Encoding and Monitoring Responsibility Sensitive Safety (RSS) Rules for Automated Vehicles in Signal Temporal Logic (STL)

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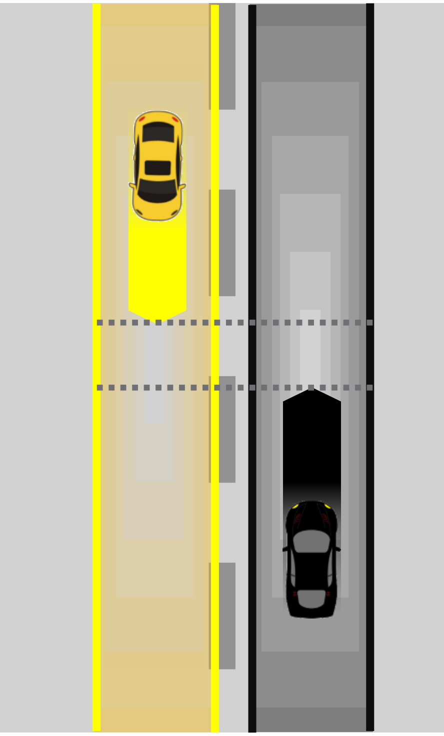
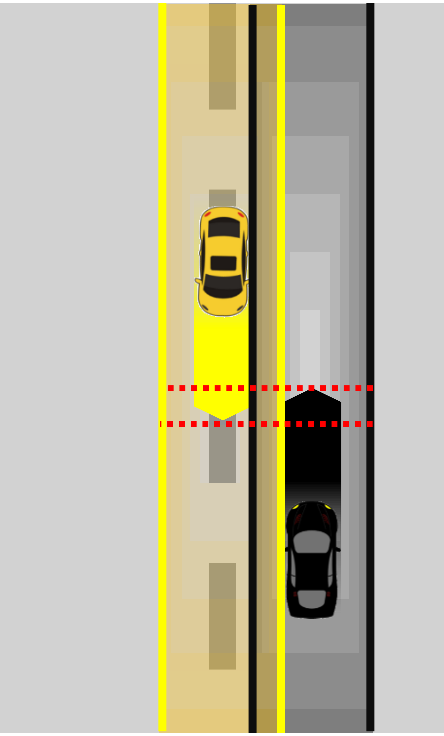
Motivation

- Responsibility Sensitive Safety (RSS) Rules
  - Developed by Intel Mobileye to capture safe driver behavior for Automated Driving Systems (ADS)
  - Alternative viewpoint: when an ADS should not be blamed for an accident



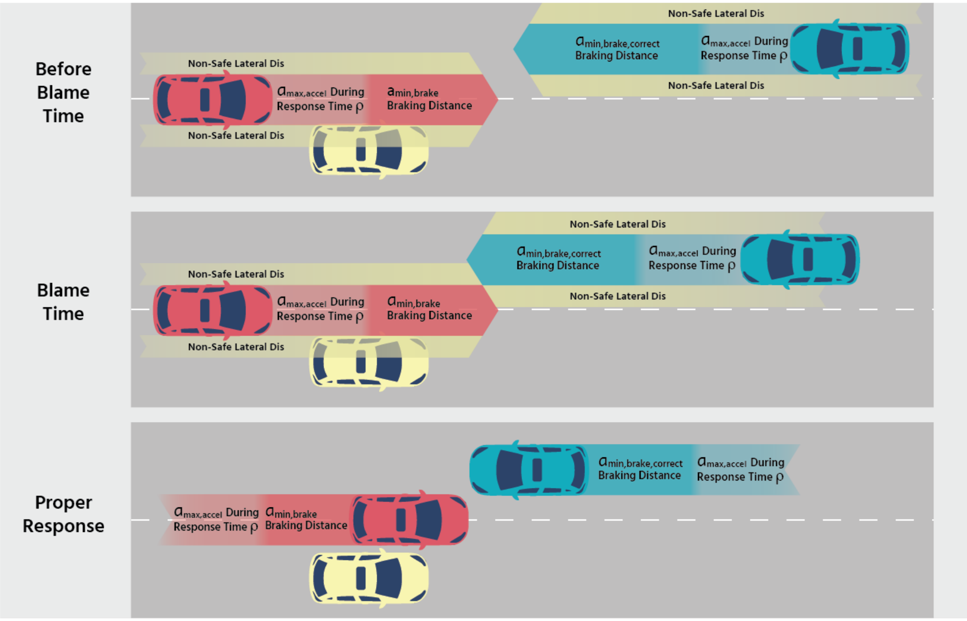


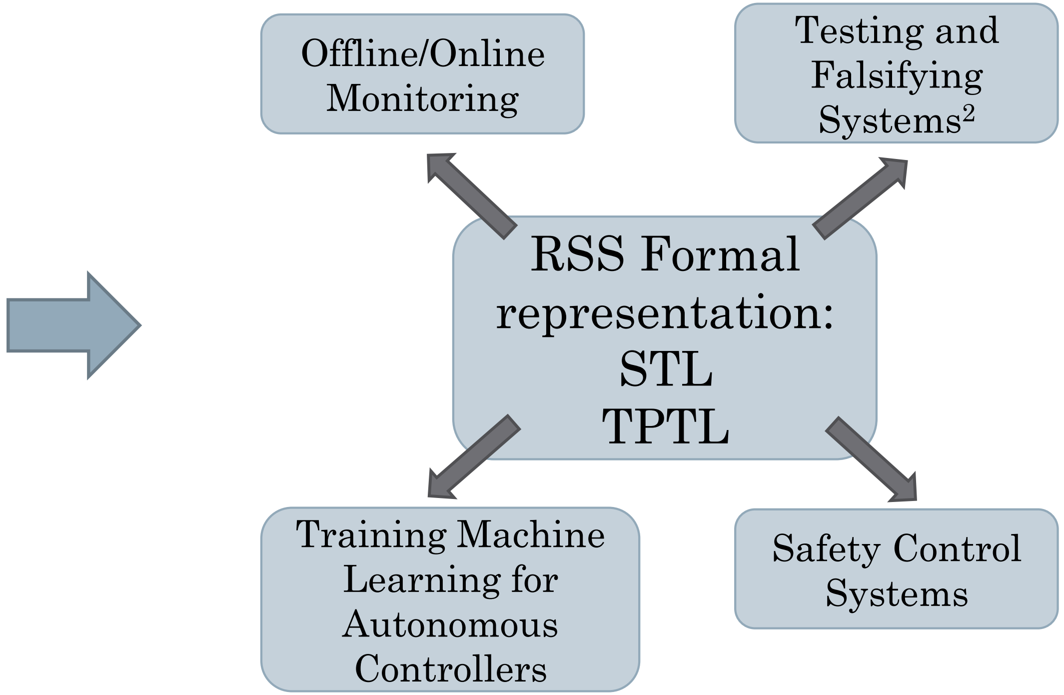
Waymo recorded video of an accident

Problem Definition & Solution Overview

Problem: How to represent and use the RSS rules in practice?

Responsible Sensitive Safety Rules[1]





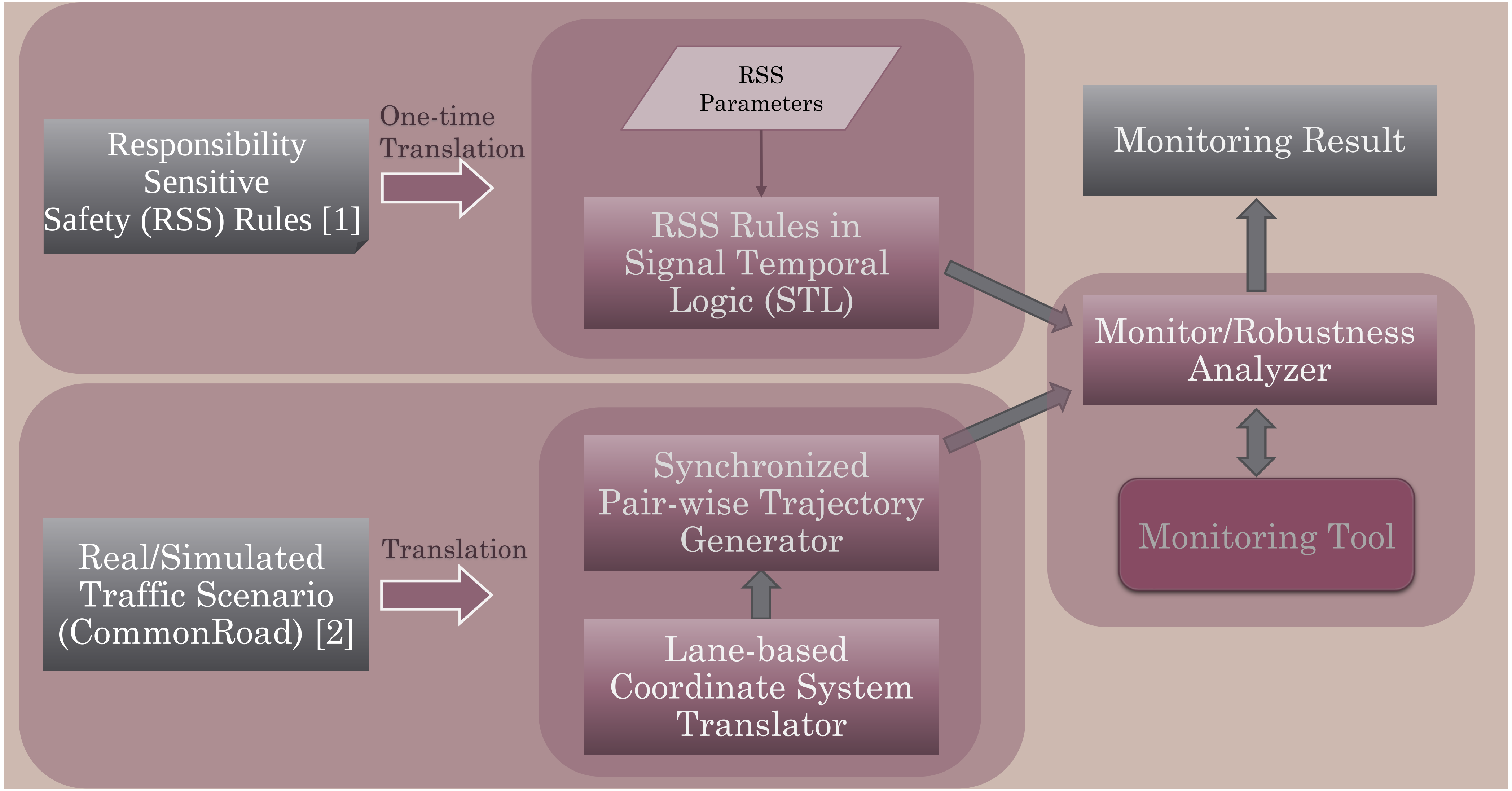
Solution: Formalizing the RSS rules in STL/TPTL

- use formalized RSS rules in standardizing, designing, training, testing and controlling ADSs.

