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FORESEEN Project

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FORmal mEthodS for attack dEtEction in autonomous driviNg systems

Statistical Model Checking for the Analysis of Attacks in Connected Autonomous Vehicles

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1. Introduction

- **Cyber-Physical Systems** (CPSs) are characterized by cooperating hardware and software components, connected with the external world. (Smart Grids, Transportation Systems, Manufacturing, Energy Systems, IoTs etc…)
- **Cybersecurity** is a relevant activity in CPSs. Examples of attacks on CPSs could be on sensors, actuators or controllers, or even on the communication or computing components.
- Modern **autonomous vehicles** are highly computerized CPSs, thus providing a wide range of access points for a potential attacker, who could gain full control over the vehicle and turn off all safety measures installed on it.

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Introduction

In this work, we show

- The use of statistical model checking for the analysis of attacks in connected autonomous vehicles
- The use of timed automata to model physics, system behavior and cyber-attacks
- The framework can be used to model uncertainties and stochastic behaviors

Related works

Examples of SMC in CPS:

- To gauge the performance of electrical converters [1]
- To validate the safety properties of autonomous lanes switching on a motorway [2]
- To validate a Bayesian perception framework used to detect potential collision at crossroads [3]

On platooning:

- Platooning is a driving strategy where multiple vehicles travel closely together in a coordinated group [4]
- The advent of 5G has enabled centralized approaches for vehicle coordination [5]

[1] M. Novak, U. M. Nyman, T. Dragicevic, and F. Blaabjerg, “Statistical model checking for finite-set model predictive control converters: A tutorial on modeling and performance verification,” IEEE Industrial Electronics Magazine, vol. 13, no. 3, pp. 6–15, 2019
[2] M. Barbier et al, “Validation of perception and decision-making systems for autonomous driving via statistical model checking,” in 2019 IEEE Intelligent Vehicles Symposium (IV), p. 252–259, June 2019.
[3] B. Barbot, B. Bérard, Y. Duplouy, and S. Haddad, “Statistical model-checking for autonomous vehicle safety validation,” in Conference SIA Simulation Numérique, (France), Société des Ingénieurs de l’Automobile, Mar. 2017.
[4] C. Bergenhem, S. Shladover, E. Coelingh, C. Englund, and S. Tsugawa, “Overview of platooning systems,” in Proceedings of the 19th ITS World Congress, (Vienna, Austria), pp. 22–26, Oct. 2012.
[5] C. Quadri, V. Mancuso, M. A. Marsan, and G. P. Rossi, “Edge-based platoon control,” Computer Communications, vol. 181, pp. 17–31, 2022.

2. Background – UPPAAL and UPPAAL SMC

- UPPAAL is a model checker
- It's used to *formally verify* properties on a **network of timed automata**
- A timed automaton is a *finite state machine* with **clocks** and **variables**
- Time is *continuous* and clocks measure time progress
- Automata can synchronize with each other with synchronization primitives
- **UPPAAL SMC** is an extension that allows *statistical verification* of complex and/or stochastic networks of timed automata

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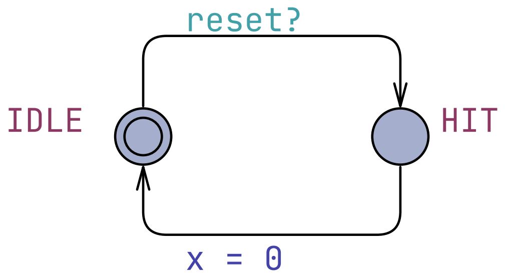
UPPAAL and UPPAAL SMC

Location

The initial location of the automaton is marked with 2 conc. circles



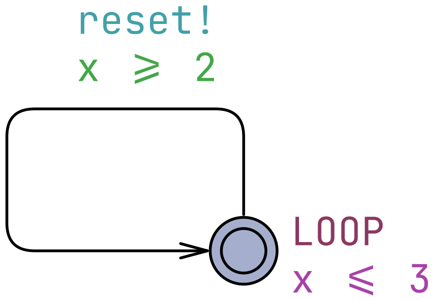
Synchronization

- Within a location, an edge is traversed if a sync with ? is received
- When traversing an edge the syncs with ! are emitted

Assignments to clocks and variables

Transition guard

An expression that must be true for the process to transition through that edge



Invariant

A logical conjunction of simple conditions on clocks that holds true when the process is in the location

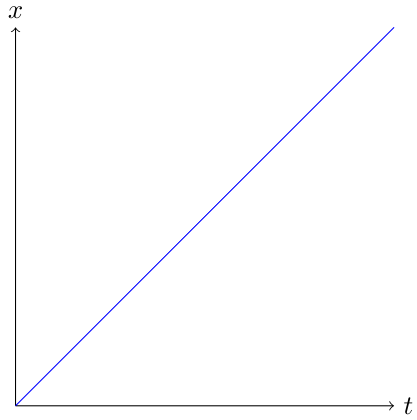
UPPAAL SMC

- Some systems may be too large to be evaluated with classical model checking
- It allows to implement stochastic behaviors
- UPPAAL SMC allows custom clocks' rates
- The custom rates are put in logical AND in the *invariant expression* of a location e.g. `x' == 0.5 and x <= 10`

