Intent-Aware Autonomous Driving: A Case Study on Highway Merging Scenarios

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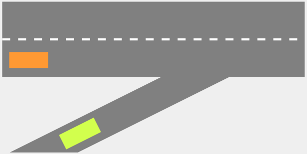
MAD-Games: Multi-Agent Dynamic Games Workshop, IROS 2023
October 01, 2023

Consider a scenario ...



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Note: Fading colors indicate trajectory planned farther in the future.

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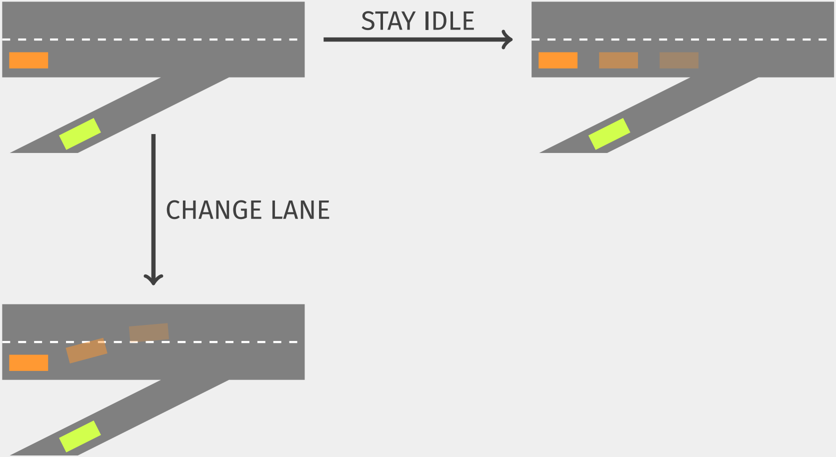

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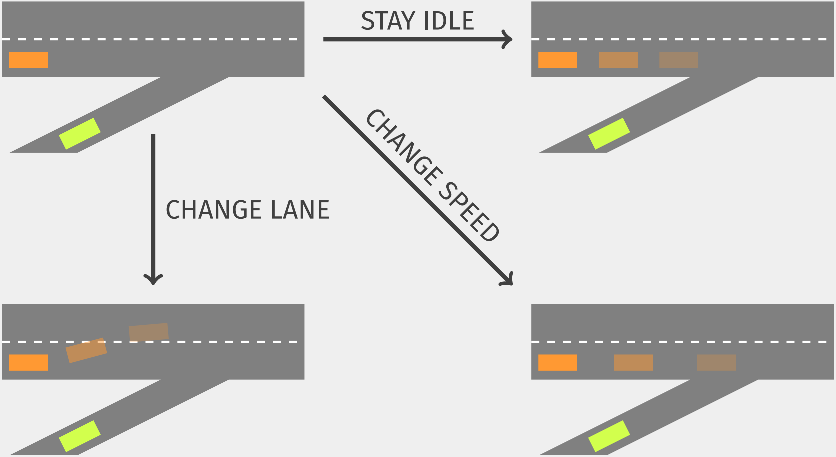

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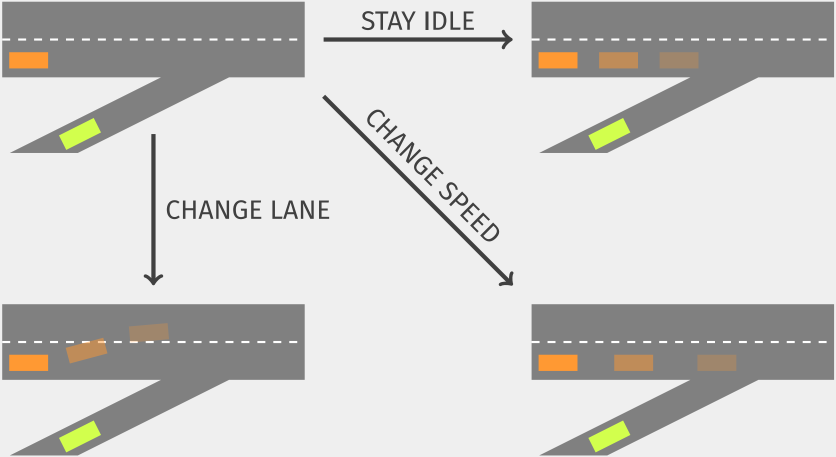
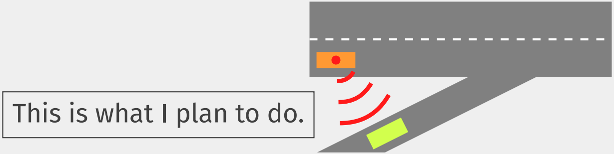


Communicating the intent can help them collaborate!

