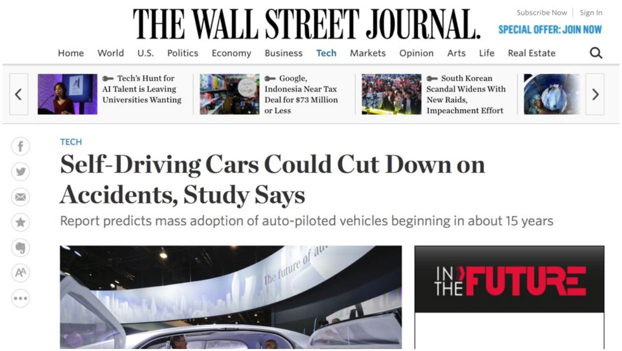
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement 861570.

Motivation

Safety is of pivotal importance for (automated) driving.

Road deaths from WHO

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TECH

Self-Driving Cars Could Cut Down on Accidents, Study Says

Report predicts mass adoption of auto-piloted vehicles beginning in about 15 years


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Self-driving cars

Google's self-driving car in broadside collision after other car jumps red light

Autonomous Lexus SUV could not prevent accident that caved in front and rear passenger-side doors, setting off airbags and forcing it to be towed away


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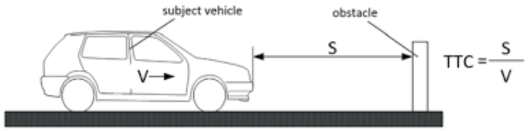
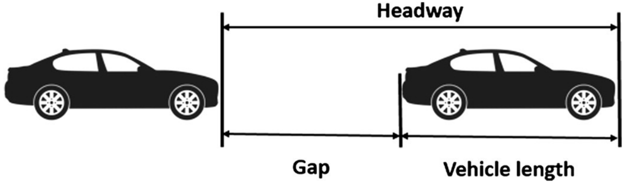
Tesla says autopilot involved in second car crash

Motivation

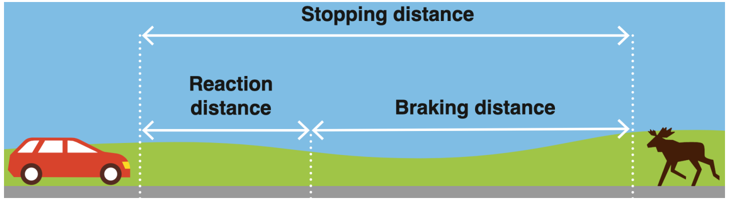
- Time based
  - Time to Collision (TTC)



  - Time to Headway



- Distance based
  - Stopping distance



One-dimensional and deterministic metrics cannot address motion uncertainties.

How to address motion uncertainties?
How to ensure safety?

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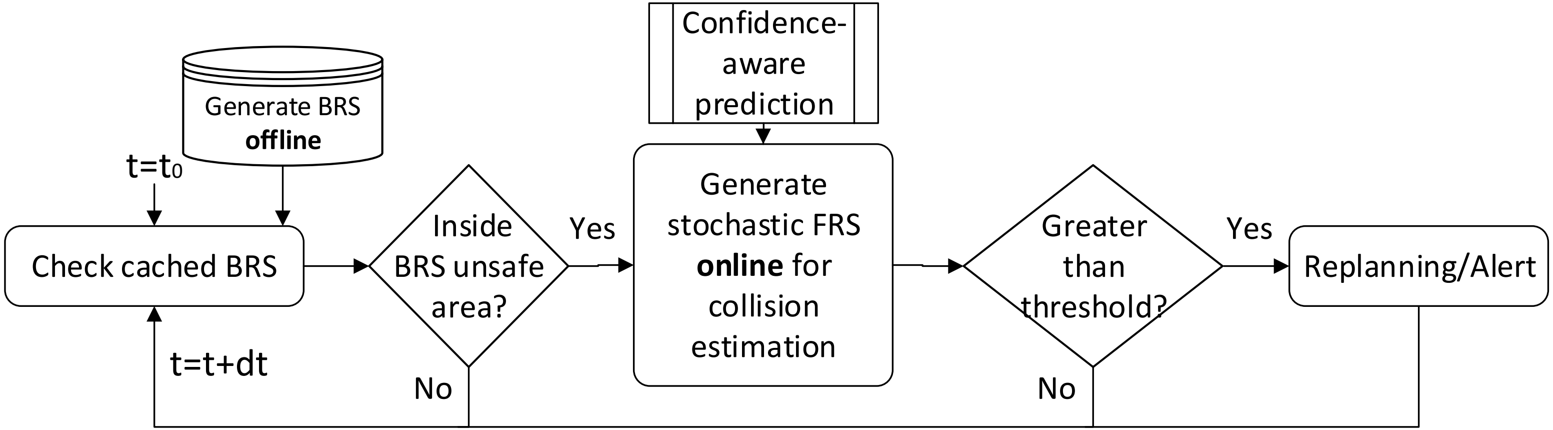
How to ensure safety? *How to address uncertainties?*