This is normally omitted for time clocks

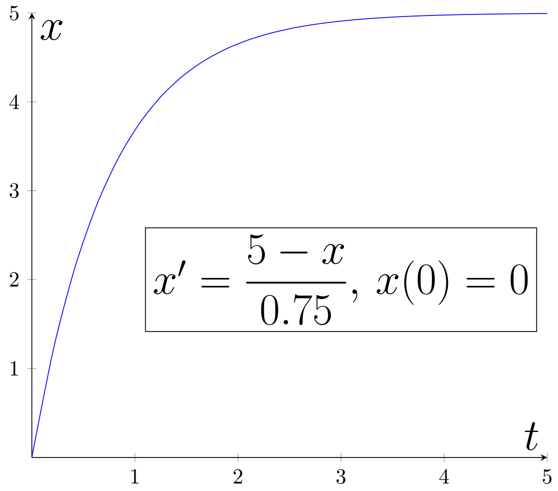
`x'==1`

Default behavior

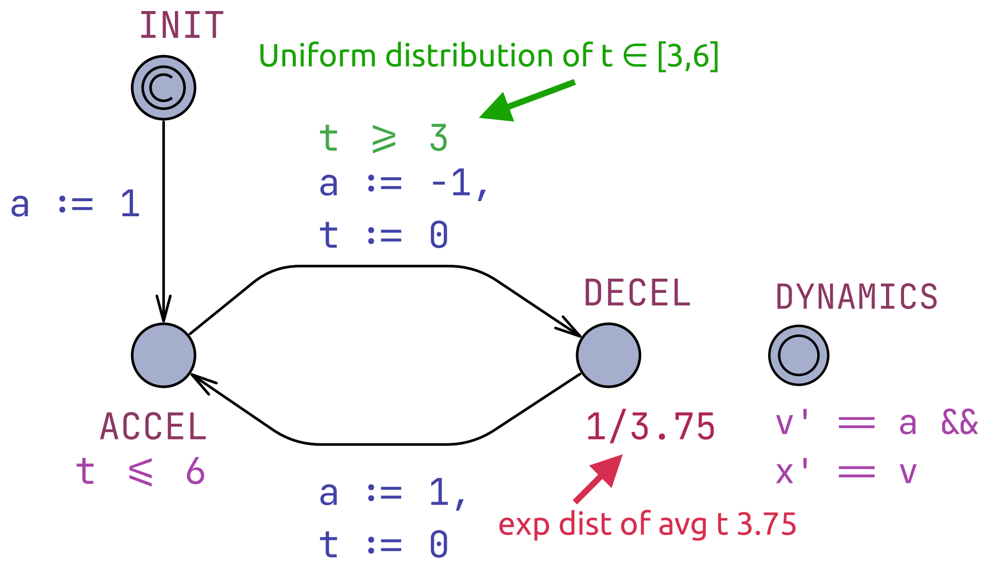


`x'==`$expr$

Custom rate



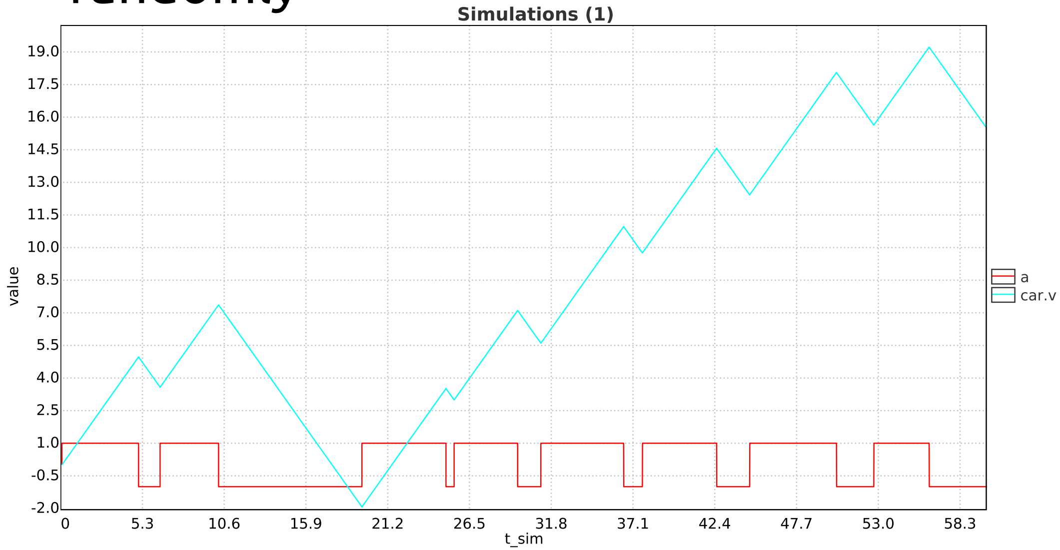
UPPAAL SMC – Simple Car



Driver

Car

- Custom clocks can be used to **model physics**
- Example: a **driver** and a **car**
- The driver accelerates and brakes randomly