Note: Fading colors indicate trajectory planned farther in the future.

What is Intent-Sharing?



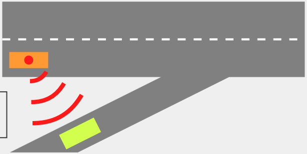
Definition: Intent-Sharing

Information about *planned future actions* of the sending entity provided by that entity for potential utilization by receiving entities.[1]

[1] "Taxonomy and definitions for terms related to cooperative driving automation for on-road motor vehicles," SAE International, Tech. Rep., 2021. `https://www.sae.org/standards/content/j3216_202107/`

What is Intent-Sharing?

This is what I plan to do.



Definition: Intent-Sharing

Information about *planned future actions* of the sending entity provided by that entity for potential utilization by receiving entities.[1]

- The receiving entity does not have to accept the information.
- The sender executes its planned trajectory irrespective of how the receiver responds.

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Our Objectives

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Q3: How to choose an intent to induce the optimal cooperative driving behavior?

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Outline

1. Formulation as a Dynamic Game
2. Implementation for Highway Merging
3. Experiments and Results

Agent 2

Agent 1

Formulation of Intent-Aware AD

$$\text{Agent 2} \xrightarrow{\text{Intent } \mathbf{i}^2} \text{Agent 1}$$

Intent-Sender

Intent-Receiver

Formulation of Intent-Aware AD

$$\mathbf{s}_t = [\mathbf{s}_t^e, \mathbf{s}_t^1, \mathbf{s}_t^2] \qquad a_t = [a_t^1, a_t^2]$$

$$\text{Agent 2} \xrightarrow{\text{Intent } \mathbf{i}^2} \text{Agent 1}$$

Intent-Sender

Intent-Receiver

$$\begin{aligned} &\max_{\pi^2} \ \mathbb{E}\left[\sum_{t=0}^{H} r_t^2 \,\middle|\, \mathbf{s}_0^e, \mathbf{s}_0^2\right] \\ s.t. \quad & \mathbf{s}_{t+1}^2 \sim p^2(\mathbf{s}_t^e, \mathbf{s}_t^2, a_t^2), \ t = 0, \ldots, H-1 \\ & a_t^2 \sim \pi^2(\mathbf{s}_t^e, \mathbf{s}_t^2, \mathbf{i}^2), \quad t = 0, \ldots, H-1 \\ & (\mathbf{s}_t^2)_{t=0}^{H} \in \mathbf{i}^2 \end{aligned}$$

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Intent-Receiver

$$\begin{aligned} &\max_{\pi^1} \ \mathbb{E}\left[\sum_{t=0}^{H} r_t^1 \,\middle|\, \mathbf{s}_0\right] \\ s.t. \quad & \mathbf{s}_{t+1} \sim p(\mathbf{s}_t, a_t), \quad t = 0, \dots, H-1 \\ & a_t^1 \sim \pi^1(\mathbf{s}_t, \mathbf{i}^2), \quad t = 0, \dots, H-1 \\ & (\mathbf{s}_t^2)_{t=0}^{H} \in \mathbf{i}^2 \end{aligned}$$

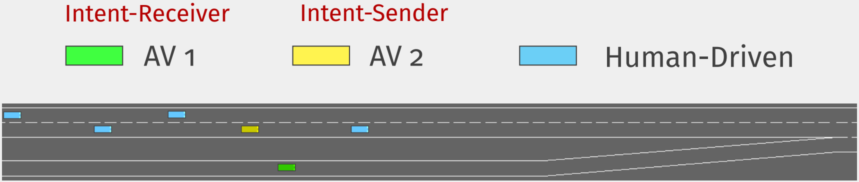

Figure: Initial configuration of our highway merge environment.

Intent-Receiver Intent-Sender

AV 1 AV 2 Human-Driven

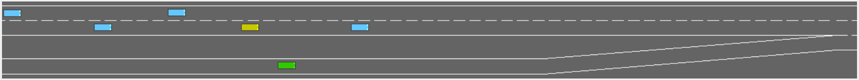

Figure: Initial configuration of our highway merge environment.