Goal

To develop a two-level **reachability-based confidence-aware** collision detection framework



BRS: Backword reachable set
FRS: Forward reachable set
Stochastic FRS, where each state has assigned a possibility
Assume ego has a planned trajectory

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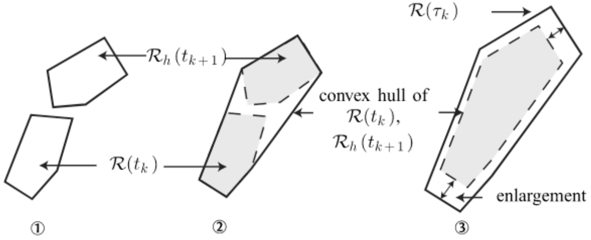
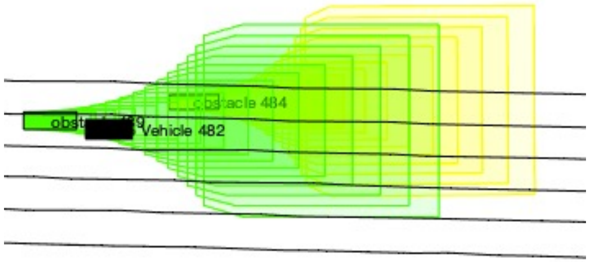
- **Forward Reachable Set (FRS)**
  (M. Althoff from TU Munich, Germany)
  - Consider max acc capacity
  - Formal safety verification





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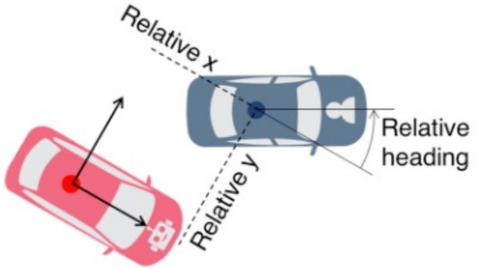
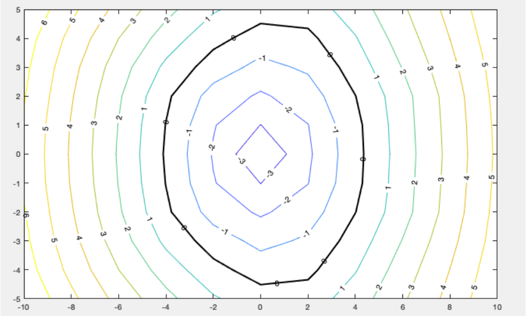
- **Backward Reachable Set (BRS)**

  (C. Tomlim from Berkeley, USA)

  - Pursuit-evasion game -> Hamilton Jacobi partial differential equation (HJ PDE) -> Solve PDE to check if crash occurs
  - Offline computation by discretising states: speed, position, and angle
  - Online use: a look-up table
  - Formal safety verification



