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Behavioral Analysis and Impact Assessment of Automated Driving Systems' Interaction With Traffic Lights

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Introduction

Motivations

- Autonomous vehicle (AV) deployment is accelerating, but AV behavior remains poorly understood.
- Infrastructure planners and operators lack confidence in forecasting how AVs will interact with existing infrastructure (e.g., traffic lights).[1]
- Current studies focus mainly on car-following[2] and lane-changing[3] maneuvers on freeways and highways, with less studies on the behaviors at signalized intersections and their system-level impacts.

Contributions

- Behavior understanding:
  - First modeling of autonomous driving system (ADS)–traffic light interactions.
  - Calibrated and validated with real-world field data.
  - Captures five interaction scenarios and behavioral modules.
- Impact assessment: Evaluated mobility and safety impacts under varying AV penetration and demand levels.

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Methodology

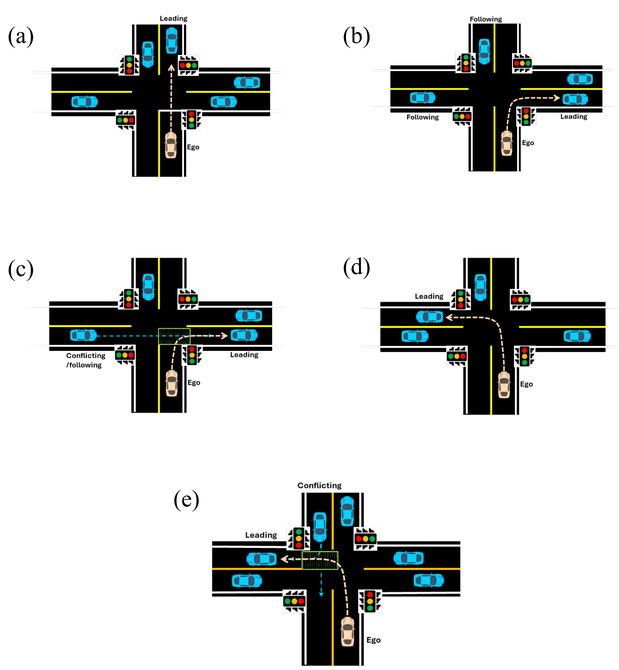
Five key modules:

- Module 1: Follow the lead vehicle to proceed (car-following model).
- Module 2: Make stop decision.
- Module 3: Stop before the stop line (car-following model).
- Module 4: Make merge decision (right-of-way rule).
- Module 5: Make cross decision (right-of-way rule).

Seven Models for five scenarios (figure 1):

- Model 1: Stop behavior on red and yellow = module 1+ module 2 + module 3.
- Model 2: Straight movement on green = module 1.
- Model 3: Protected right turn on arrow green = module 1.
- Model 4: Protected left turn on arrow green = module 1.
- Model 5: Permitted right turn on circular green = module 1.
- Model 6: Right turn on circular red = module 1 + module 2 + module 3 + module 4.
- Model 7: Permitted left turn on circular green = module 1 + module 3 + module 5.

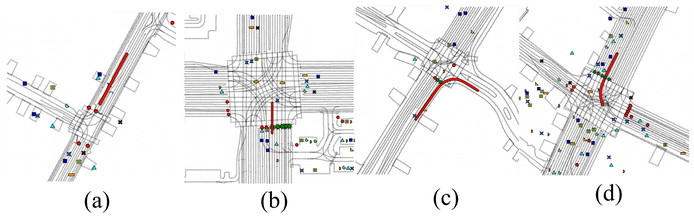
Figure 1 illustrates traffic scenarios: (a) straight movement, (b) right turn without conflict vehicles, (c) right turn with conflict vehicles, (d) left turn without conflict vehicles, and (e) left turn with conflict vehicles.



All images source: FHWA.

Calibration and Validation

Figure 2 shows the data samples[4] in the Waymo Open dataset[5], illustrating ADS and traffic light interactions: (a) stop behavior, (b) straight movement behavior, (c) right turn behavior, and (d) left turn behavior.



Position and speed root mean square errors (RMSEs) were used in the objective function.

$$\min_{\boldsymbol{\beta}^m} \frac{1}{I^m}\sum_{i=1}^{I^m}\left(RMSE_v^{m,i} + RMSE_{x,y}^{m,i}\right)$$

$$RMSE_v^{m,i} = \sqrt{\frac{1}{N^{m,i}}\sum_{n=1}^{N^{m,i}}\left(v_n^{m,i} - \hat{v}_n^{\,m,i}(\boldsymbol{\beta}^m)\right)^2}$$

$$RMSE_{x,y}^{m,i} = \sqrt{\frac{1}{N^{m,i}}\sum_{n=1}^{N^{m,i}}\left(x_n^{\,m,i} - \hat{x}_n^{\,m,i}(\boldsymbol{\beta}^m)\right)^2 + \left(y_n^{m,i} - \hat{y}_n^{\,m,i}(\boldsymbol{\beta}^m)\right)^2}$$

$N^{m,i}$ = total number of time steps of model m's instance i.

Results

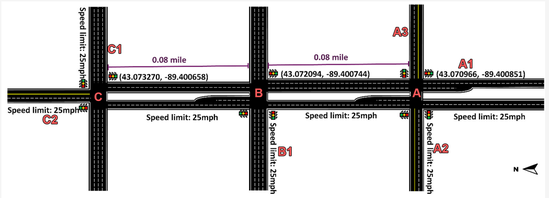
Table 1 shows model calibration results.

Parameter \ Model	Stop Behavior on Red and Yellow	Straight Movement on Green	Protected Left Turn on Arrow Green	Protected Right Turn on Arrow Green	Permitted Right Turn on Circular Green	Right Turn on Circular Red	Permitted Left Turn on Circular Green
Maximum acceleration (m/s²)	4.77	1.25	1.42	2.14	1.84	1.25	1.53
Comfortable deceleration (m/s²)	4.00	6.00	8.50	7.50	0.67	2.50	1.97
Maximum deceleration (m/s²)	7.50	—	—	—	—	—	—
Minimum gap (m)	2.50	2.21	0.55	0.55	1.11	1.75	1.97
Desired time headway (s)	1.63	1.09	0.55	0.89	1.78	1.75	0.75
Desired speed (m/s)	10.55*	20.00*	—	—	—	—	—
Desired speed on entry lane (m/s)	—	—	10.50*	6.08*	5.59*	7.50*	6.20*
Desired speed on exit lane (m/s)	—	—	14.50*	8.50*	22.00*	12.50*	13.50*
Desired speed when entering junction (m/s)	—	—	8.17	6.25	5.54	12.50	9.87
Desired speed when exiting junction (m/s)	—	—	14.50	6.51	6.02	12.50	11.61
Base impatience	—	—	—	—	0.50	0.25	0.20

—Parameter not applicable to specific model.
*The calibrated speed applies only to a short segment immediately following the turn.

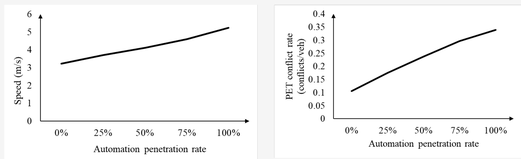
Case Study

Figure 3 shows the case study network, as implemented in SUMO[6], selected for ADS model implementation.



Study area: University of Wisconsin-Madison, Madison, WI

Figure 4 presents network performance with different automation penetration rates, illustrating the mobility-safety tradeoff trend because of ADS's style.



Mobility improvement: Around 80% speed improvement at high ADS penetration.

Safety impact: Number of conflicts roughly triples at high ADS penetration.

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