[1] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "**On a formal model of safe and scalable self-driving cars**," arXiv:1708.06374v6, 2018.
[2] Cumhur Erkan Tuncali, Georgios Fainekos, Hisahiro Ito, James Kapinski, "**Sim-ATAV: Simulation-based Adversarial Test generation framework for Autonomous Vehicles (AV)**", HSCC 2018

* Figure is taken from Mobileye "**Implementing the RSS Model on NHTSA Pre-Crash Scenarios**"

Solution Architecture



[1] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "**On a formal model of safe and scalable self-driving cars**," arXiv:1708.06374v6, 2018.
[2] Matthias Althoff, Markus Koschi, and Stefanie Manzinger, "**CommonRoad: Composable Benchmarks for Motion Planning on Roads**", 2017 IEEE Intelligent Vehicles Symposium (IV)

Summary of Our Contribution

- We demonstrate that the RSS model can be encoded in assume-guarantee STL requirements.
- To motivate how the resulting STL requirements could be used in practice, we monitor multiple real driving data scenarios* offline over some of the RSS rules written in STL [1].
- Finally, we have released our case-study and experiments publicly available as part of S-TALIRO available at: https://cpslab.assembla.com/spaces/s-taliro_public/ .

[1] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "**On a formal model of safe and scalable self-driving cars**," arXiv:1708.06374v6, 2018.
* Matthias Althoff, Markus Koschi, and Stefanie Manzinger, "**CommonRoad: Composable Benchmarks for Motion Planning on Roads**", 2017 IEEE Intelligent Vehicles Symposium (IV)

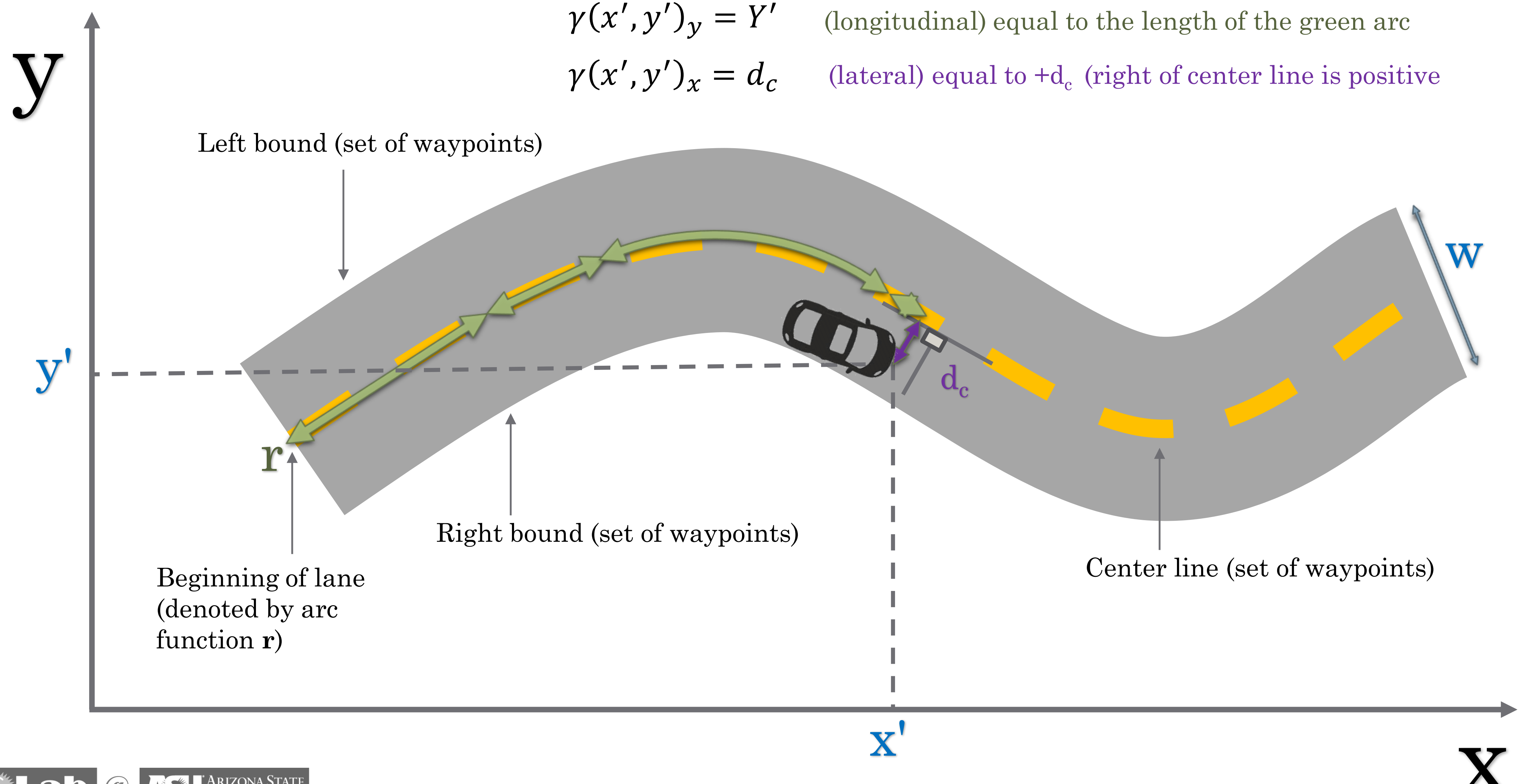
Outline

- Preliminaries
  - Lane-based Coordinate System
  - RSS Safe Distances
  - Metric/Signal Temporal Logic
- RSS Translation into STL
- Monitoring RSS Rules in DP-TALIRO
- Experimental Results
- Conclusion

Lane-based Coordinate System

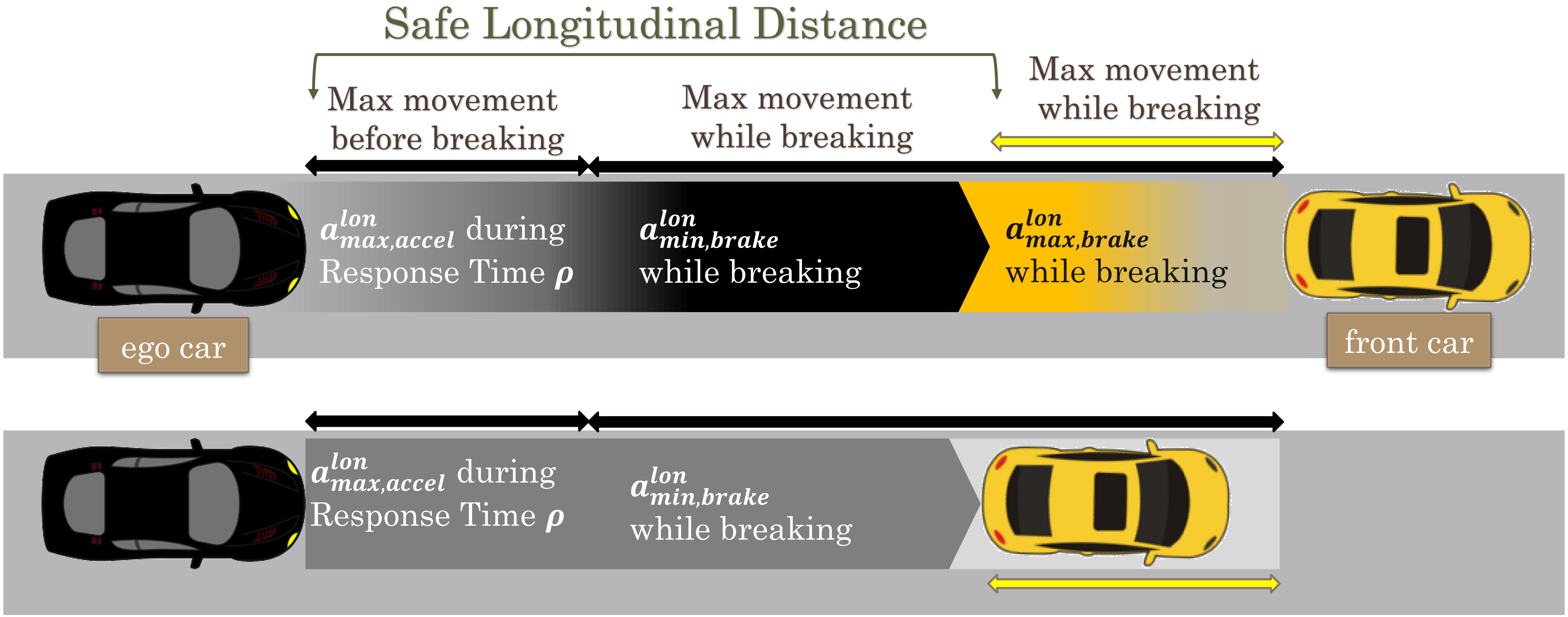
$\gamma(x',y')_y = Y'$ (longitudinal) equal to the length of the green arc

$\gamma(x',y')_x = d_c$ (lateral) equal to $+d_c$ (right of center line is positive



Safe Longitudinal Distance in One-Way Traffic

All cars move at the same direction from left to the right



Longitudinal Minimum Safe Distances

- **Based on Lemma 2 of RSS [1]:**
- Ego vehicle ***b*** is always behind the Front ***f***

$$d_{min,lon} = \max\left(d_{b,preBrake} + d_{b,brake} - d_{f,brake}, 0\right),$$

- Maximum frontal movement by accelerating as maximally allowed (before taking any action w.r.t reaction time)

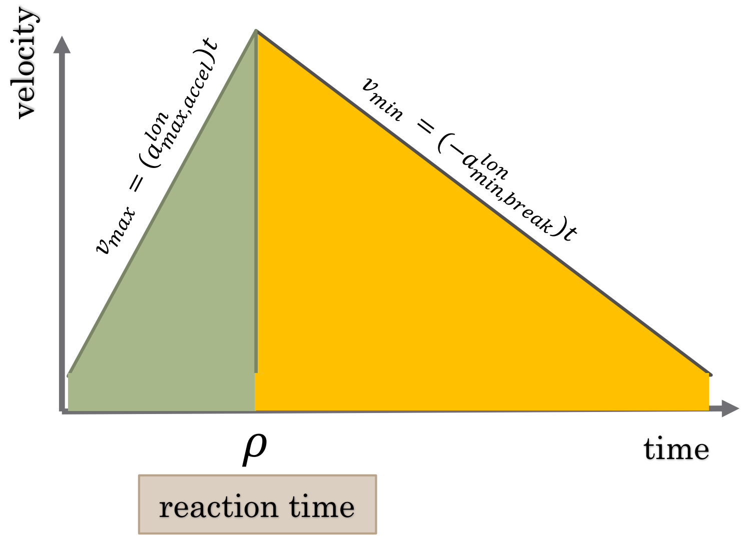
$$d_{b,preBrake} = v_b^{lon}\rho + \frac{1}{2}a_{max,accel}^{lon}\rho^2$$