UPPAAL SMC

Queries are used to estimate the probability of an expression being true

```
Pr[t_sim ≤ 60] (<> t_sim ≥ 55 && car.v > 10)          0.771707 ± 0.0472945 (95% CI)
Pr[t_sim ≤ 60] ([] t_sim ≥ 55 imply car.v > 10)                ≤ 0.0499441 (95% CI)
```

- The operator <> checks if the condition holds for at least an instant
- The operator [ ] checks if the condition holds from start to finish
- The engine will continue to accumulate traces to estimate the probability until the set *confidence interval* is satisfied

Statistical model checking for CPS

- It can model stochastic behaviors
- It can model physics with the derivative notation
- It can mix time-continuous an time-discrete components
- Given a confidence interval, the tool will automatically gather enough traces to estimate a probability of a certain event

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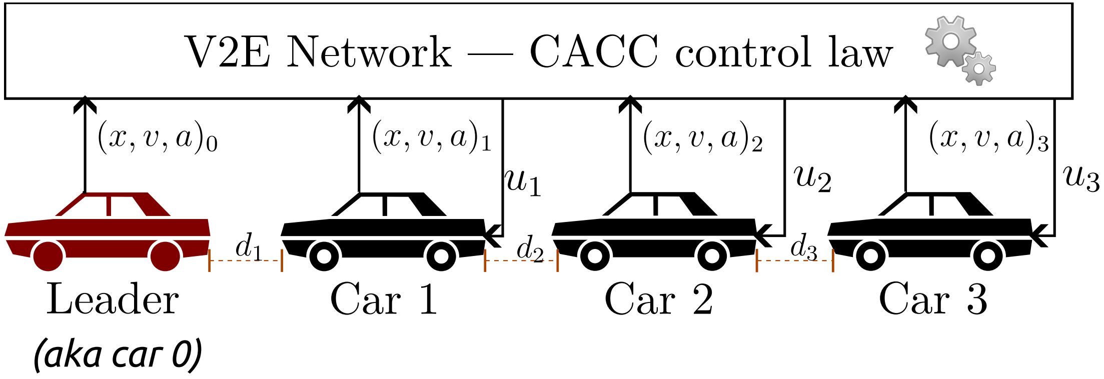
The [*longitudinal*] platoon



$$d_i = x_{i-1} - x_i - 4$$

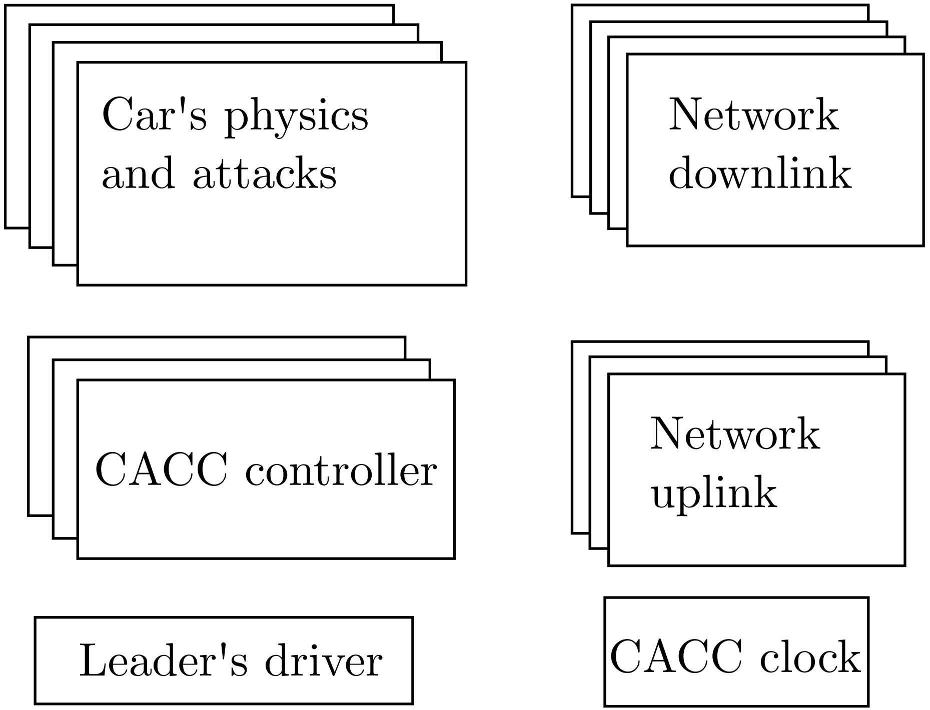
- The follower cars follow the leader
- They try to maintain a safety distance D from the car in front
- The **Cooperative Adaptive Cruise Control** (CACC) [1] control law is used

$$u_i = \alpha_1 a_{i-1} + \alpha_2 a_0 + \alpha_3 (v_i - v_{i-1}) + \alpha_4 (v_i - v_0) + \alpha_5 (D - d_i)$$

[1] Rajamani, R. and Han-Shue Tan and Boon Kait Law and Wei-Bin Zhang "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons" 2000

