Compositional and Contract-based Verification for Autonomous Driving on Road Networks

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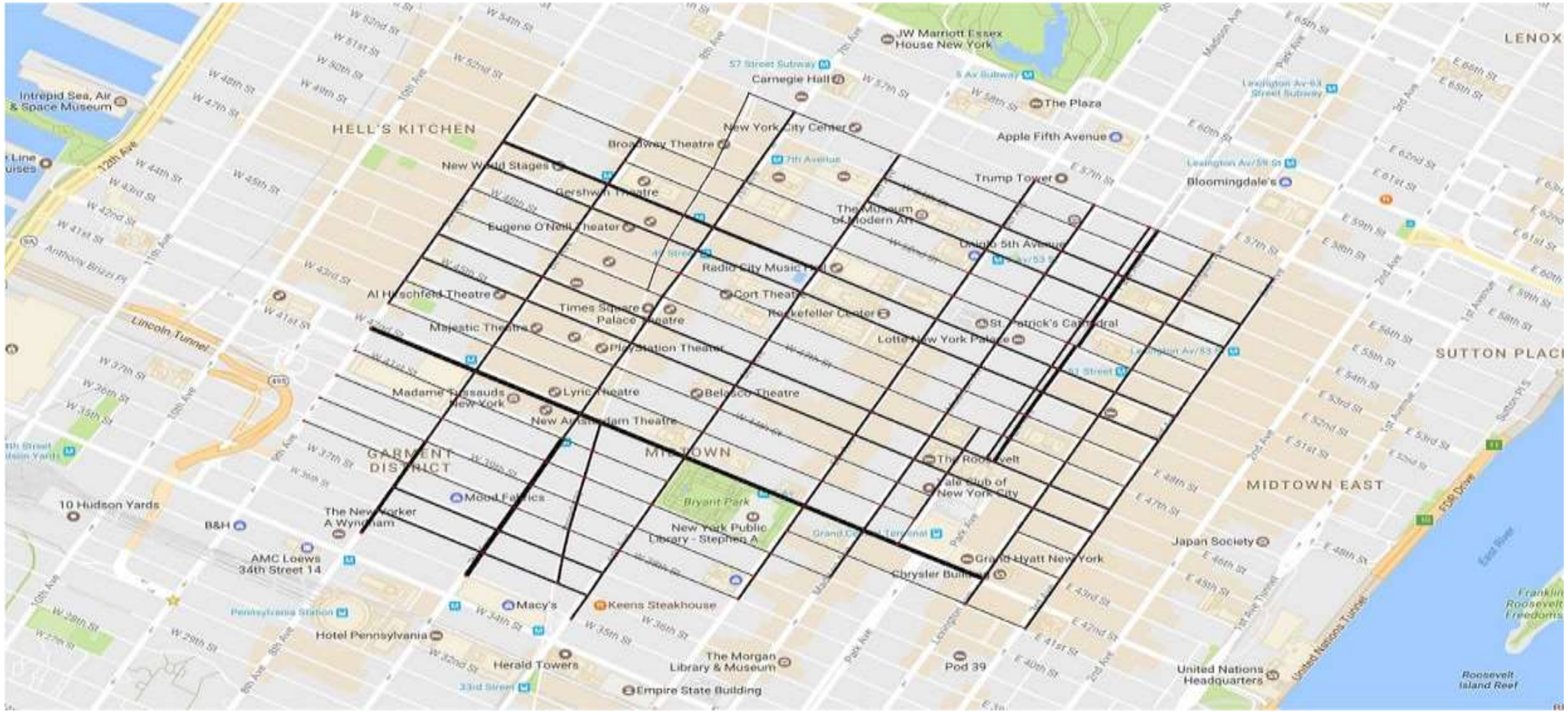
Massachusetts Institute of Technology

CSAIL

How can we obtain safety guarantees?



Problem Definition

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Verification Components		
System	Model	Specification – Controller Contract $\mathcal{S}$
• **Controller:** $$\mathbf{u}_{\boldsymbol{k}} = C\left(\boldsymbol{z}_k^{0:N}\right),$$ where $\boldsymbol{z}_k^i$ is state of car i at time k with **The controller is assumed to abide by the controller contract $\mathcal{S}$.**		

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	• **Ego-Car:** $V = (\mathcal{Z}, \mathcal{R}, \mathcal{U}, f, h)$ with $z_{k+1} = f(z_k)$, where
	$\dot{\mathbf{z}} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\delta} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} v\cos(\theta) \\ v\sin(\theta) \\ \frac{v}{L}\tan(\delta) \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \underbrace{\begin{bmatrix} u^\delta \\ u^a \end{bmatrix}}_{\mathbf{u}}$
	