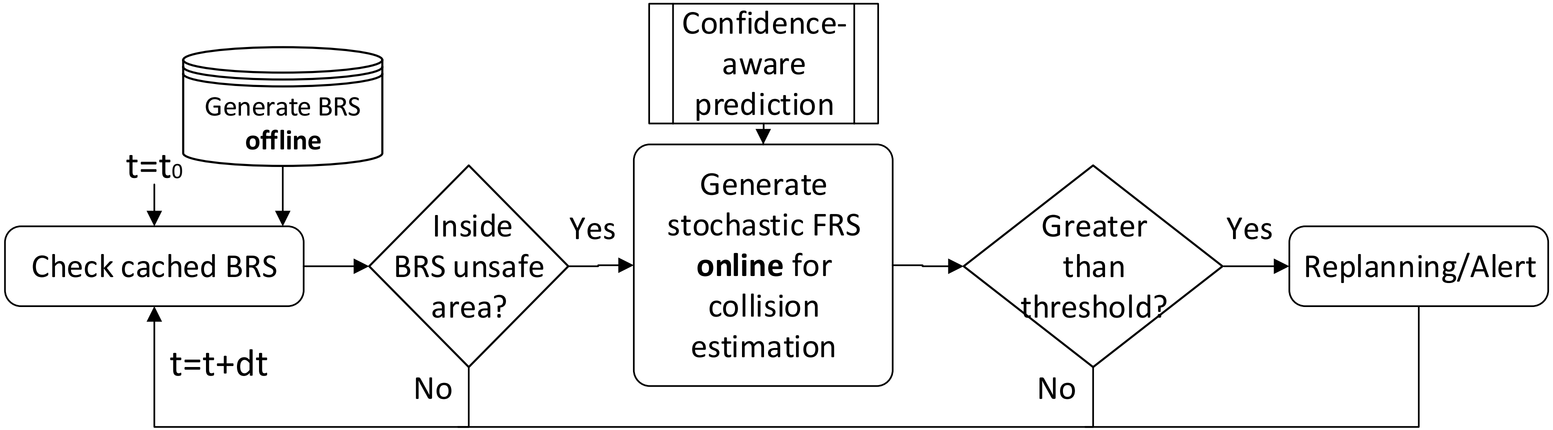


Sliced zero-level BRS subset, within which the sur vehicle can hit the ego (origin)

BRS is still over conservative due to the worst interaction assumption.

Goal

To develop a two-level **reachability-based confidence-aware** collision detection framework



BRS: Backword reachable set

FRS: Forward reachable set

Stochastic FRS, where each state has assigned a possibility

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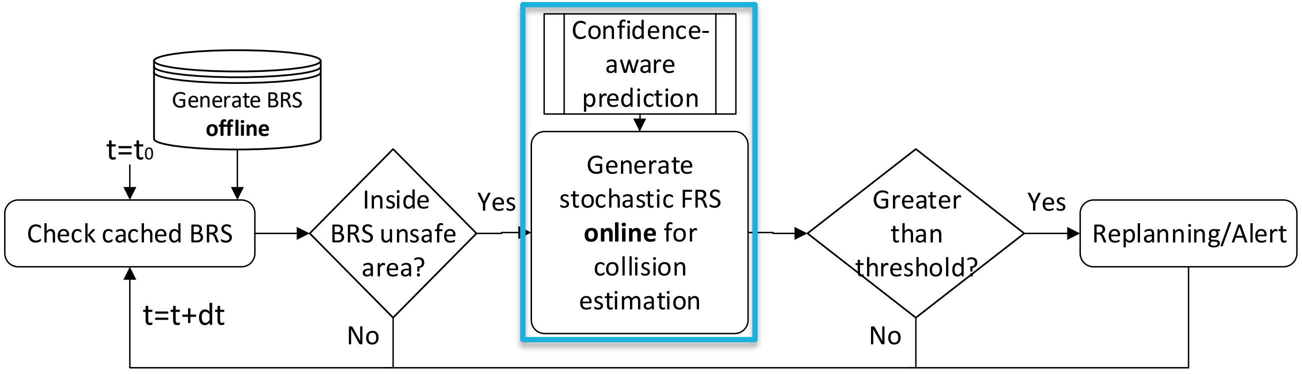
Goal

To develop a two-level **reachability-based confidence-aware** collision detection framework



- **Key components** for stochastic FRS
  - State transition matrix (Base)
  - Learning-based multi-modal prediction (Input)
  - Confidence-aware concept (Infuse to the input prediction)

State transition matrix Φ Althoff et al. (2010)