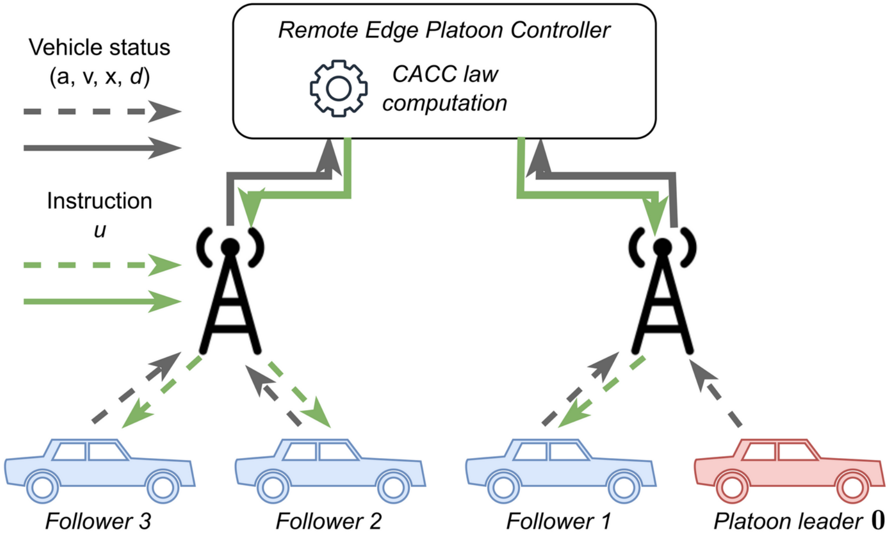
Modeling the platoon

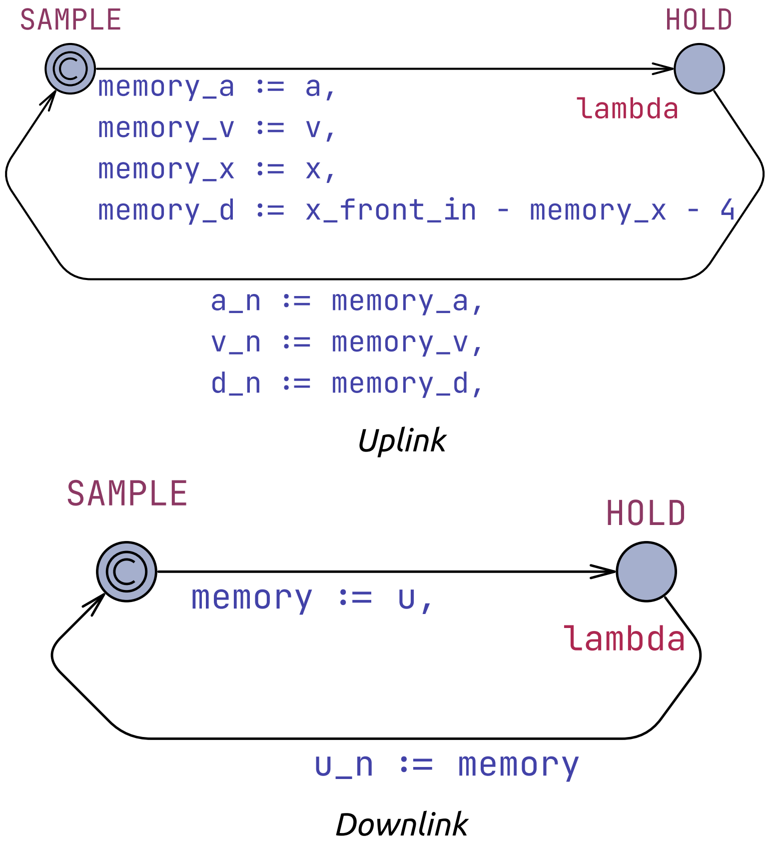
- We modeled the platoon using six timed automata