1. How can we represent intents?
2. How can intent-sender AV 2 comply with these intents?
3. How can intent-receiver AV 1 utilize the shared intent?

Representation of Intents

Commitment to complying with a shared intent $\Longrightarrow$ Restriction on admissible future behavior

Definition: Intent

An intent is specified by a *subset of actions*, $\mathcal{A}' \subseteq \mathcal{A}$, that the intent-sender AV is *restricted to choose from*, such that:

$$\mathbf{i}_{\mathcal{A}'} := [\mathbb{1}_{a \in \mathcal{A}'}]_{a \in \mathcal{A}}$$

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In this case study:

- $\mathcal{A} = \{\texttt{IDLE}, \texttt{LANE\_LEFT}, \texttt{LANE\_RIGHT}, \texttt{FASTER}, \texttt{SLOWER}\}$.
- Intent-sender AV commits to complying with an intent for the *entire duration* of a simulation episode.

AV 2's Compliance with the Intents

$$\mathcal{A} = \{\texttt{IDLE}, \texttt{LANE\_LEFT}, \texttt{LANE\_RIGHT}, \texttt{FASTER}, \texttt{SLOWER}\}$$

$$\begin{aligned} \mathbf{i}_{\texttt{IDLE}} &= [1, 0, 0, 0, 0] \\ \mathbf{i}_{\texttt{LANE\_LEFT}} &= [1, 1, 0, 0, 0] \\ \mathbf{i}_{\texttt{FASTER}} &= [1, 0, 0, 1, 0] \\ \mathbf{i}_{\texttt{SLOWER}} &= [1, 0, 0, 0, 1] \end{aligned}$$

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\end{aligned}$$

Randomly choose $\mathbf{i}^2$.

AV 2's Compliance with the Intents

$$\mathcal{A} = \{\texttt{IDLE}, \texttt{LANE\_LEFT}, \texttt{LANE\_RIGHT}, \texttt{FASTER}, \texttt{SLOWER}\}$$

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$\boxed{\text{Randomly choose } \mathbf{i}^2.}$ $\xrightarrow{\mathbf{i}^2 = \mathbf{i}_{\texttt{IDLE}}}$ $\boxed{\text{Choose } a_t^2 = \texttt{IDLE} \ \forall\, t}$

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\end{aligned}$$

Randomly choose $\mathbf{i}^2$.

$\mathbf{i}^2 \neq \mathbf{i}_{\texttt{IDLE}}$ → Assign action-trigger position *pos*. → Execute $a \in \mathcal{A}' - \{\texttt{IDLE}\}$ when $x^2 = pos$. Choose IDLE elsewhere.

$\mathbf{i}^2 = \mathbf{i}_{\texttt{IDLE}}$ → Choose $a_t^2 = \texttt{IDLE} \ \forall\, t$

$$\mathbf{s}^e = \left[[x^k, y^k, v_x^k, v_y^k] \right]_{k \in \mathcal{K}}$$
$$\mathbf{s}^1 = [x^1, y^1, v_x^1, v_y^1]$$
$$\mathbf{s}^2 = [x^2, y^2, v_x^2, v_y^2]$$

where human-driven vehicles $\mathcal{K}$ constitute the external state.

$$
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\end{aligned}
$$

where human-driven vehicles $\mathcal{K}$ constitute the external state.

Auxiliary state due to communication:

$$
\mathbf{z}^{1 \leftarrow 2} = \begin{cases} \mathbf{i}^2, & \text{if AV 2 shares its intent with AV 1} \\ \mathbf{0}, & \text{otherwise.} \end{cases}
$$

AV 1's RL-based Intent Utilization [2/2]

$$r_t^1 = r_t^s + r_t^l + r_t^c + r_t^m$$

AV 1's RL-based Intent Utilization [2/2]

high speed reward

right lane reward

collision reward

merge reward

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AV 1's RL-based Intent Utilization [2/2]

high speed reward

right lane reward

collision reward

merge reward

$$r_t^1 = r_t^s + r_t^l + r_t^c + r_t^m$$

$$r_t^m = \begin{cases} {\color{red}r^q} + {\color{green}r^f} + {\color{green}r^r} + {\color{blue}r^e}, & \text{if successful merge at } t \\ 0, & \text{otherwise.} \end{cases}$$

Merging AV is rewarded for quick, safe, and efficient merge.