- Discretised time and state $p_i(k)$
- Deterministic heuristic rules for discretised input probability (Markovian)

$$\Phi_{ji} = \sum_{u \in \mathcal{U}} \Phi_{ji}^{u}$$

- State transition $\mathbf{p}(k+1) = \Phi \cdot \mathbf{p}(k)$

offline

Real vehicle motions are not Markovian! The real control input not only depends on current state, but also previous states and sur environment

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Multi-modal prediction to determine input probability for Φ

- Non-Markovian process, using previous tracks for prediction
  - A multi-modal **input** predictor (variation of previous work, Wang et al., 2022)

- Output probabilistic input distribution at each predicted time step, then do integrals to calculate $\Phi^{u}_{ji}(k)$

$$\Phi_{ji}(k) = \sum_{u \in \mathcal{U}} \Phi^{u}_{ji}(k)$$

$$\mathbf{p}(k+1) = \Phi(k) \cdot \mathbf{p}(k)$$

online

Results largely depend on the prediction accuracy!

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Wang, et al. " Probabilistic Risk Metric for Highway Driving Leveraging Multi-Modal Trajectory Predictions." *IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 10, pp. 19399-19412, Oct. 2022*

Confidence-aware prediction

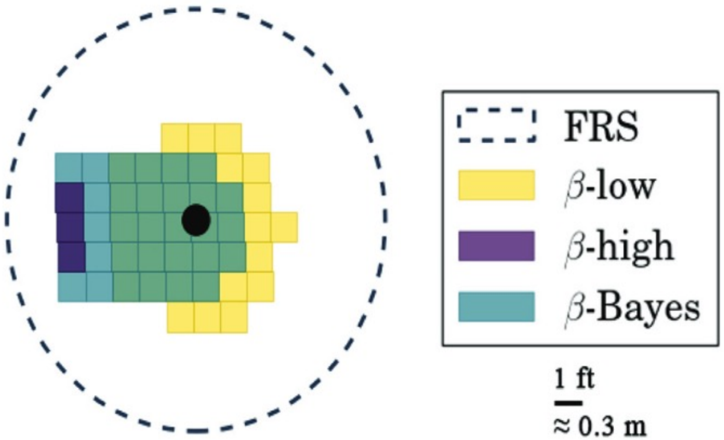
- A Bayesian belief vector for different distributions

Single normal distribution

↓

Multiple confidence-aware normal distributions

$$\boldsymbol{\beta} = [1/2, 1, 2]$$
$$b^0(\boldsymbol{\beta}) = [1/3, 1/3, 1/3]$$