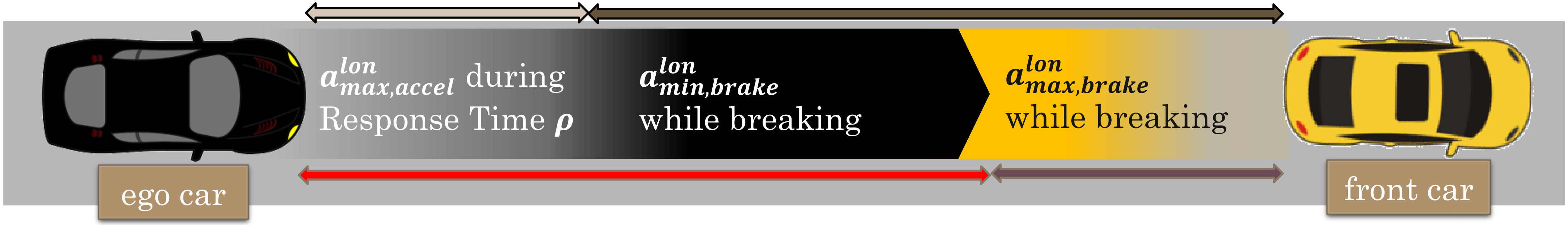
- Maximum frontal movement after braking as minimally required

$$d_{b,brake} = \frac{\left(v_b^{lon} + \rho a_{max,accel}^{lon}\right)^2}{2a_{min,brake}^{lon}}$$

- Minimum frontal movement by braking as maximally allowed

$$d_{f,brake} = \frac{{v_f^{lon}}^2}{2a_{max,brake}^{lon}}$$





[1] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "**On a formal model of safe and scalable self-driving cars**," arXiv:1708.06374v6, 2018.

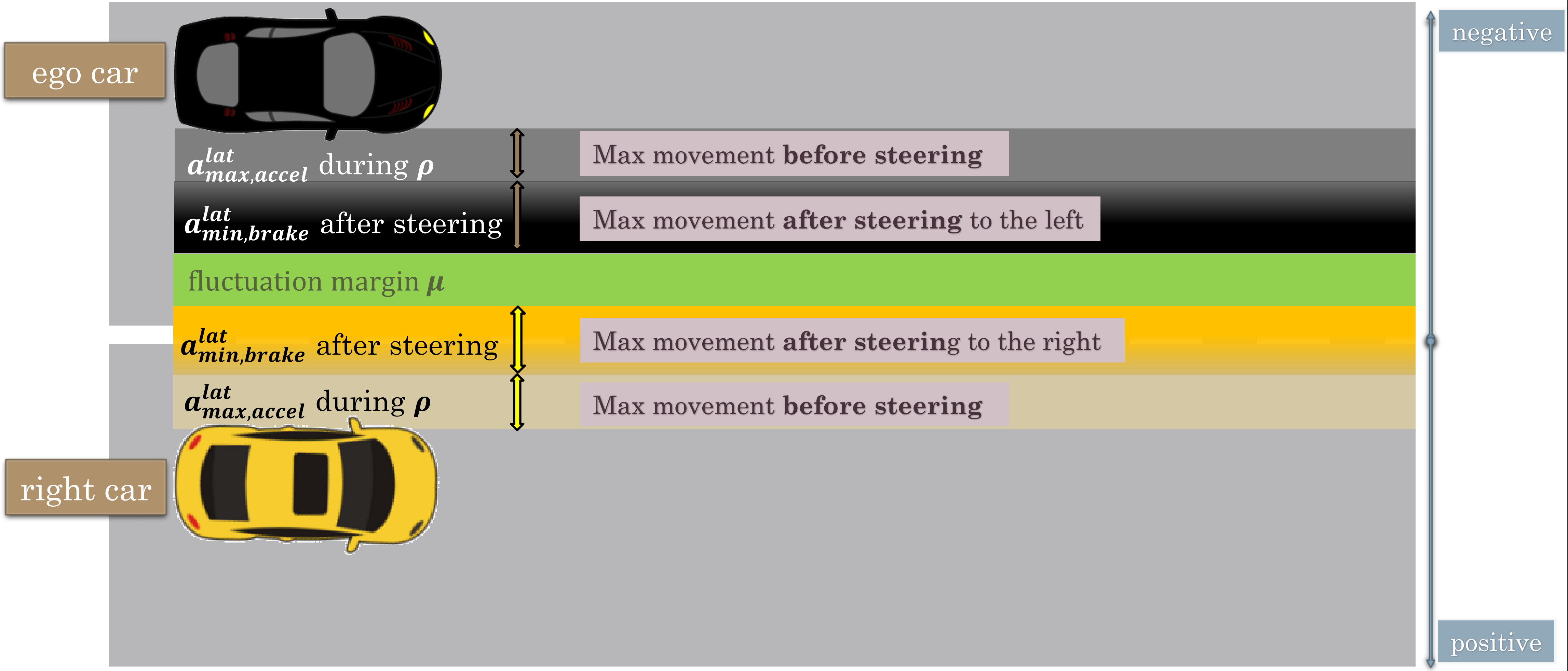
Longitudinal Minimum Safe Distances (cont')

- $D_{f,b} = longitudinal\ disntance\ - d_{min,lon}$
- $D_{f,b} > 0$ is **safe**
- $D_{f,b} \leq 0$ is **unsafe**

- Longitudinal **dangerous threshold time** is as follows:
- was $(D_{f,b} > 0), and\ now\ (D_{f,b} < 0)$

Safe Lateral Distance in One-Way Traffic

All cars move at the same direction from left to the right

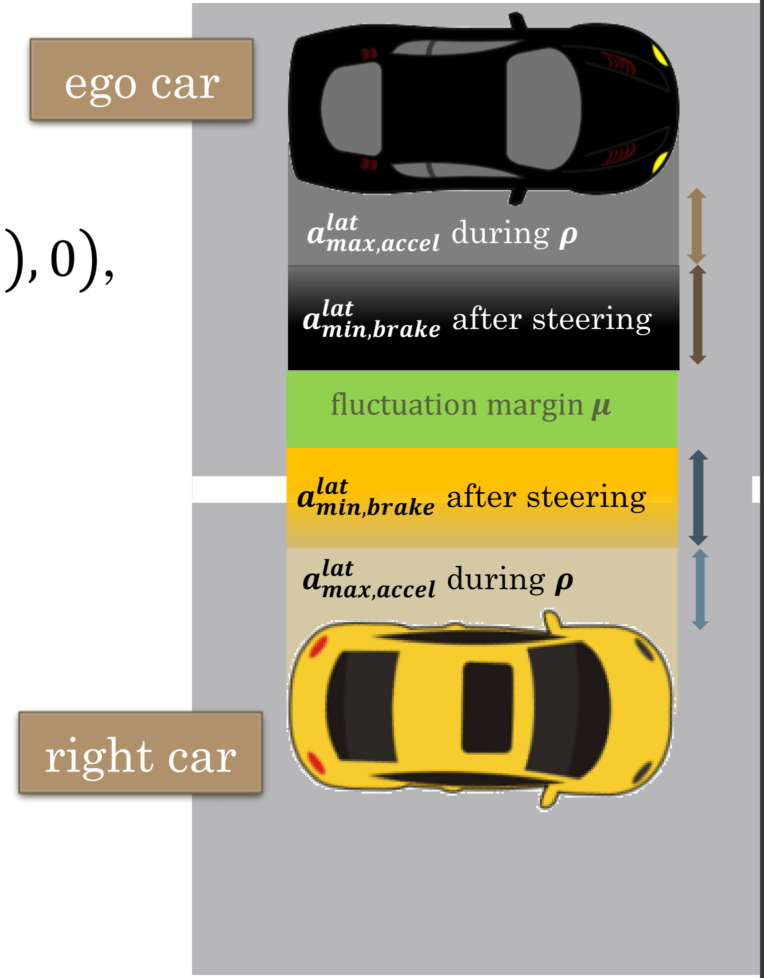


Lateral Minimum Safe Distances

- **Based on Lemma 4 of RSS [1]:**
- If Ego vehicle l is on the left of any car in the Front r

$$d_{min,lat} = \boldsymbol{\mu} + \max\left(d_{l,preBrake} + d_{l,brake} - \left(d_{r,preBrake} - d_{r,brake}\right), 0\right),$$

- Maximum to the right movement by accelerating as maximally allowed (before taking any action w.r.t reaction time) $d_{l,preBrake} = \frac{v_l^{lat} + v_{l,\rho}^{lat}}{2}\rho$
- Maximum to the right movement after braking as minimally required $d_{l,brake} = \frac{{v_{l,\rho}^{lat}}^2}{2a_{min,brake}^{lat}}$
- Maximum to the left movement by accelerating as maximally allowed (before taking any action w.r.t reaction time) $d_{r,preBrake} = \frac{v_r^{lat} + v_{r,\rho}^{lat}}{2}\rho$
- Maximum to the left movement after braking as minimally required $d_{r,brake} = \frac{{v_{r,\rho}^{lat}}^2}{2a_{min,brake}^{lat}}$



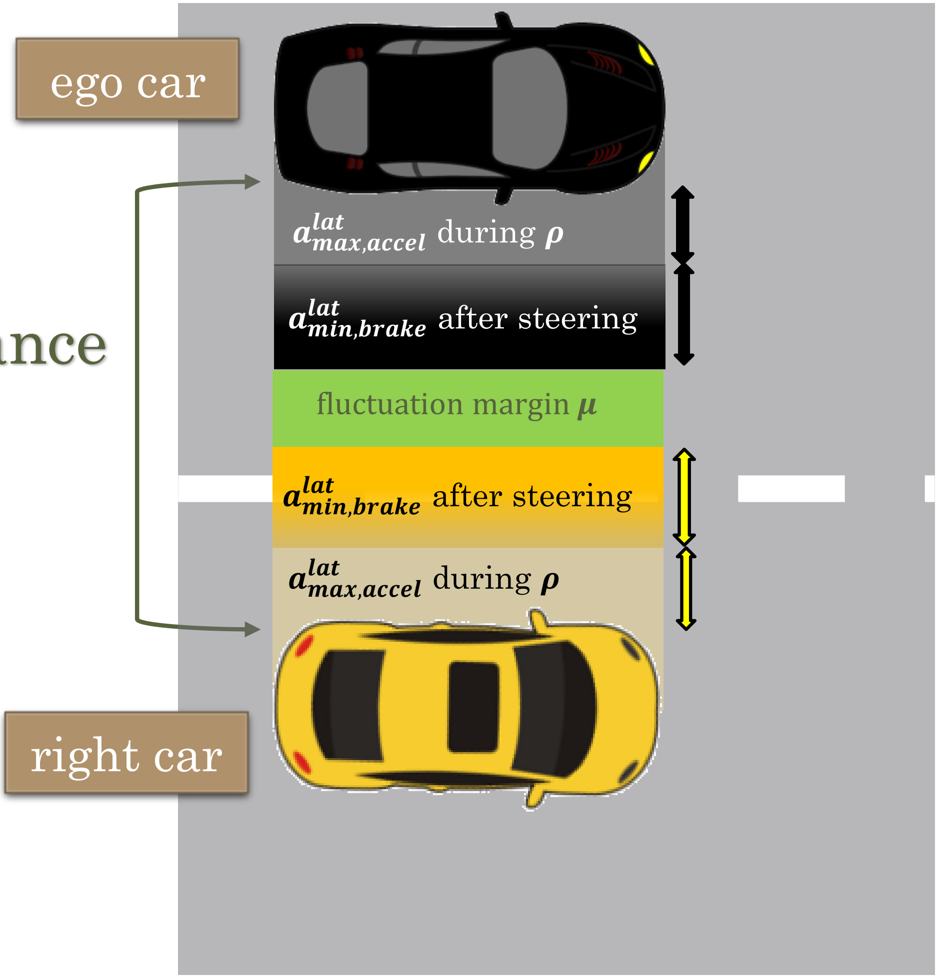
$$v_{l,\rho}^{lat} = v_l^{lat} + \rho a_{max,accel}^{lat}, \quad v_{r,\rho}^{lat} = v_r^{lat} - \rho a_{max,accel}^{lat}$$

[1] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "**On a formal model of safe and scalable self-driving cars**," arXiv:1708.06374v6, 2018.