	• **Road Geometries:** $m = (\mathcal{Z}, \mathfrak{I}, \mathfrak{D}, S, A)$
	  • Straight Roads
	  • Intersections
	
	• **Traffic Model**: $T = (\mathcal{V}(0), \mathfrak{I}, \mathfrak{D}, S)$
	  • Spline Representation
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	• **Traffic Model**: $T = (\mathcal{V}(0), \mathfrak{I}, \mathfrak{O}, S)$
	  • Spline Representation
	  • Traffic Scheduler
		• **Safety:** $\inf_{\mathbf{z} \in B(\mathbf{z}_k), \mathbf{o} \in O_k} \lvert\mathbf{z} - \mathbf{o}\rvert > \pi_{safety}$
		
		• **Speed Limit:** $\lvert v\rvert \leq v_{max}$
		
		• **Dynamic Limitation:** $\lvert\delta\rvert \leq \delta_{max}$, $\lvert u^\delta\rvert \leq \dot{\delta}_{max}$, $a_{min} \leq u^a \leq a_{max}$

Technical Challenges

- Verification is HARD
- Computational tractability often not feasible
- Model complexity increases cost
- Realistic scenarios requires scalable models

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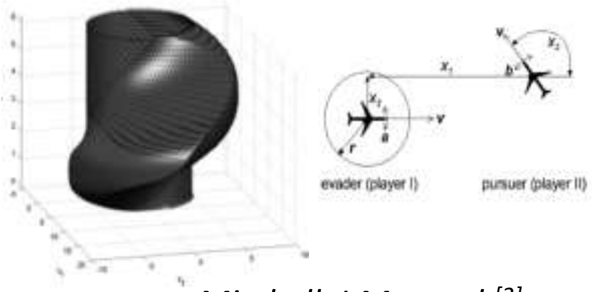
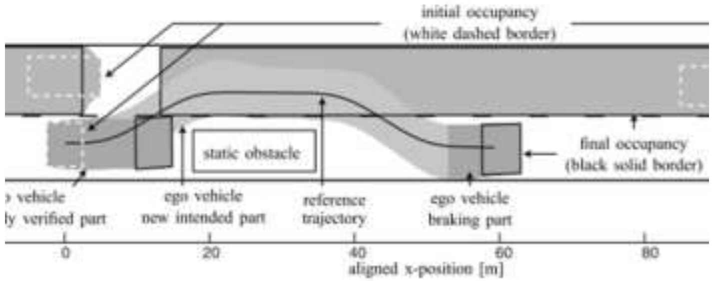
How do we maintain computational tractability while capturing realistic scenarios?

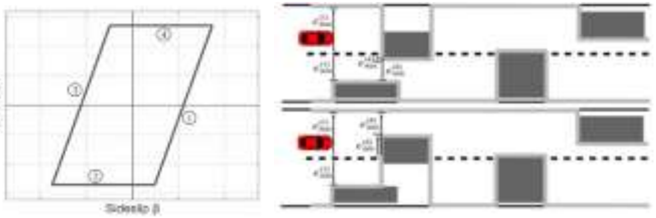
Related Work



Mitchell, I.M., et.al.[2]



Althoff, M., et.al.[3]



Erlien, S.M., et.al.[4]

- Backwards Reachability from Goal
- Formulation as Hamilton-Jacobi PDE
- Solution over Discretized State Space

- Online Verification of Planned Maneuvers
- Rough Approximations for Reachable Sets
- Safe Backup Trajectory

- Shared Steering Control
- Safety Guarantees through Dynamical and Road Constraints
- MPC Looks for Possible Trajectory to Ensure Safety

[2] Mitchell, I.M., et. al.: A time-dependent Hamilton-Jacobi formulation of reachable sets for continuous dynamic games. IEEE Transactions on Automatic Control 50(7), 947–957 (2005)
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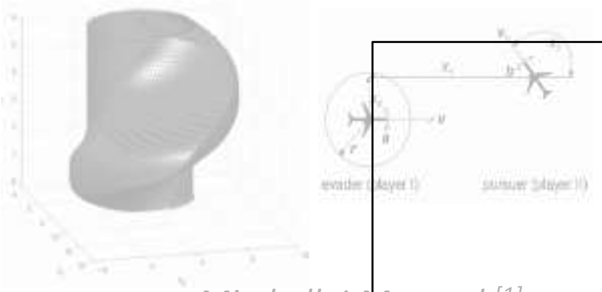
Related Work