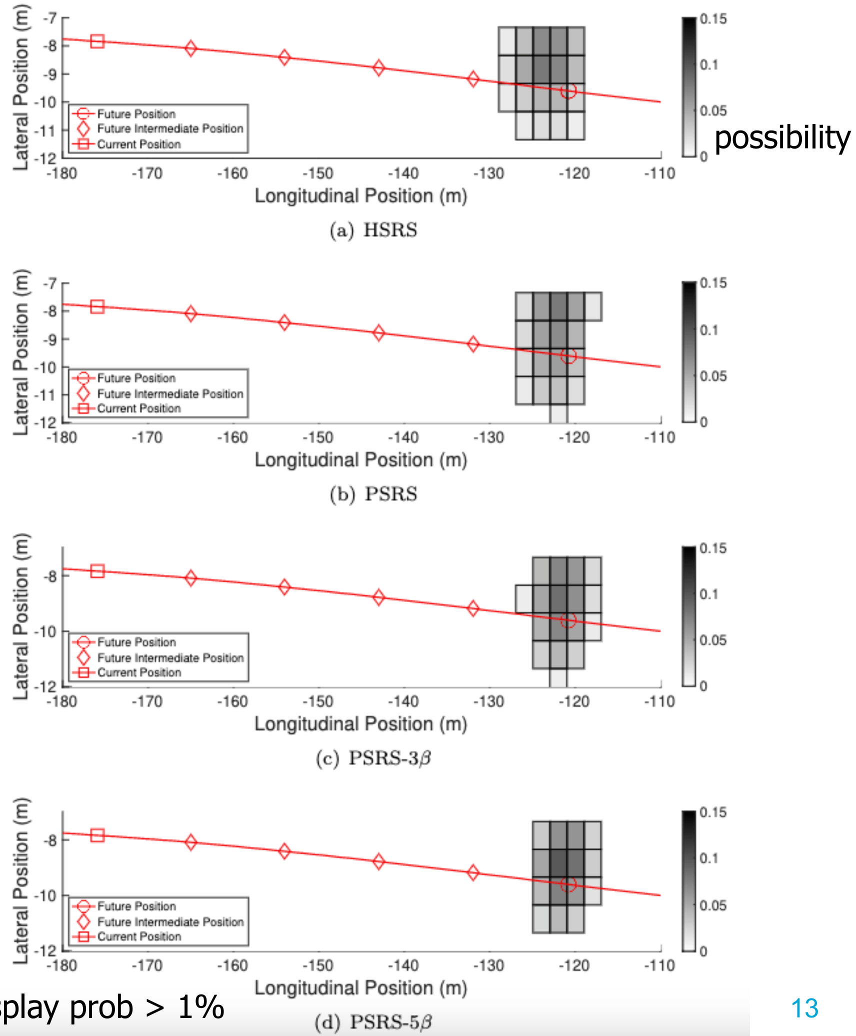


Confidence-aware Q-value pedestrian prediction (Fridovich-Keil et al.,2020)

- To address the **predictor performance**, the belief vector is updated with posterior estimation

Results: Stochastic FRS

HSRS: Stochastic FRS via heuristic rules (baseline)
PSRS: Prediction based stochastic FRS
PSRS-3β: Prediction based stochastic FRS using 3β
$$\boldsymbol{\beta} = [1/2, 1, 2]$$
PSRS-5β: Prediction based stochastic FRS using 5β
$$\boldsymbol{\beta} = [1/3, 1/2, 1, 2, 3]$$
(Predict 5 time steps in 2 seconds)



(a) HSRS

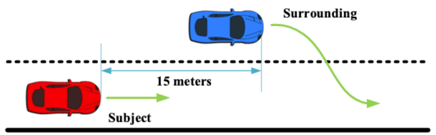
(b) PSRS

(c) PSRS-3β

(d) PSRS-5β

*only display prob > 1%

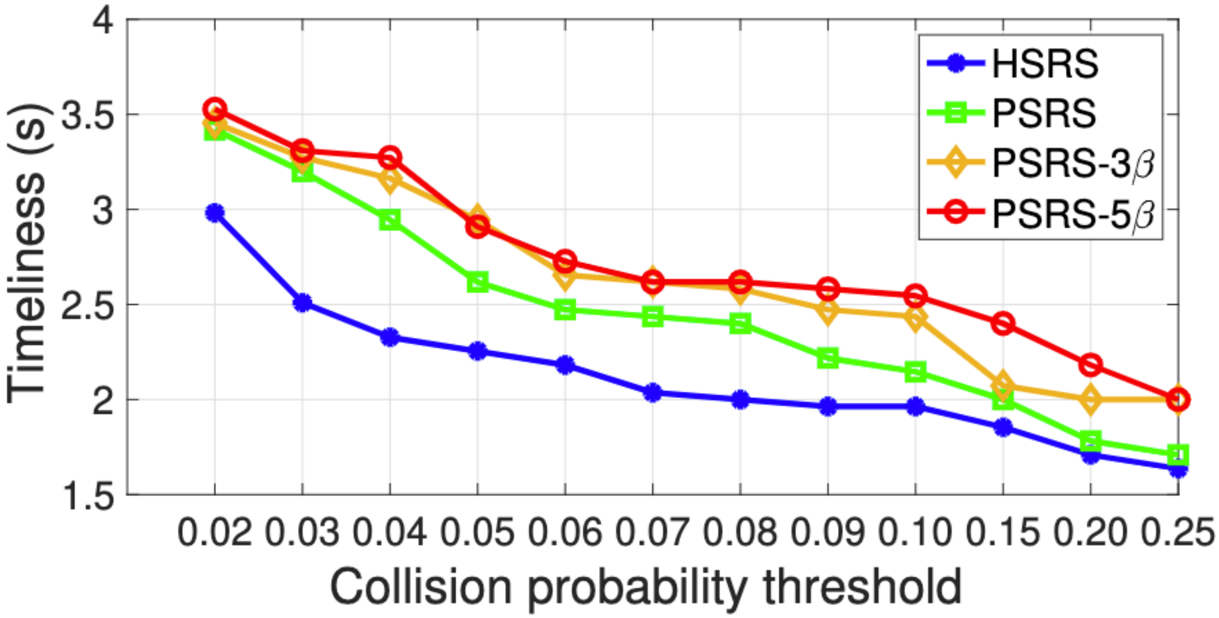
Results: Stochastic FRS



Simulated risky cut-in events

V ~ [20, 35]