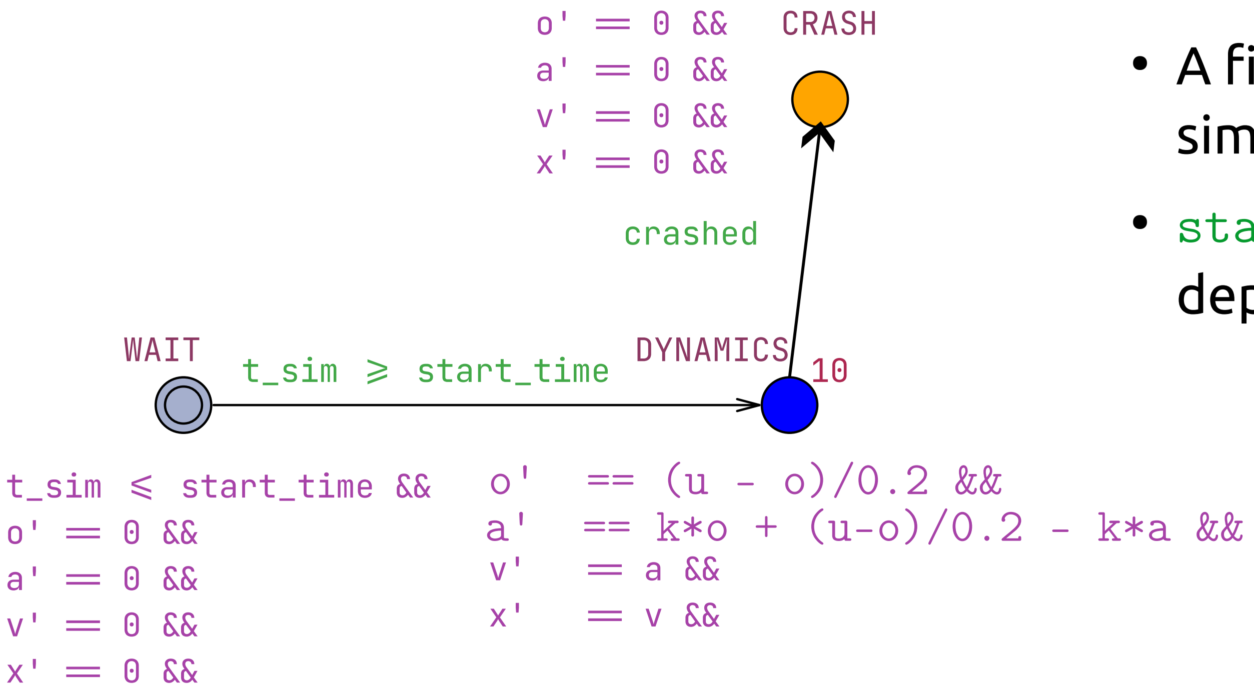
The network

- Data are delayed by 1/lambda seconds, on average





The car



Car's physics

- u is the reference acceleration computed by CACC
- A first-order filter (a, o) is used to simulate the *actuation delay*
- start_time is used to delay the departure of the car

Attacks on the platoon

- We consider the case of **data alteration** of one of the car's state variable (we'll consider car 1 under attack)
- We alter the value of *position*, *speed* and *acceleration* reported back to the centralized controller at the network edge from car 1
- The attack starts at a certain time $t_{\mathrm{A}} = 30\mathrm{s}$
- We add a **spurious signal** with parameter A