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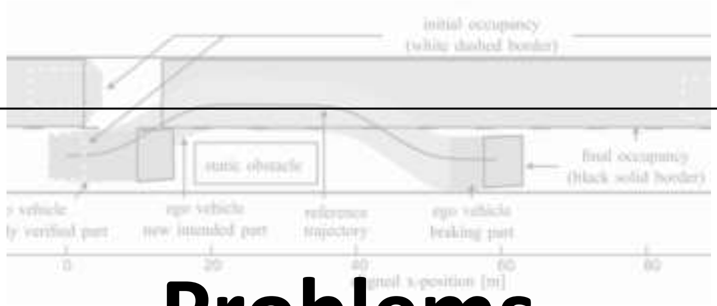

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Problems

- **Accurate but very specific**
- **More general but low-fidelity**

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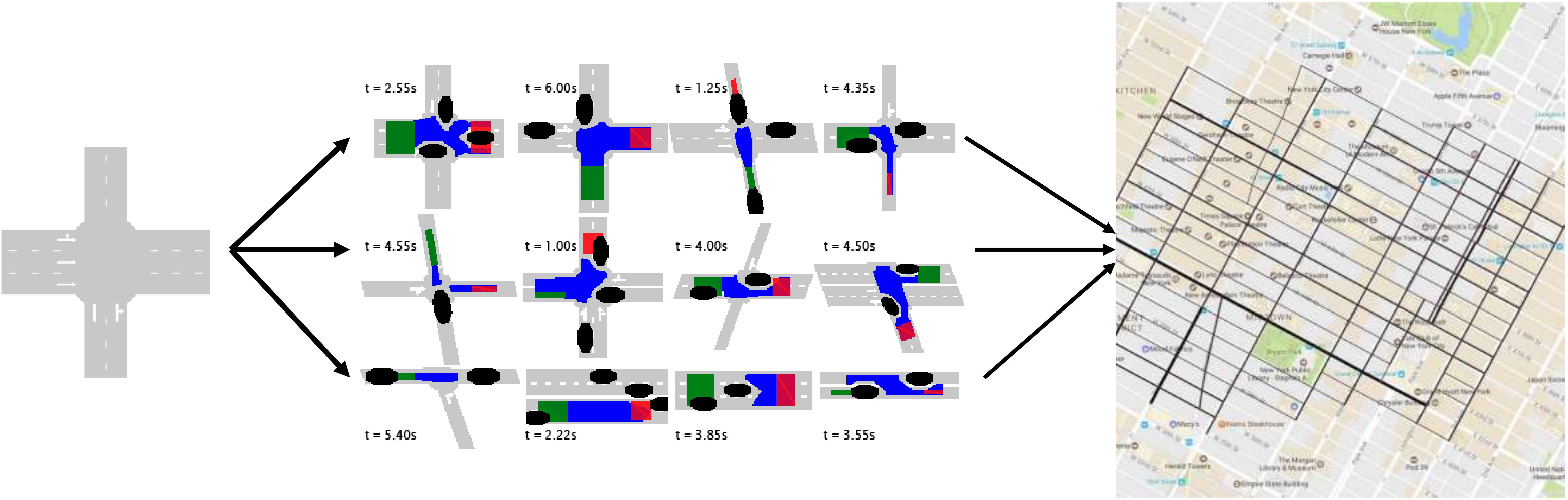
Two Step Approach