Lateral Minimum Safe Distances (cont')

- $D_{l,r} = lateral\ disntance\ - d_{min,lat}$
- $D_{l,r} > 0$ is **safe**
- $D_{l,r} \leq 0$ is **unsafe**

Safe Lateral Distance



- Lateral **dangerous threshold time** is as follows:
- was $(D_{l,r} > 0)$, *and now* $(D_{l,r} < 0)$

Metric Temporal Logic* (MTL)

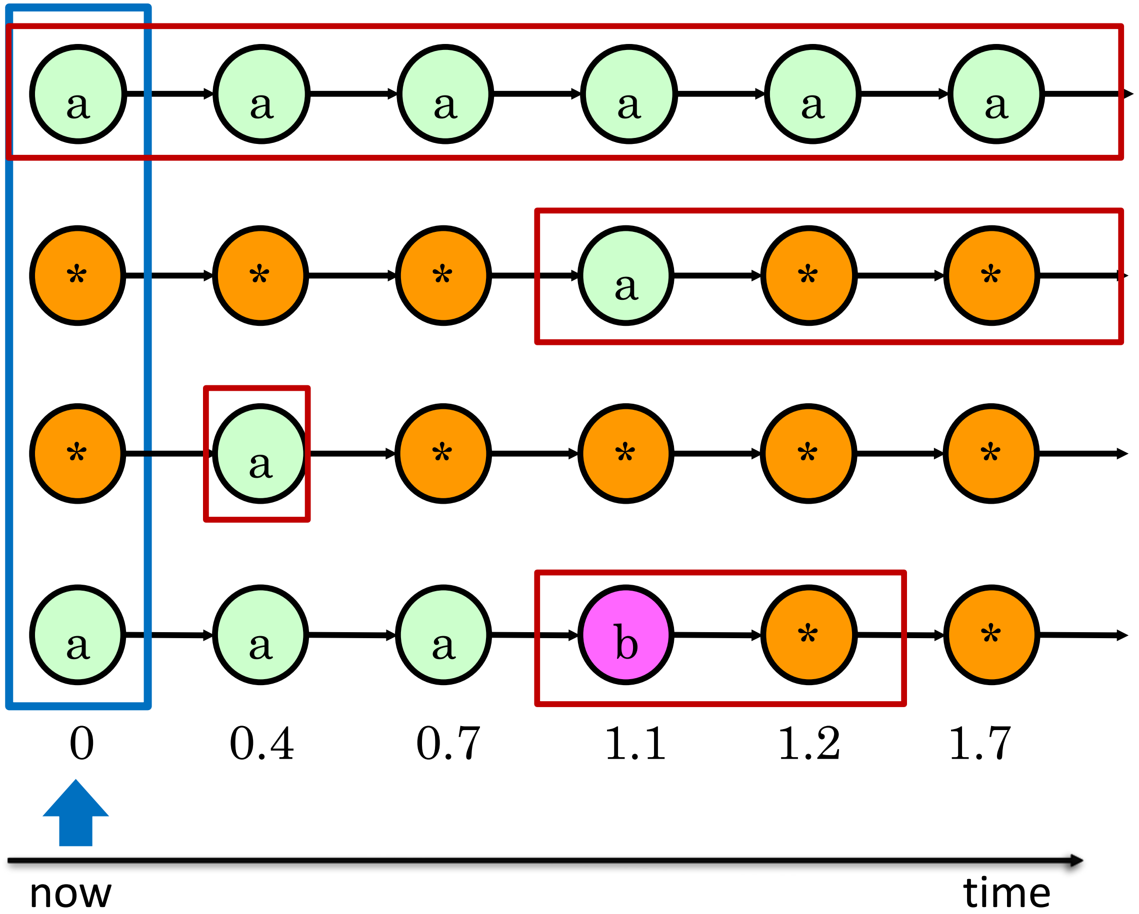
- Syntax: $\phi \ ::= \top \ |p| \ \neg\phi \ | \ \phi_1 \vee \phi_2 | \Box_I \phi \ | \Diamond_I \phi | \bigcirc\phi | \ \phi_1 U_I \phi_2 | \ \phi_1 R_I \phi_2$
- Semantics:

$G_{[0,\infty)} a \equiv \Box_{[0,\infty)} a$ - Always a

$F_{[1,3]} a \equiv \Diamond_{[1,3]} a$ - Eventually a

$Xa \equiv \bigcirc a$ - Next a

$a \ U_{[1,1.5]} \ b$ -a until b



* R. Koymans "Specifying real-time properties with metric temporal logic" Real-Time Systems, 2(4):255–299, 1990

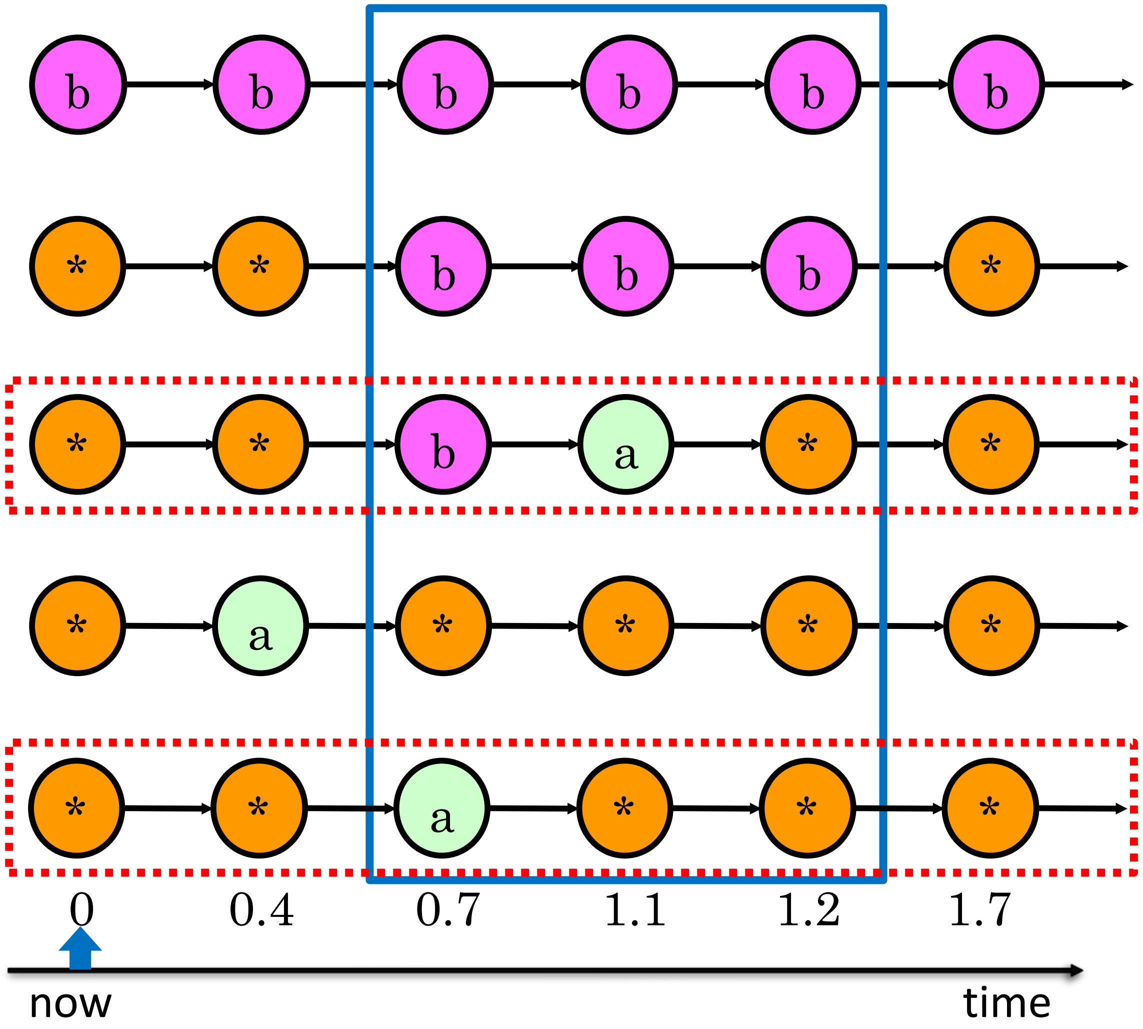
Metric Temporal Logic* (MTL)

- Syntax: $\phi ::= \top \mid p \mid \neg\phi \mid \phi_1 \vee \phi_2 \mid \Box_I \phi \mid \Diamond_I \phi \mid \bigcirc \phi \mid \phi_1 U_I \phi_2 \mid \phi_1 R_I \phi_2$
- Semantics:

$a\,\overline{R}_{[0.5,1.5]}\,b$ - a release b

Satisfy b in the interval [0.5,1.5] unless a has happened in the past.

The requirement to satisfy b in the interval [0.5,1.5] is released when a was true in the past.