Simulation time

$$a(t) = \hat{a}(t) + A \sin\left(\frac{2\pi}{10} t\right)$$

Modified accel — *Unaltered accel* — *Frequency of 0.1Hz*

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Attacks on the platoon

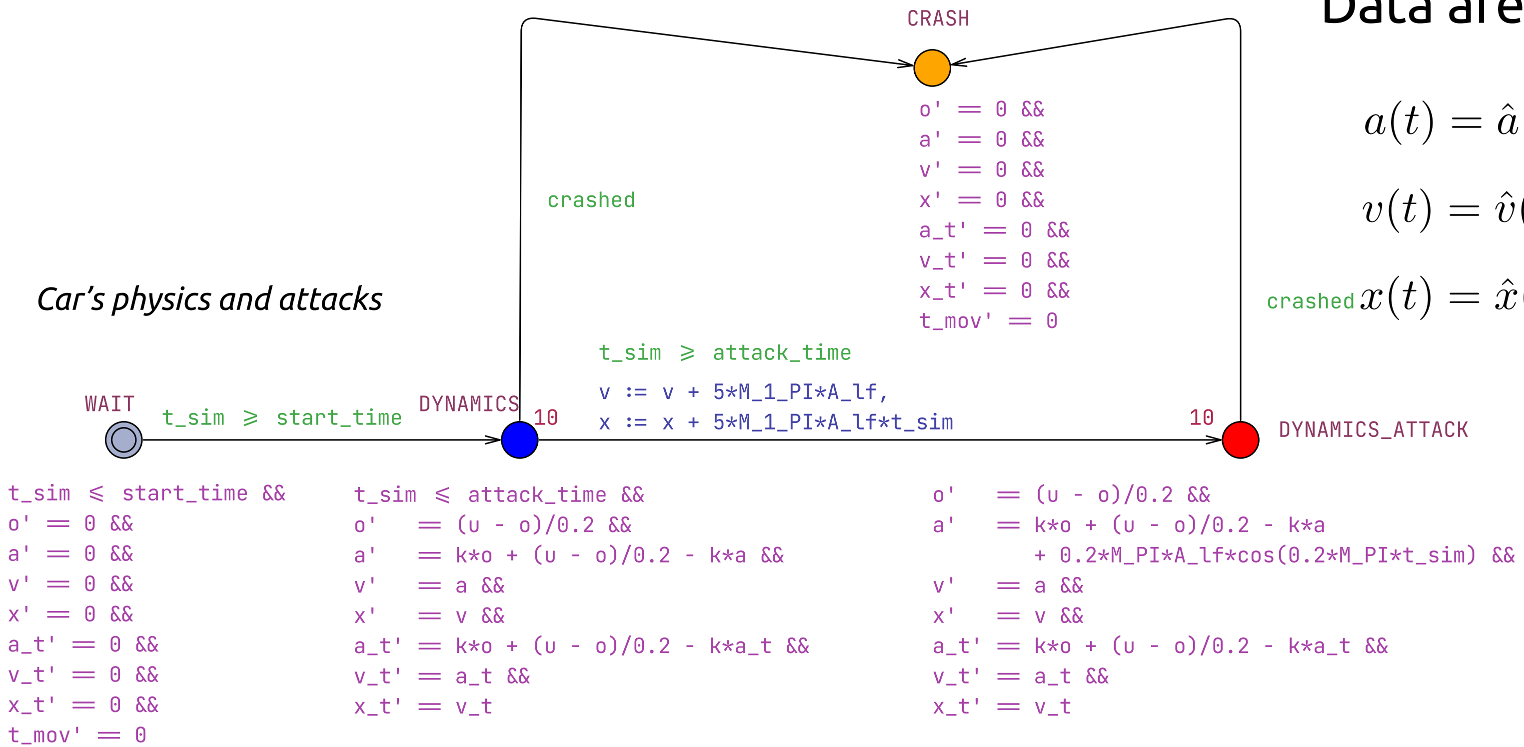
Data are altered **consistently**

$$a(t) = \hat{a}(t) + A\sin\left(\frac{2\pi}{10}t\right)$$

$$v(t) = \hat{v}(t) - \frac{5}{\pi}A\cos\left(\frac{2\pi}{10}t\right) + \frac{5}{\pi}A$$

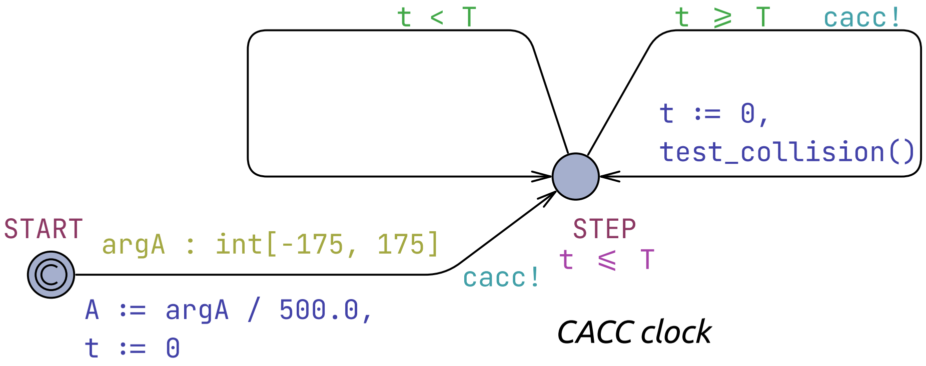
$$x(t) = \hat{x}(t) - \frac{25}{\pi^2}A\sin\left(\frac{2\pi}{10}t\right) + \frac{5}{\pi}At$$

Car's physics and attacks

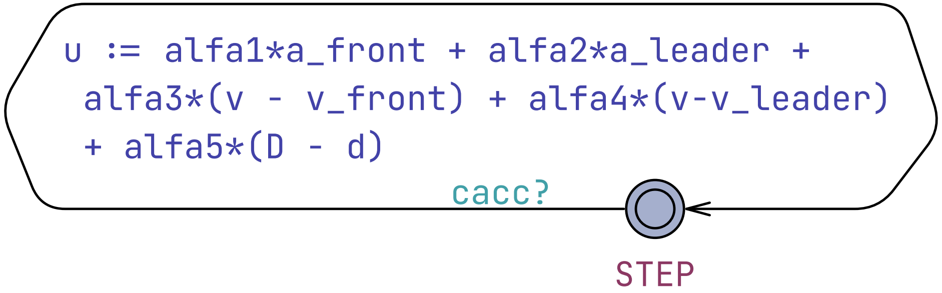


These addenda are the initial conditions on x and v

Centralized controller and temporization



CACC clock



CACC controller

- Using T = 10 ms
- Every T a `cacc!` sync is fired, causing the update of the control law
- The `test_collision()` procedure checks if cars have crashed