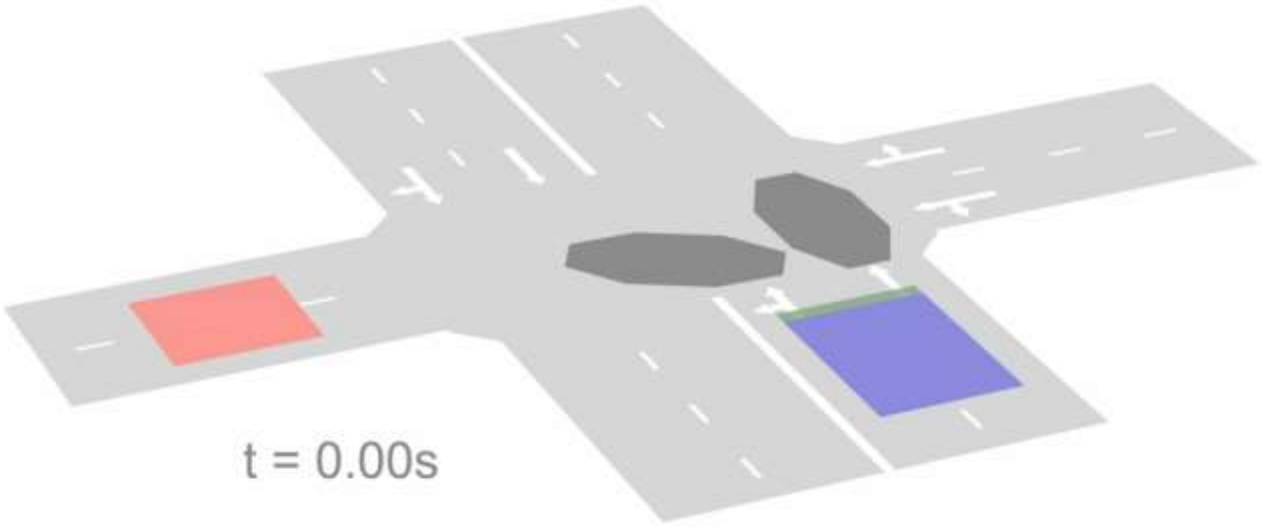


Library of Road Geometries

Parallel Local Verification

Global Guarantees

Local Verification – Results



= Ego Car

= Other Car

= Entry Region

= Exit Region

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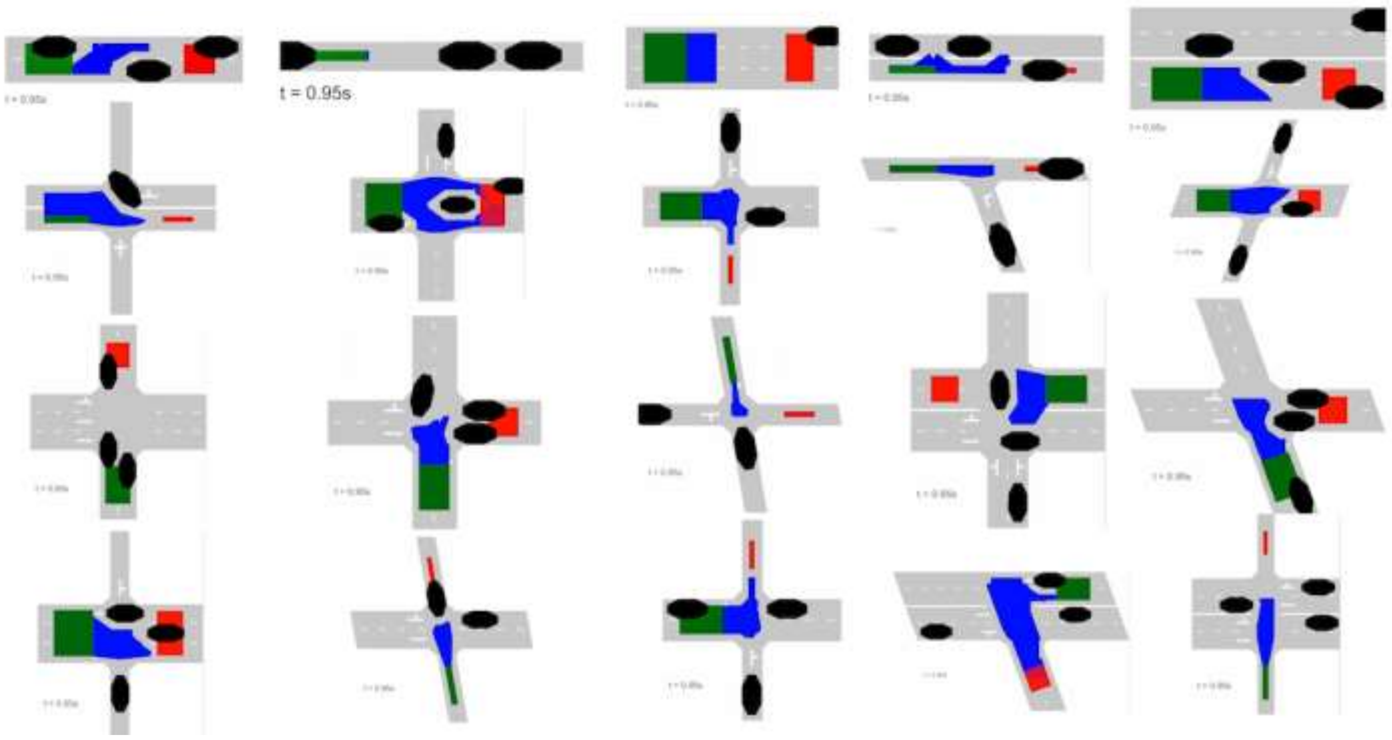

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