* R. Koymans "Specifying real-time properties with metric temporal logic" Real-Time Systems, 2(4):255–299, 1990

Longitudinal Safety Requirements

- **Longitudinal Safety Requirement for Ego vehicle:**

$$\varphi^{lon}_{resp} \equiv \square\left(\left(S^{lon}_{b,f} \wedge \bigcirc \neg S^{lon}_{b,f}\right) \rightarrow \bigcirc\, \boldsymbol{P}^{lon}\right)$$

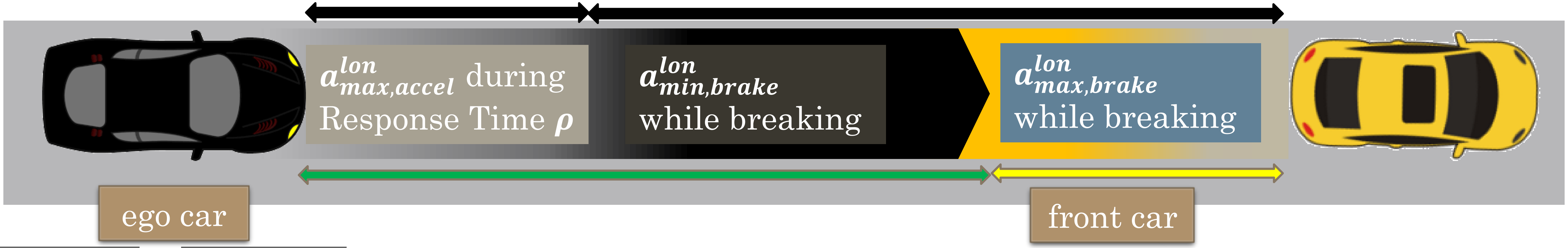
$$\boldsymbol{P}^{lon} \equiv \left(S^{lon}_{b,f}\, \bar{\mathcal{R}}_{[0,\rho)} \left(A^{lon}_{b,maxAcc} \wedge A^{lon}_{f,maxBr}\right)\right) \wedge \left(S^{lon}_{b,f}\, \bar{\mathcal{R}}_{[\rho,+\infty)} \left(A^{lon}_{b,minBr} \wedge A^{lon}_{f,maxBr}\right)\right)$$

$$S^{lon}_{b,f} \equiv \gamma\left(y_f, x_f\right)_y - \gamma(y_b, x_b)_y - d_{min,lon} > 0$$

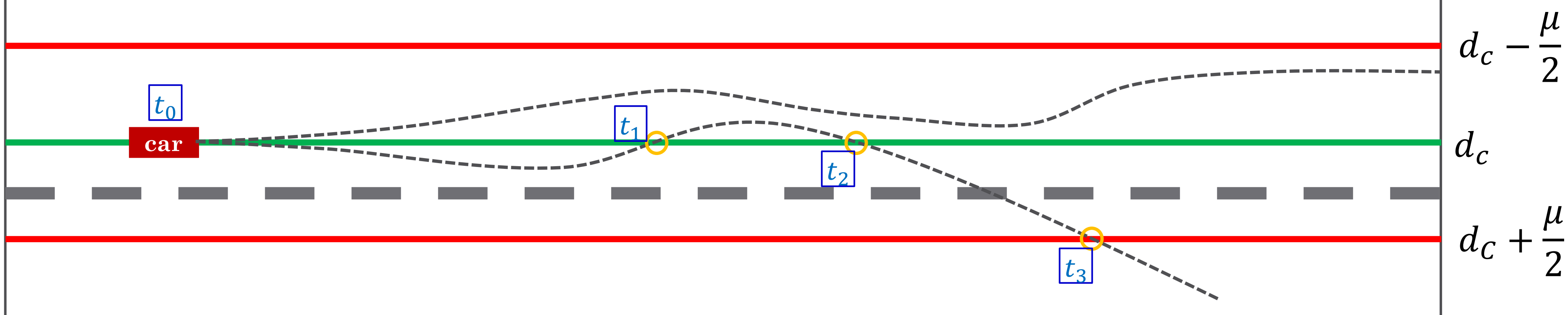
$A^{lon}_{b,maxAcc} \equiv a^{lon}_{b} \leq a^{lon}_{max,accel}$

$A^{lon}_{b,minBr} \equiv a^{lon}_{b} \leq -a^{lon}_{min,brake}$

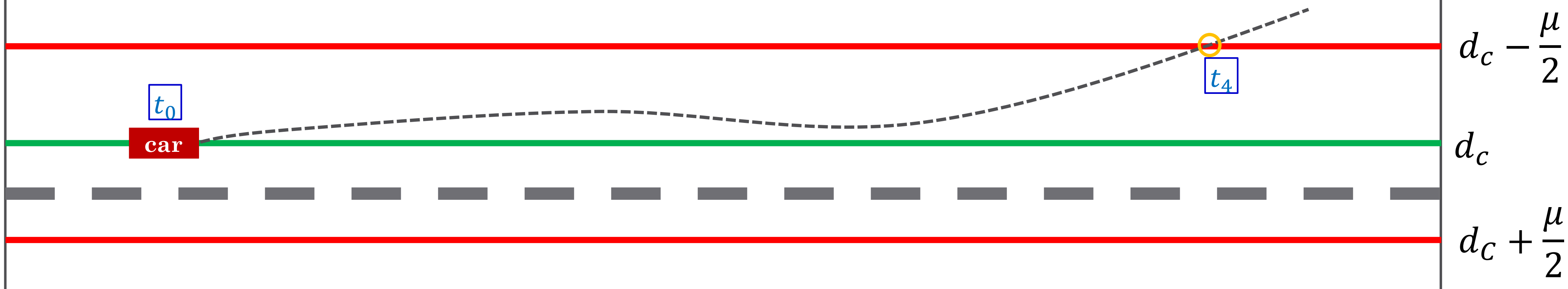
$A^{lon}_{f,maxBr} \equiv a^{lon}_{f} \geq -a^{lon}_{max,brake}$



μ –lateral-velocity



From time t_0 to t_2 predicate $\boldsymbol{V^{lat}_{l,stop}}$ is true (zero-mu-lateral velocity)



From time t_0 to t_4 predicate $\neg\boldsymbol{V^{lat}_{l,nneg}}$ is true (non-positive mu-lateral velocity)

Lateral Safety Requirements

- **Lateral Safety Requirement for Ego vehicle:**

$$\varphi_{resp}^{lat} \equiv \Box\left(\left(S_{l,r}^{lat} \wedge \bigcirc \neg S_{l,r}^{lat}\right) \rightarrow \bigcirc\, \boldsymbol{P^{lat}}\right)$$

$$\boldsymbol{P^{lat}} \equiv \left(P_{o,\rho}^{lat} \wedge P_{\rho,\infty}^{lat,1} \wedge P_{\rho,\infty}^{lat,2}\right)$$

$$P_{o,\rho}^{lat} \equiv S_{l,r}^{lat}\bar{\mathcal{R}}_{[0,\rho)}\left(A_{l,maxAccel}^{lat} \wedge A_{r,maxAccel}^{lat}\right)$$

$$P_{\rho,\infty}^{lat,1} \equiv \left(\left(S_{l,r}^{lat} \vee V_{l,stop}^{lat}\right)\bar{\mathcal{R}}_{[\rho,+\infty)}A_{l,minBrake}^{lat}\right) \wedge \left(\left(S_{l,r}^{lat} \vee V_{r,stop}^{lat}\right)\bar{\mathcal{R}}_{[\rho,+\infty)}A_{r,minBrake}^{lat}\right)$$

$$P_{\rho,\infty}^{lat,2} \equiv \left(S_{l,r}^{lat}\bar{\mathcal{R}}_{[\rho,+\infty)}\left(V_{l,stop}^{lat} \rightarrow \bigcirc\, V_{l,npos}^{lat}\right)\right) \wedge \left(S_{l,r}^{lat}\bar{\mathcal{R}}_{[\rho,+\infty)}\left(V_{r,stop}^{lat} \rightarrow \bigcirc\, \Box\left(V_{r,nneg}^{lat}\right)\right)\right)$$

$$S_{l,r}^{lat} \equiv \gamma(y_r, x_r)_\alpha - \gamma(y_l, x_l)_\alpha - d_{min,lat} > 0$$

$$V_{l,stop}^{lat} \equiv v_l^{\mu-lat} = 0,\ V_{r,stop}^{lat} \equiv v_r^{\mu-lat} = 0$$

$$V_{l,npos}^{lat} \equiv v_l^{\mu-lat} \leq 0,\ V_{r,nneg}^{lat} \equiv v_r^{\mu-lat} \geq 0$$

(i) Computed at signal level
(ii) Formalized as TPTL formula

ego car

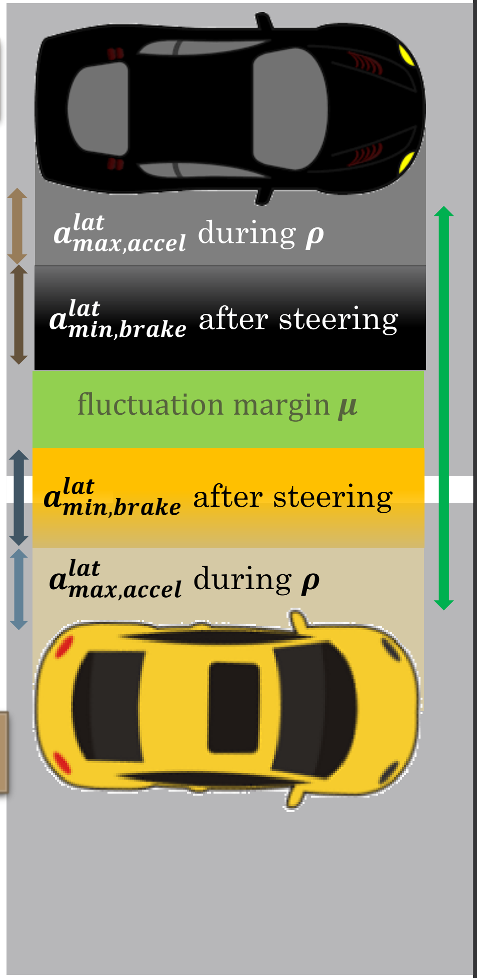
$$A_{l,maxAccel}^{lat} \equiv |a_l^{lat}| \leq a_{max,accel}^{lat}$$

$$A_{l,minBrake}^{lat} \equiv a_l^{lat} \leq -a_{min,brake}^{lat}$$

$$A_{r,minBrake}^{lat} \equiv a_r^{lat} \geq a_{min,brake}^{lat}$$

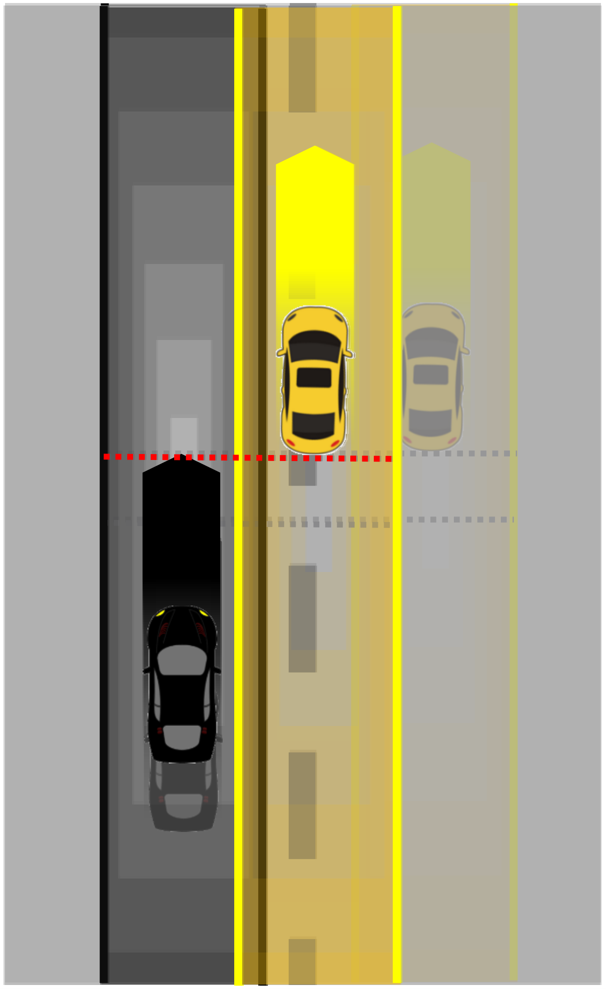
$$A_{r,maxAccel}^{lat} \equiv |a_r^{lat}| \leq a_{max,accel}^{lat}$$