33 out of 256 crash cases



Average performance for 33 crash events with different thresholds. Timeliness is the time the crash occurs after the collision probability reaches the threshold.

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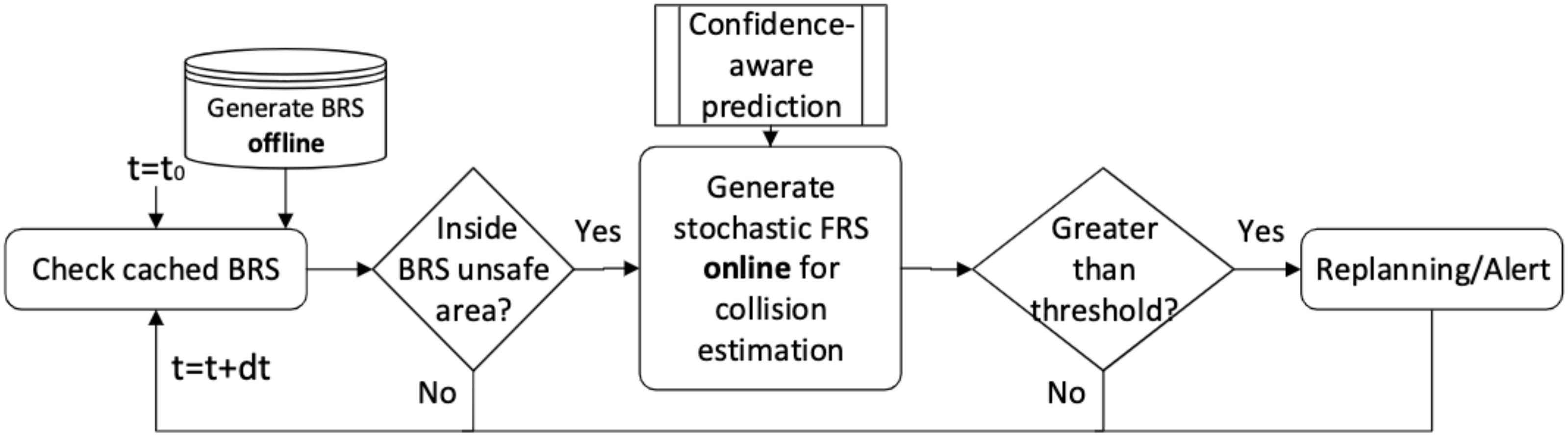
Results: Integrated framework