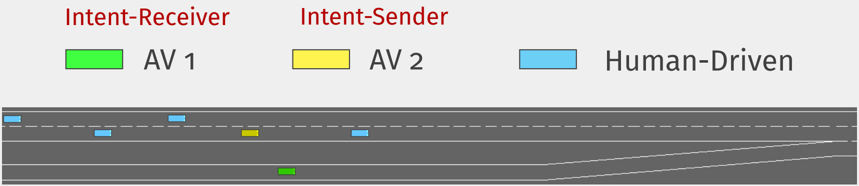


Figure: Initial configuration of our highway merge environment.

Hypothesis: Knowing AV 2's intent will aid AV 1 in performing a better merge.

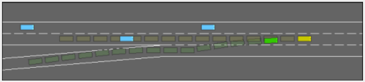
Two scenarios: with and without intent-sharing.

SB3's DQN was used for learning driving policies.

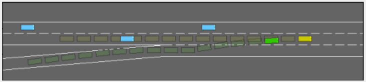
PERFORMANCE

Table: Performance of Learned Merging Policies with and without Intent-Sharing.

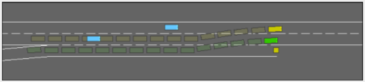
Intent	Action-Trigger Positions (m)	With Intent-Sharing		Without Intent-Sharing	
		Cumulative Reward	Crash Rate (%)	Cumulative Reward	Crash Rate (%)
$\mathbf{i}_{\texttt{IDLE}}$	N/A	**2.725 ± 0.087**	**0.0**	1.416 ± 2.566	20.0
$\mathbf{i}_{\texttt{LANE\_LEFT}}$	220	**3.616 ± 0.000**	**0.0**	3.144 ± 0.338	**0.0**
	250	**3.481 ± 0.000**	**0.0**	2.855 ± 0.577	**0.0**
	280	**3.481 ± 0.000**	**0.0**	2.701 ± 0.514	**0.0**
$\mathbf{i}_{\texttt{FASTER}}$	190	**3.149 ± 0.000**	**0.0**	2.848 ± 0.389	**0.0**
	220	**2.993 ± 0.000**	**0.0**	2.660 ± 0.354	**0.0**
	250	**2.767 ± 0.000**	**0.0**	2.587 ± 0.272	**0.0**
$\mathbf{i}_{\texttt{SLOWER}}$	160	**2.957 ± 0.742**	**0.0**	1.490 ± 3.072	20.0
	190	**2.898 ± 0.562**	**0.0**	1.436 ± 2.894	20.0
	220	**2.736 ± 0.486**	**0.0**	−0.121 ± 3.010	40.0



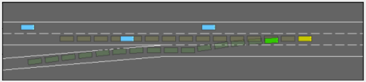
(a) IDLE – With Intent-Sharing



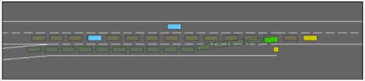
(b) IDLE – Without Intent-Sharing



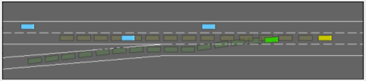
(c) LANE_LEFT at 280 m – With Intent-Sharing



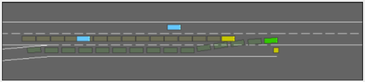
(d) LANE_LEFT at 280 m – Without Intent-Sharing



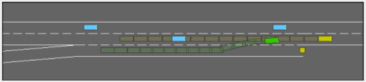
(e) FASTER at 220 m – With Intent-Sharing



(f) FASTER at 220 m – Without Intent-Sharing



(g) SLOWER at 190 m – With Intent-Sharing



(h) SLOWER at 190 m – Without Intent-Sharing

Figure: Snapshots at merge with visible past trajectories.

Conclusion and Future Work

Summary:

- We formulate intent-aware AD as a multi-agent decision problem.
- Using a case study with two AVs in a highway merging scenario, we demonstrate the benefit of intent-aware AD for the intent-receiver AV.

Directions for Future Work:

- Choosing of intent via joint learning of intent-sender and intent-receiver agents.
- Scaling beyond two-agent-one-intent setting.
- Extending to scenarios beyond merging.

Thank you!