right car



Basic Proper Response: From Laterally Unsafe to Unsafe

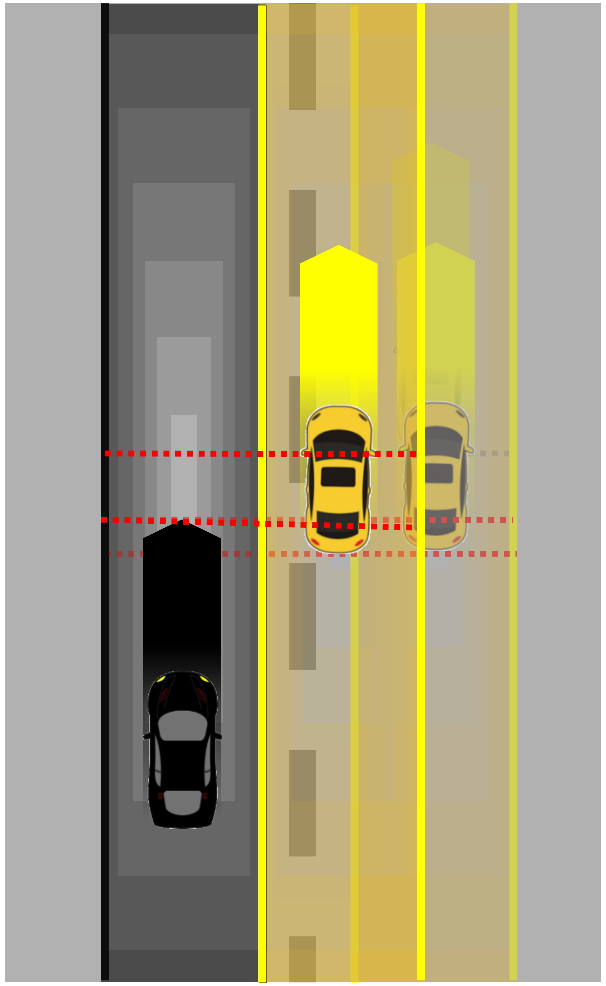
Laterally Unsafe



$$\varphi^{lon} \equiv \square\left(\left(\neg S^{lat}_{l,r} \wedge S^{lon}_{b,f} \wedge \circ\left(\neg S^{lat}_{l,r} \wedge \neg S^{lon}_{b,f}\right)\right) \rightarrow \circ\, P^{lon}\right)$$

Basic Proper Response: From Longitudinally Unsafe to Unsafe

Longitudinally UnSafe

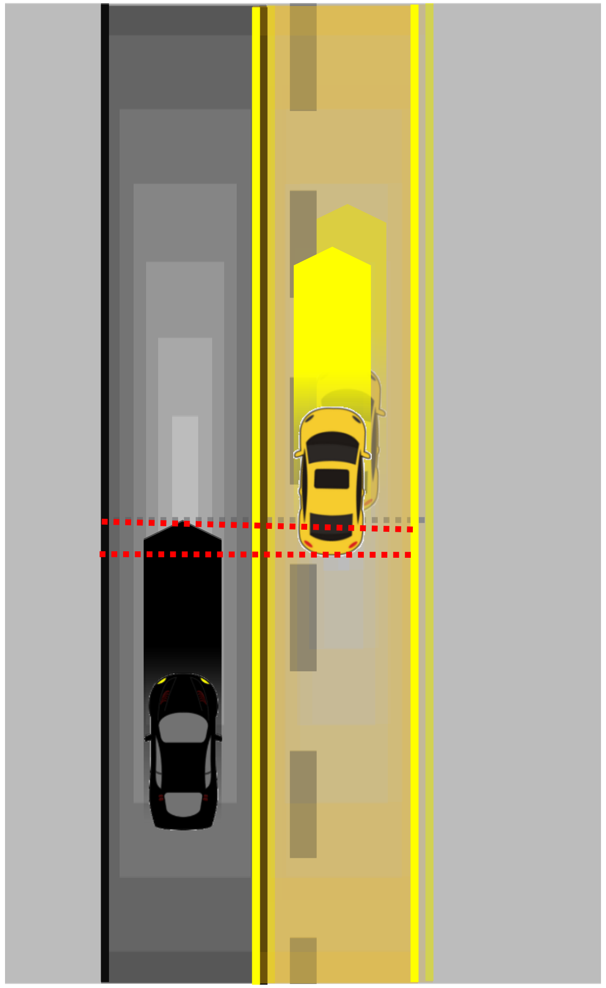


$$\varphi^{lat} \equiv \square\left(\left(\neg S_{b,f}^{lon} \wedge S_{l,r}^{lat} \wedge \circ\left(\neg S_{b,f}^{lon} \wedge \neg S_{l,r}^{lat}\right)\right) \rightarrow \circ\, P^{lat}\right)$$

Basic Proper Response: From Safe to Unsafe

Unsafe

Safe



$$\varphi^{lat,lon} \equiv \square\left(\left(S^{lat}_{l,r} \wedge S^{lon}_{b,f} \wedge \circ\left(\neg S^{lat}_{l,r} \wedge \neg S^{lon}_{b,f}\right)\right) \rightarrow \circ\left(P^{lon} \wedge P^{lat}\right)\right)$$

Basic Proper Response Specification

- $\boldsymbol{\varphi_{resp}^{lat,lon}} \equiv \varphi^{lon} \wedge \varphi^{lat} \wedge \varphi^{lat,lon}$
- $\varphi^{lon} \equiv \square\left(\left(\neg S_{l,r}^{lat} \wedge S_{b,f}^{lon} \wedge \circ\left(\neg S_{l,r}^{lat} \wedge \neg S_{b,f}^{lon}\right)\right) \rightarrow \circ\, P_{lat}^{lon}\right)$
- $\varphi^{lat} \equiv \square\left(\left(\neg S_{b,f}^{lon} \wedge S_{l,r}^{lat} \wedge \circ\left(\neg S_{b,f}^{lon} \wedge \neg S_{l,r}^{lat}\right)\right) \rightarrow \circ\, P_{lon}^{lat}\right)$
- $\varphi^{lat,lon} \equiv \square\left(\left(S_{l,r}^{lat} \wedge S_{b,f}^{lon} \wedge \circ\left(\neg S_{l,r}^{lat} \wedge \neg S_{b,f}^{lon}\right)\right) \rightarrow \circ\left(P_{lat}^{lon} \vee P_{lon}^{lat}\right)\right)$
- P_{lat}^{lon} and P_{lon}^{lat} are modified versions of P^{lon} and P^{lat} where the propositions $S_{l,r}^{lat}$ and $S_{b,f}^{lon}$ are replaced with the formula $(S_{l,r}^{lat} \vee S_{b,f}^{lon})$.

Remarks on $\boldsymbol{\varphi_{resp}^{lat,lon}} \equiv \varphi^{lon} \wedge \varphi^{lat} \wedge \varphi^{lat,lon}$

- (1)
  - $\varphi^{lat,lon} \equiv \square\left(\left(S_{l,r}^{lat} \wedge S_{b,f}^{lon} \wedge \circ\left(\neg S_{l,r}^{lat} \wedge \neg S_{b,f}^{lon}\right)\right) \rightarrow \circ\left(P_{lat}^{lon} \vee P_{lon}^{lat}\right)\right)$

$\varphi^{lat,lon}$ is implicitly defined in Def. 10.

Def 10 implies conjunction; however this is too conservative.

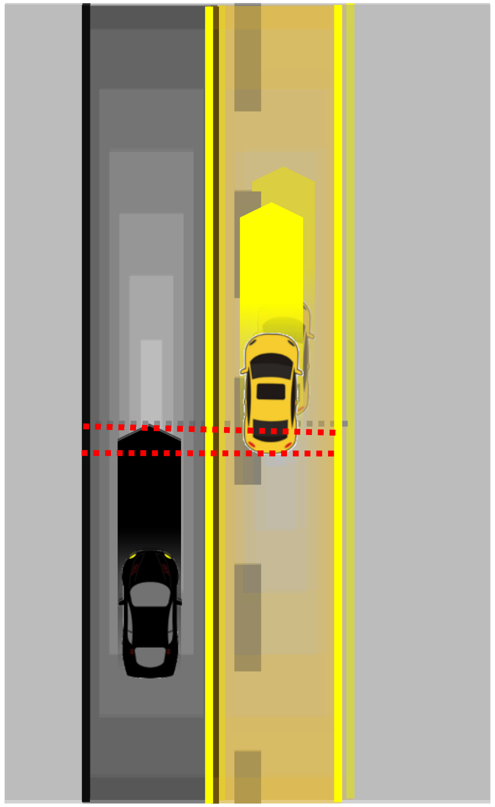
$P^{lon} \wedge P^{lat}$

- (2)
  - $S_{l,r}^{lat}\bar{\mathcal{R}}_I A^{\mathrm{lat}}$ rewritten as: $\left(S_{l,r}^{lat} \vee S_{b,f}^{lon}\right)\bar{\mathcal{R}}_I A^{\mathrm{lat}}$
  - $S_{b,f}^{lon}\bar{\mathcal{R}}_I A^{\mathrm{lon}}$ rewritten as: $\left(S_{l,r}^{lat} \vee S_{b,f}^{lon}\right)\bar{\mathcal{R}}_I A^{\mathrm{lon}}$

How a situation became dangerous does not imply it must become safe the same way

- (3)
  - $\boldsymbol{\varphi_{resp}^{lat,lon}} \equiv \varphi^{lon} \wedge \varphi^{lat} \wedge \varphi^{lat,lon} \wedge \varphi^{\neg lat,\neg lon}$
  - $\varphi^{\neg lat,\neg lon} \equiv \left(\neg S_{l,r}^{lat} \wedge \neg S_{b,f}^{lon}\right) \rightarrow \circ\left(P_{lat}^{lon} \vee P_{lon}^{lat}\right)$

What if a situation is unsafe from the beginning



Shalev-Shwartz, S., Shammah, S., & Shashua, A. (2018). **On a formal model of safe and scalable self-driving cars**. *arXiv preprint arXiv:1708.06374 v6*.