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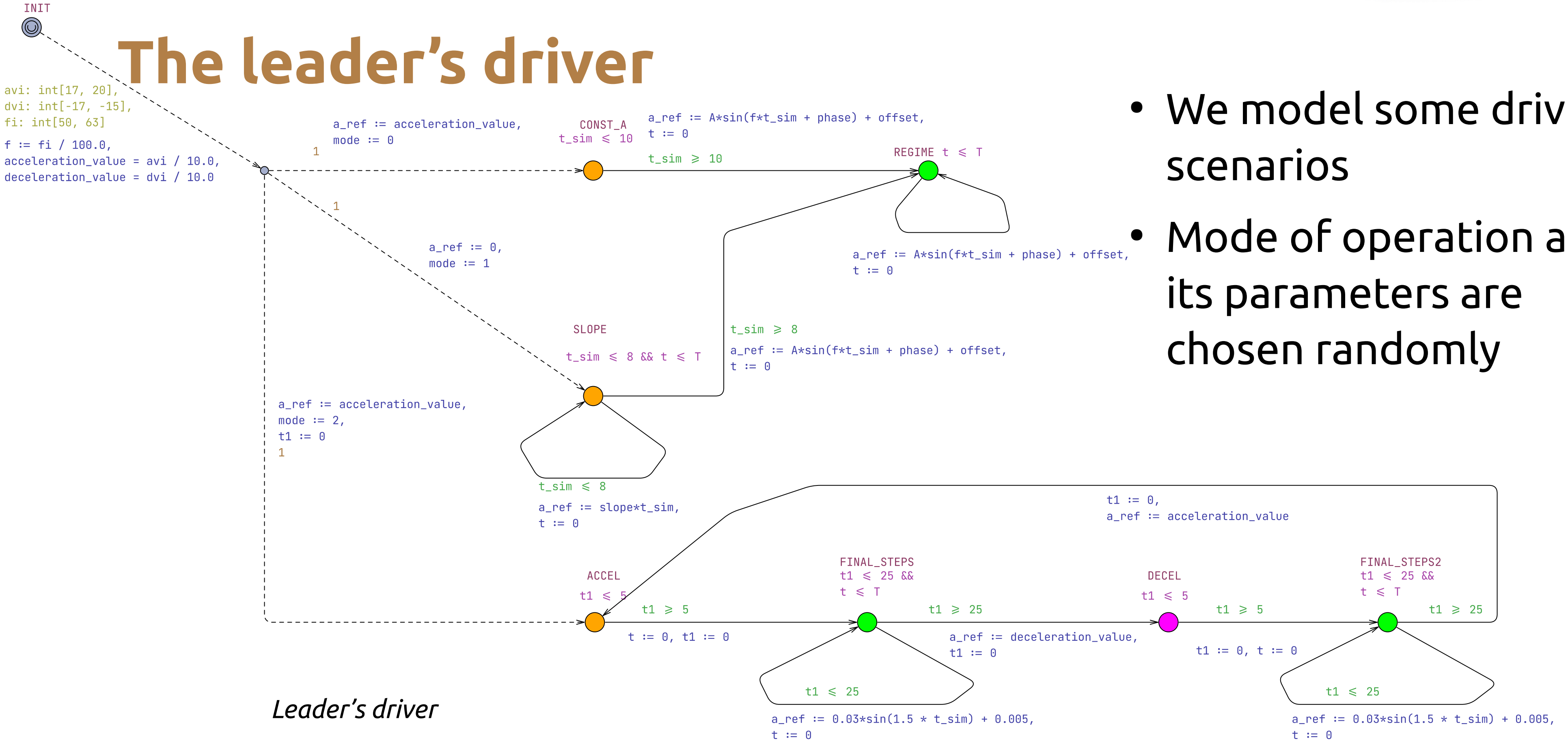
The leader's driver

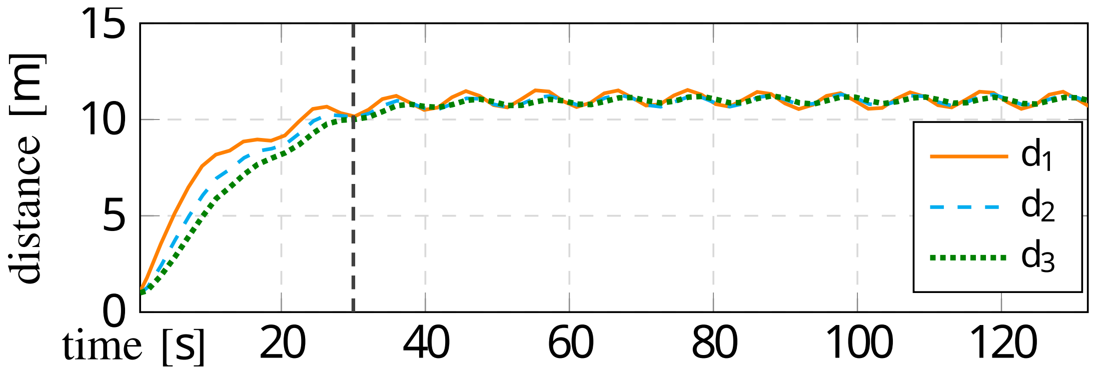
- We model some driving scenarios
- Mode of operation and its parameters are chosen randomly



Leader's driver

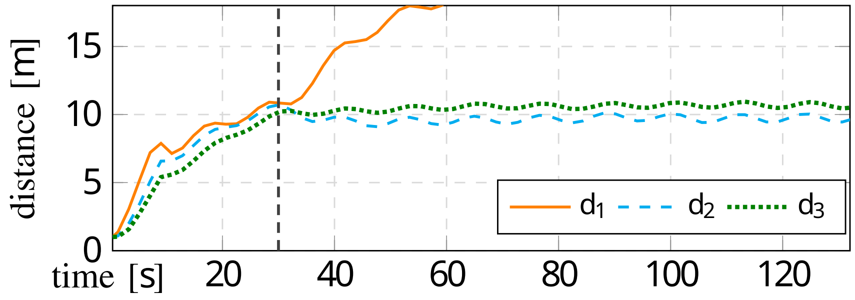
Simulation

- Let us consider some example of simulation traces
- Simulation are performed via the `simulate` query
- The attack takes place on car 1 after 30 seconds