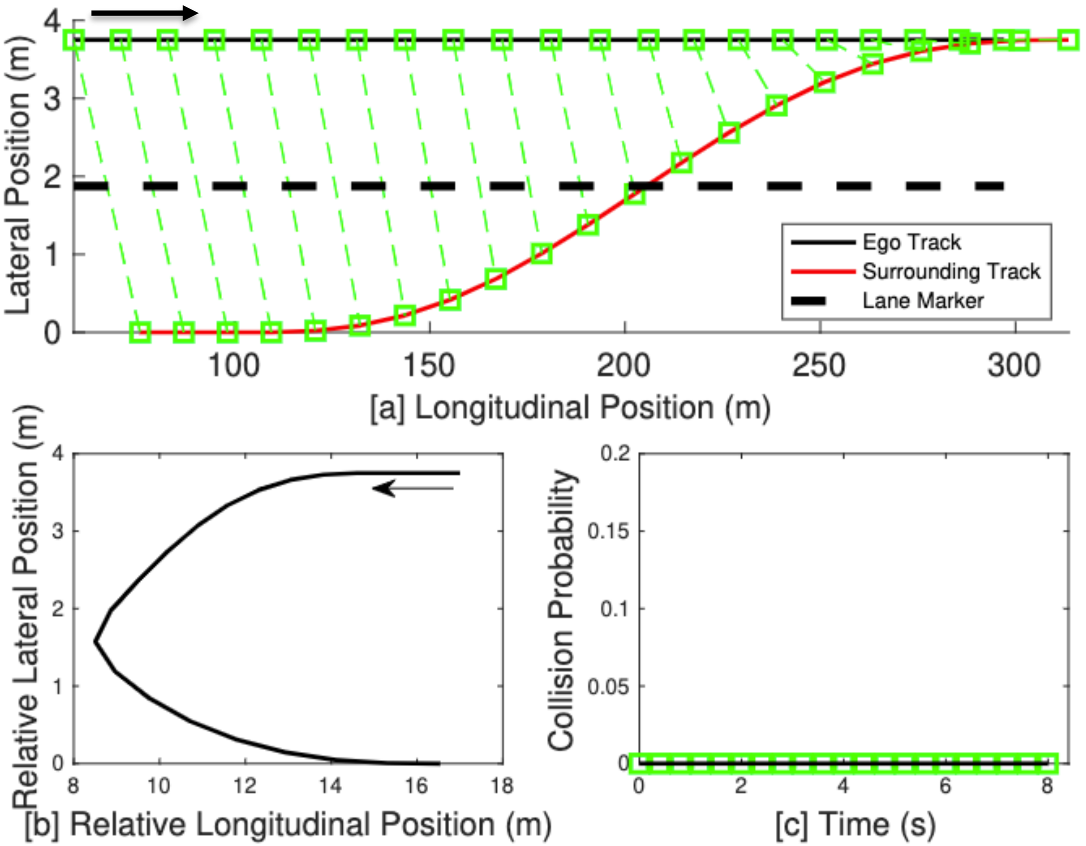
Validate the proposed collision detection framework in both risky and non-risky events

Results: Integrated framework

Simulated cut-in non-risky event

V_sub = 30 m/s, V_sur = 28 m/s

Green: theoretically safe by the BRS.



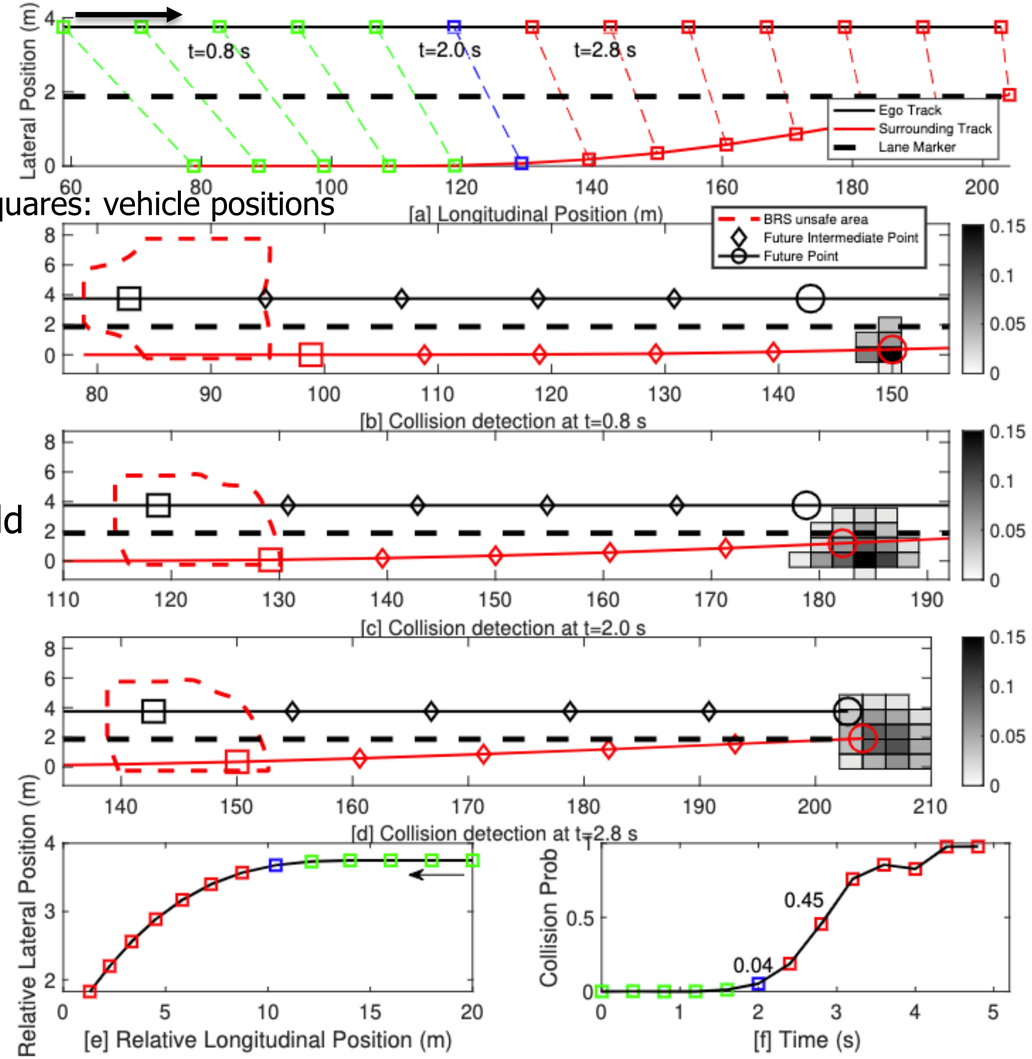
*dash lines connect vehicle positions at the same time step