CommonRoad Real Scenarios

- A composable framework for benchmarking motion planning on roads.
- Highway scenarios without intersection
- Vehicles in the same lane move the same direction
- Longitudinal Distance: Front-Rear Safety Requirement
- Lateral Distance: Left-Right Safety Requirement

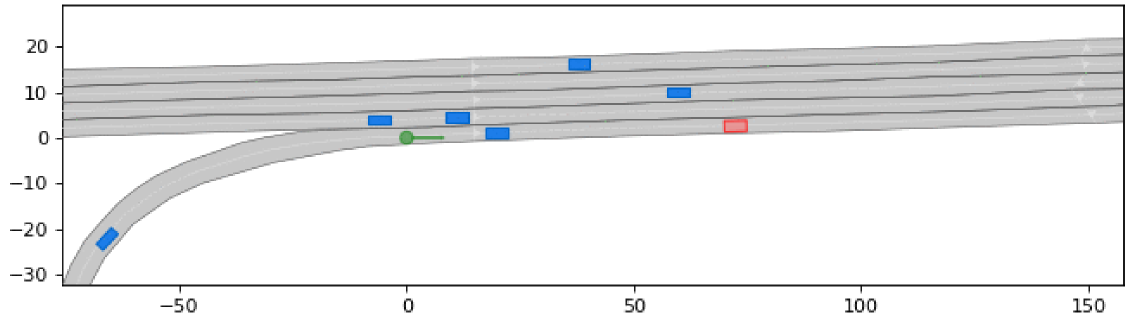
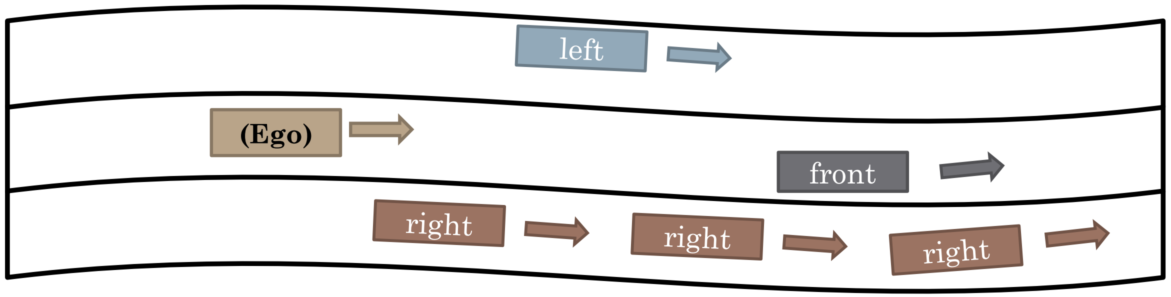
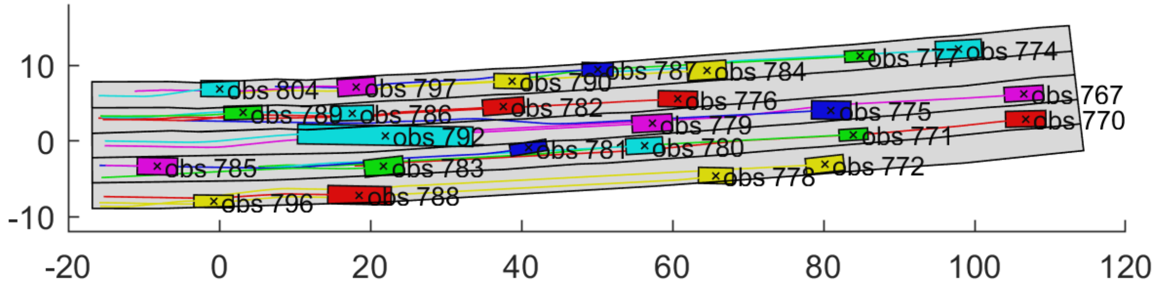
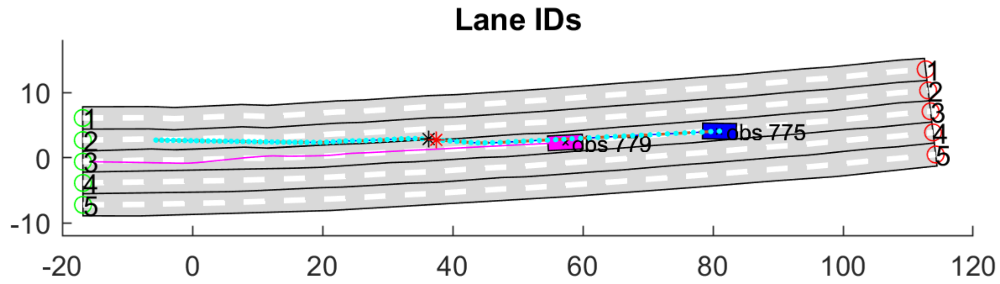


Image taken from: https://commonroad.in.tum.de



Case Study



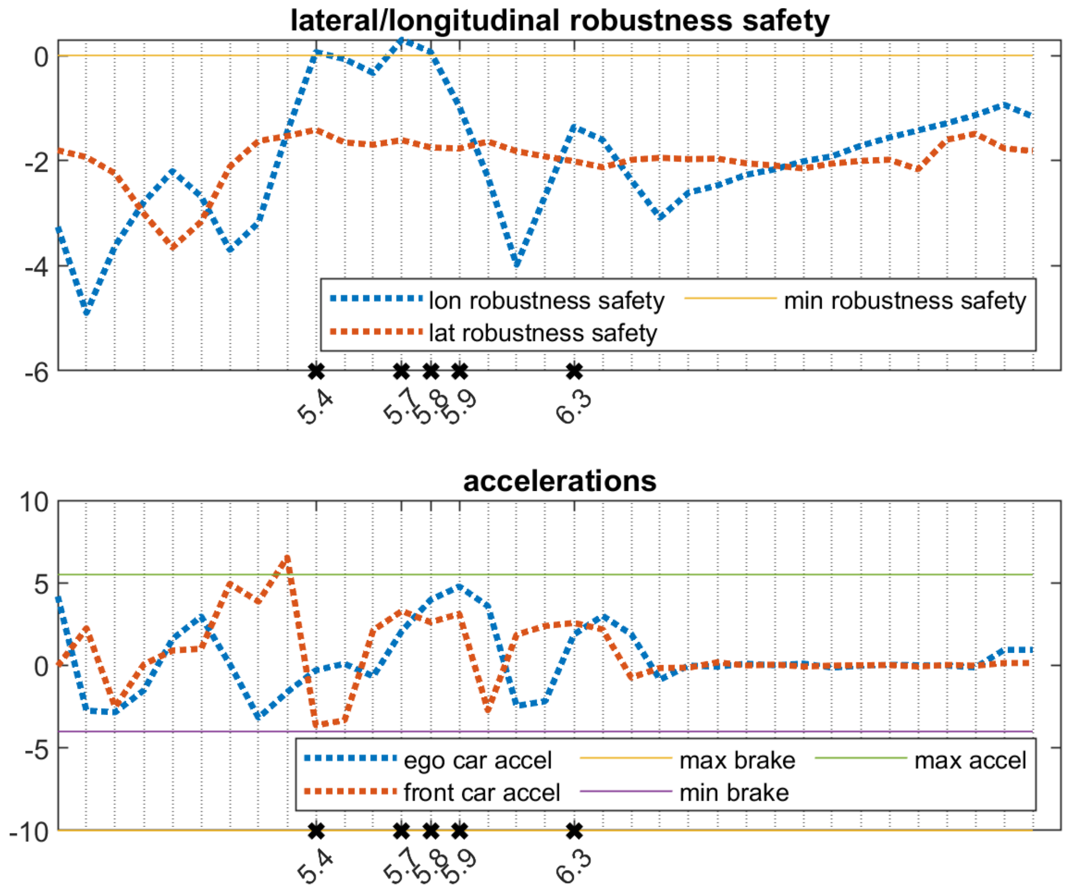


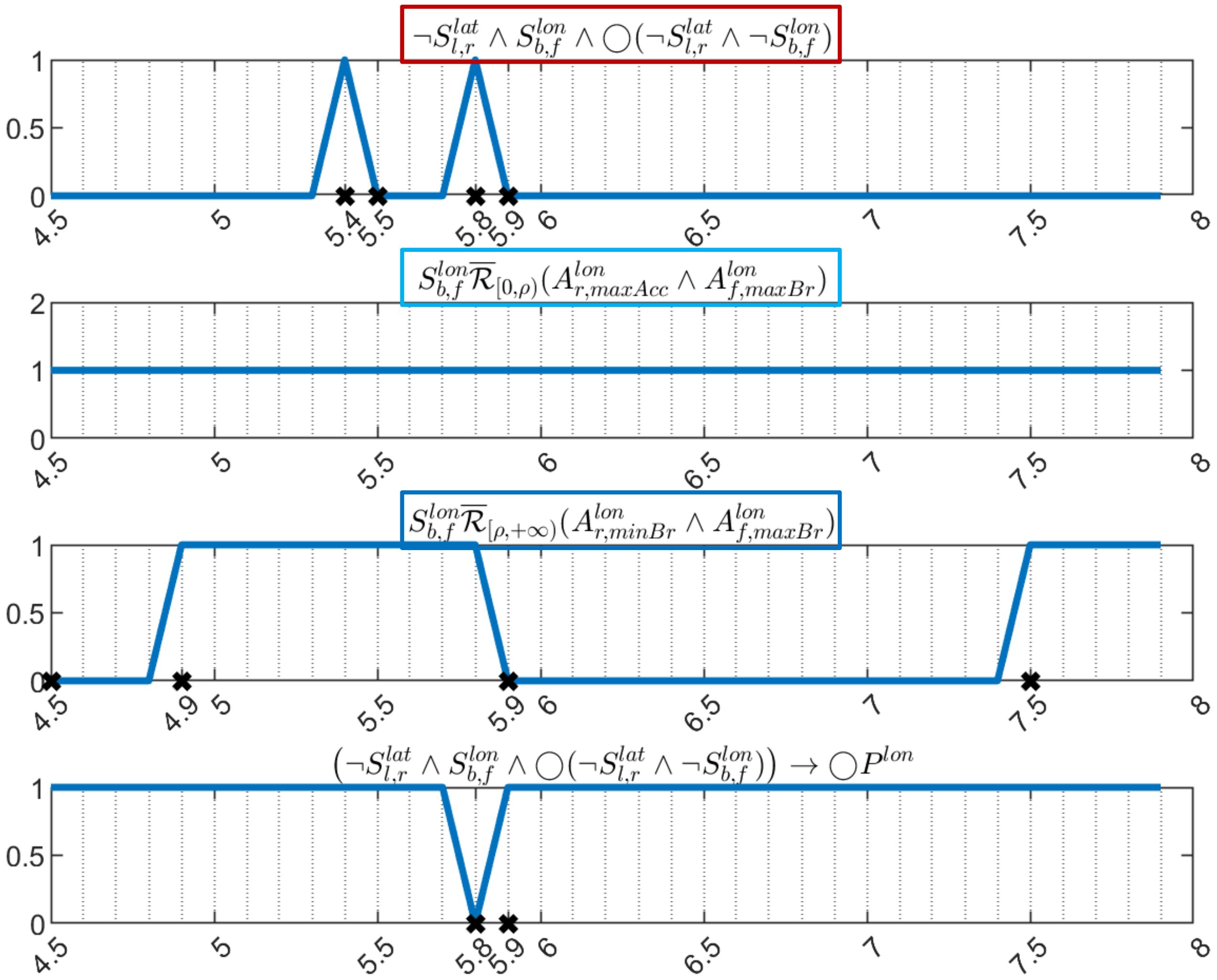
- $a^{lon}_{max,acc} = 5.5\ m/s^2$
- $a^{lat}_{max,acc} = 3\ m/s^2$
- $a^{lon}_{min,brake} = 4\ m/s^2$
- $a^{lon}_{max,brake} = 10\ m/s^2$
- $a^{lat}_{min,brake} = 3\ m/s^2$
- $a^{lat}_{max,brake} = 3\ m/s^2$
- $\rho = 0.5$
- $\mu = 0.4\ m$