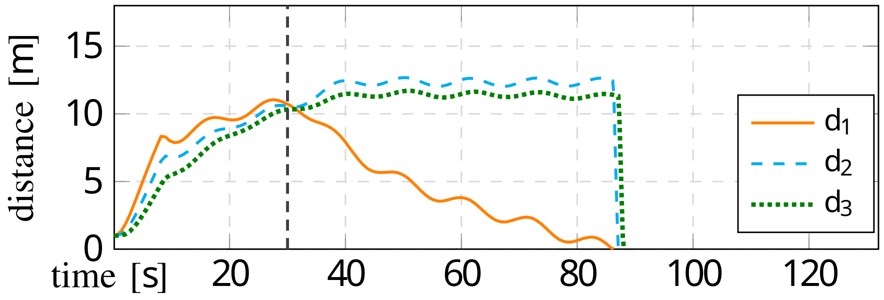
- With no attack the system behaves as expected.
- Distances converge to 11 meters

Simulation



Attack with A > 0

No crash but the car 1 distances itself from the leader



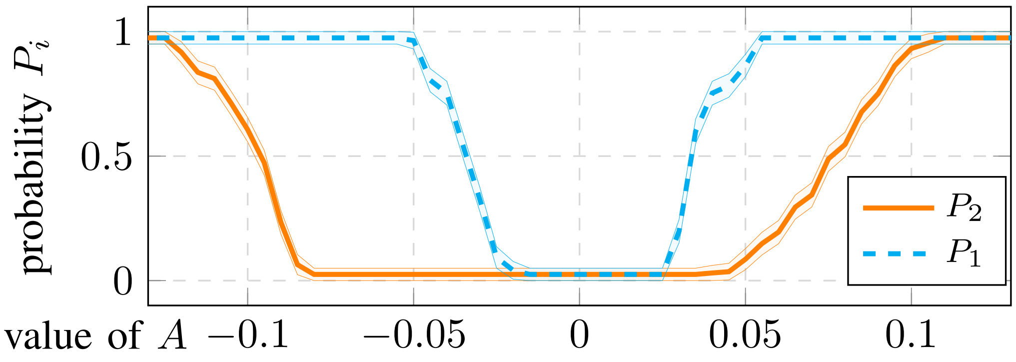
Attack with A < 0

Car 1 gets closer to the leader until they crash and cause a pile-up

Analysis of properties

Given A, let us consider the probability of having a *relative error* on the following distance of car i greater than 15%

$$\varepsilon_i = \frac{|\hat{d}_i - D|}{D} \qquad P_i = P(\varepsilon_i \geq 0.15 \,|\, 30 \leq t \leq 40)$$



- `Pr[t_sim <= 40] (<> t_sim >= 30 && fabs((x_p[0] - x_p[1] - 4)/11 - 1) > 0.15)`
- `Pr[t_sim <= 40] (<> t_sim >= 30 && fabs((x_p[1] - x_p[2] - 4)/11 - 1) > 0.15)`
- The *confidence interval* was set to 95
- Intuitively, this metrics tells us how easy it is to do attack detection in a small window of time

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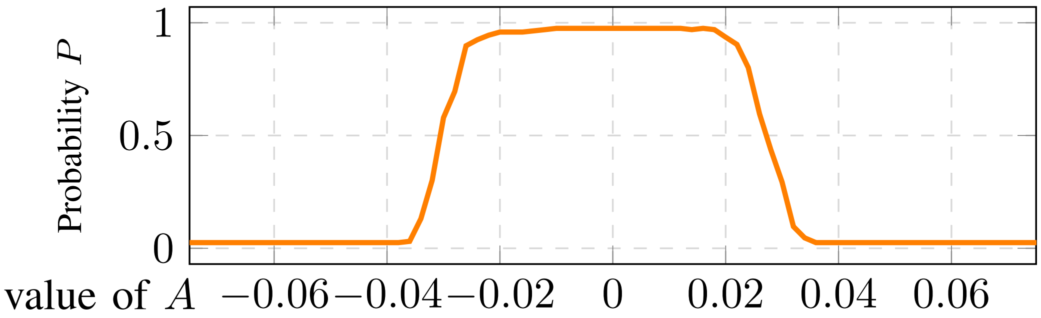
Analysis of properties

$$P(\forall t \leq 40\text{s}, \quad t \geq 30\text{s} \implies \forall i \quad \varepsilon_i < 0.15)$$




- ```
  Pr[t_sim <= 40] ([] t_sim >= 30 imply
          forall (I : int[1, 3]) fabs((x_p[i-1] - x_p[i] - 4)/11 - 1) < 0.15)
  ```
- The *confidence interval* was set to 95
- Intuitively, this tells us how the platoon overall is safe to a certain attack in a certain of window of time
  ```

Conclusions

- We've shown how SMC can be used to study the safety and resilience of CPSs to cyber-attacks
- Risk assessment of cyber-attacks can be performed
- It can be used to find properties to evaluate at runtime to check for attacks

Further work

- Increase the fidelity of the model, i.e. adding packet drops, aerodynamic draft, latitudinal movements etc…
- Study more types of attacks

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FIN
Thank you for the attention

This work is part of the FORESEEN project

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