Results: Integrated framework

Simulated cut-in risky event
(lead to crash at 5 seconds)

V_sub = 30 m/s, V_sur = 25 m/s

squares: vehicle positions



Green: theoretically safe by the BRS.

Blue: collision probability below a threshold (0.05 in this case).

Red: above the threshold. Unsafe.

*only show the stochastic FRS at the last prediction time step for convenience

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Summary

1. Developed a two-level reachability-based framework for collision detection
   – Safety can be ensured in non-risky events

2. To improve collision probability estimation, established a prediction-based confidence-aware stochastic FRS.

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Wang, et al. "Prediction-Based Reachability Analysis for Collision Risk Assessment on Highways." *IEEE Intelligent Vehicles Symposium* (2022).

Future work

1. *Implement the proposed safety assessment approaches for real-world test. Further simplify the computation of stochastic FRS.*

2. *The risk assessment is for posterior analysis. Further investigate the integration of motion planning and risk assessment*

Khaled Alaa, et al. “Probabilistic Risk Assessment for Chance-Constrained Collision Avoidance in Uncertain Dynamic Environments.” submitted to *ICRA 2023*.

Thanks for listening!

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Goal

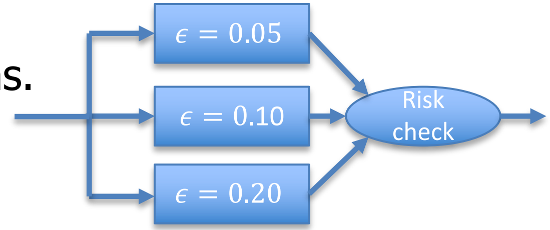
Use risk assessment for safer and more efficient motion planning.

- A scenario-based chance-constrained motion planner (de Groot et al., 2021)
  - with a parameter: risk upper bound
  - the bound is not tight

Upper Bound	Max CP
$\epsilon = 0.05$	0.0094
$\epsilon = 0.1$	0.0456
$\epsilon = 0.2$	0.0727

A robot shares dynamic environments with 6 pedestrians.

Hybrid $\epsilon = \{0.05, 0.1, 0.2\}$	0.0454



1) Plan three trajectories in parallel
2) Do one-shot risk check (Simply integrate prob density func for collision estimation)
3) Pick the least conservative plan as long as its risk below the CP threshold. <0.05

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Khaled Alaa, et al. "Probabilistic Risk Assessment for Chance-Constrained Collision Avoidance in Uncertain Dynamic Environments." submitted to *ICRA 2023*.

Probabilistic Risk Assessment for Chance-Constrained Collision Avoidance in Uncertain Dynamic Environments

Khaled Alaa, Oscar de Groot, Xinwei Wang, Jens Kober, and Javier Alonso-Mora

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