Safety Charts

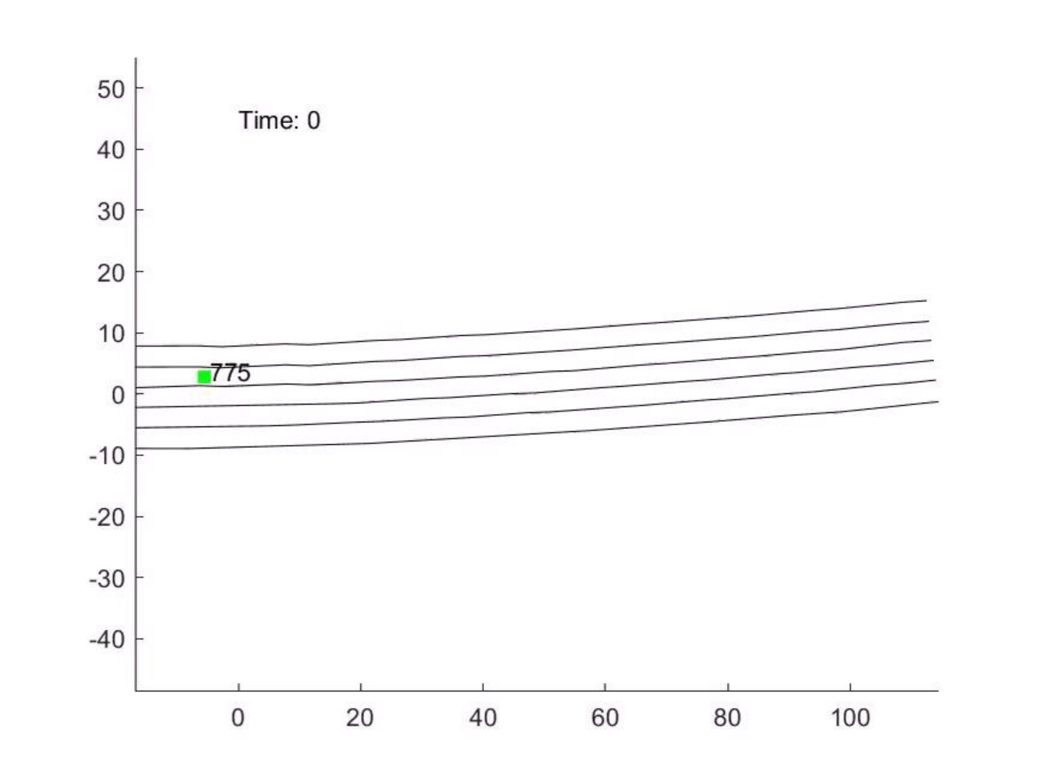
$$\varphi^{lon} \equiv \Box\left(\left(\neg S_{l,r}^{lat} \wedge S_{b,f}^{lon} \wedge \bigcirc\left(\neg S_{l,r}^{lat} \wedge \neg S_{b,f}^{lon}\right)\right) \to \bigcirc P^{lon}\right)$$

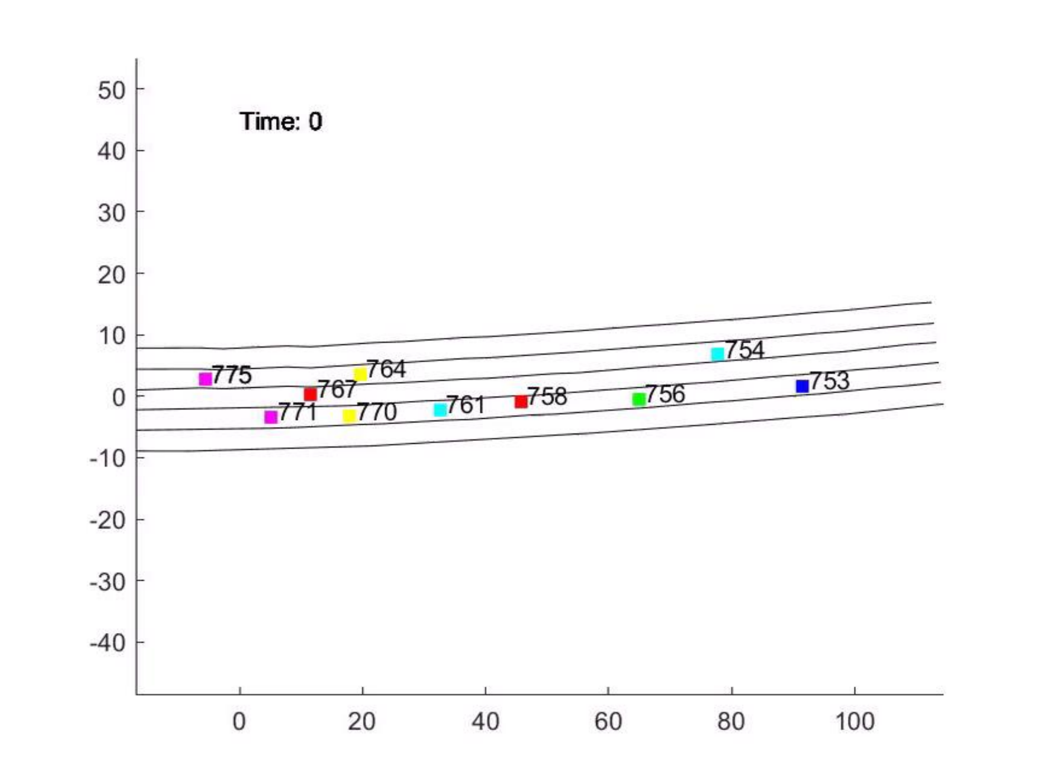
$$P^{lon} \equiv \left(S_{b,f}^{lon} \bar{\mathcal{R}}_{[0,\rho)}\left(A_{b,maxAcc}^{lon} \wedge A_{f,maxBr}^{lon}\right)\right) \wedge \left(S_{b,f}^{lon} \bar{\mathcal{R}}_{[\rho,+\infty)}\left(A_{b,minBr}^{lon} \wedge A_{f,maxBr}^{lon}\right)\right)$$





Monitoring Demo





Experimental results

Longitudinal Predicates	# of Violations φ^{lon}	# of Violations φ^{lon}_{lat}
safe_long	2	2
safe_lat	1	0
a_ego_lt_max_acc	18	18
a_ego_gt_min_brake	**190**	**184**
a_front_max_brake	9	9
Lateral Predicates	**# of Violations φ^{lon}**	**# of Violations φ^{lon}_{lat}**
safe_long	0	0
safe_lat	9	8
a_ego_lat_lt_max_acc	**188**	**186**
a_ego_lat_lt_min_brake	0	0
a_right_lat_max_acc	**256**	**256**
a_right_lat_min_brake	0	0
stopped_ego_lat	39	36
stopped_right_lat	0	0
ego_lat_velocity_neg	0	0
right_lat_velocity_pos	0	0

Lateral & Longitudinal Predicates	# of Violation $\bar{\varphi}^{lat,lon}$	# of Violation $\varphi^{lat,lon}$
safe_long	0	0
safe_lat	0	0
a_ego_lat_lt_max_acc	0	0
a_ego_lat_lt_min_brake	0	0
a_right_lat_max_acc	5	3
a_right_lat_min_brake	0	0
stopped_ego_lat	0	0
stopped_right_lat	0	0
ego_lat_velocity_neg	0	0
right_lat_velocity_pos	0	0
a_ego_lt_max_acc	0	0
a_ego_gt_min_brake	4	0
a_front_max_brake	1	1

Execution Statics		
Total violation	**722**	**703**
Violation percentage	**5.9%**	**5.74%**

Experimental results (cont’)

Lateral & Longitudinal Predicates	# of Violation $\overline{\varphi}^{\neg lat,\neg lon}$	# of Violation $\varphi^{\neg lat,\neg lon}$
safe_long	0	0
safe_lat	0	0
a_ego_lat_lt_max_acc	**172**	**166**
a_ego_lat_lt_min_brake	0	0
a_right_lat_max_acc	**177**	**161**
a_right_lat_min_brake	0	0
stopped_ego_lat	**420**	**350**
stopped_right_lat	0	1
ego_lat_velocity_neg	0	0
right_lat_velocity_pos	0	0
a_ego_lt_max_acc	6	7
a_ego_gt_min_brake	5	3
a_front_max_brake	0	1

Execution Statics		
Total violation	**780**	**689**
Violation percentage	**6.37%**	**5.63%**

item	
Average runtime per monitor execution (*ms*)	21
Average number of cars in each scenario	48
Average number of surrounding cars to be monitored	8.8
Average length of trajectories per car (*s*)	6.8

Sensitivity Analysis

parameter	values								
$a^{lon}_{max,acc}$	2.75			5.5			8.25		
$a^{lat}_{max,acc}$	1.5			3			4.5		
$a^{lon}_{max,brake}$	5			10			15		
$a^{lon}_{min,brake}$	6			4			2		
$a^{lat}_{min,brake}$	4.5			3			1.5		
ρ	0.3	0.5	2	0.3	0.5	2	0.3	0.5	2
Violations %	**0.5%**	**0.8%**	**11%**	**2.3%**	**5.2%**	**15.5%**	**6.7%**	**15%**	**23.1%**

Conclusions

- Translation of the Responsibility-Sensitive Safety (RSS) rules into Signal Temporal Logic (STL)
- The encoded formulas could be used for
  - ADS model verification
  - Automated test case generation for discovering control software bugs (our Sim-ATAV framework*)
  - Test the control and perception system stack against the RSS model
- We utilized the STL formulas to monitor off-line naturalistic driving data provided with CommonRoad.
- Computation is efficient
- The RSS rules are satisfied in the majority of the actual vehicle trajectories (assuming fast reaction times by the drivers).
- **Future works:**
  - We are completing all the RSS rules in our translation.
  - Formalize in STL the RSS rules concerning different road geometries.

* C. E. Tuncali, G. Fainekos, H. Ito, and J. Kapinski, "**Simulationbased adversarial test generation for autonomous vehicles with machine learning components**," in IEEE Intelligent Vehicles Symposium (IV), 2018.

Thank You!

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