Mixed-Traffic Intersection Management Utilizing Connected and Autonomous Vehicles as Traffic Regulators

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Outline

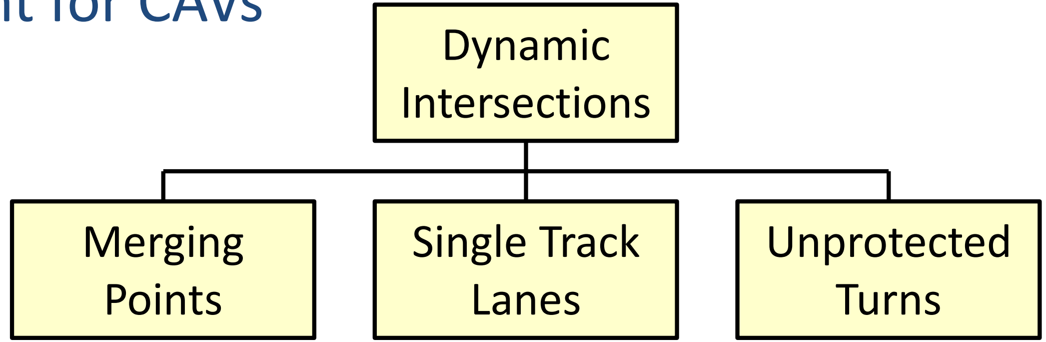
- ❑ **<u>Introduction</u>**
- ❑ Motivating Example
- ❑ System Model
- ❑ Our Approaches
- ❑ Experimental Results
- ❑ Conclusion

Connected and Autonomous Vehicles (CAV)

- Great potentials to improve safety and traffic performance
  - Precise control compared to human-driving vehicles (HV)
  - Vehicle-to-everything communication

Intersection Management

- Intersection management for CAVs
  - Modeling
  - Protocol design
  - Scheduling
  - Analysis
  - One of the highly-researched areas



- Various similar traffic scenarios
  - Provide extensibility to intersection management

Motivations

- Current studies mostly assume that traffic consists of pure CAVs, without any HV
- CAVs in **mixed-traffic** intersection protocols suffer performance loss due to the presence of HV
- It is challenging to fully utilize CAV's potentials in mixed-traffic
  - HVs do not change their behaviors to accommodate the presence of CAVs

Goal

- Lessen the performance loss caused by HV in mixed-traffic intersection
  - Being able to schedule CAVs and HVs within mixed-traffic
  - Extendable to dynamic intersections
  - Effective even without a high CAV penetration rate

Contributions

- Schedule CAVs to control the subsequent HVs
  - An optimal dynamic programming approach to a single conflict zone model
  - An optimal mixed integer linear programming (MILP) formulation for a trajectory-based model
  - An efficient MILP-based approach keeping good solution quality
- Experimental results and SUMO simulation indicate that
  - Controlling CAVs by our approaches is effective to regulate mixed-traffic even if the CAV penetration rate is low
  - This brings incentive to early adoption of CAVs

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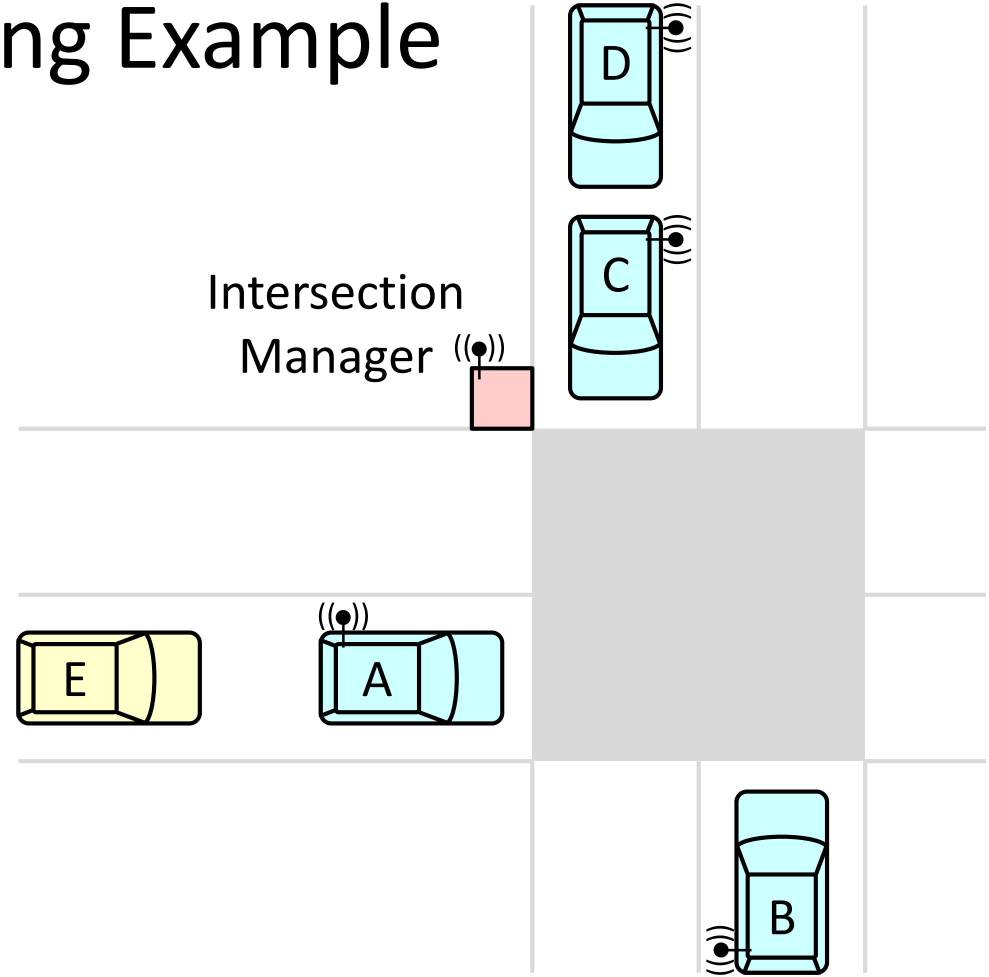
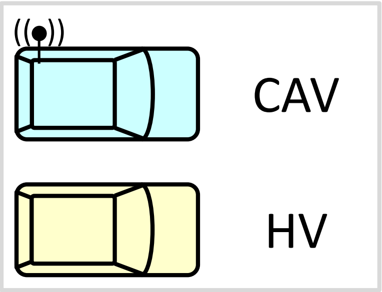
Scheduling in Mixed Traffic

- Inspired by "Dissipation of Stop-And-Go Waves via Control of Autonomous Vehicles: Field Experiments" [Stern 2018]
  - Even if only part of the traffic is controllable within a non-overtaking scenario preceding vehicles can regulate the following vehicles

Motivating Example

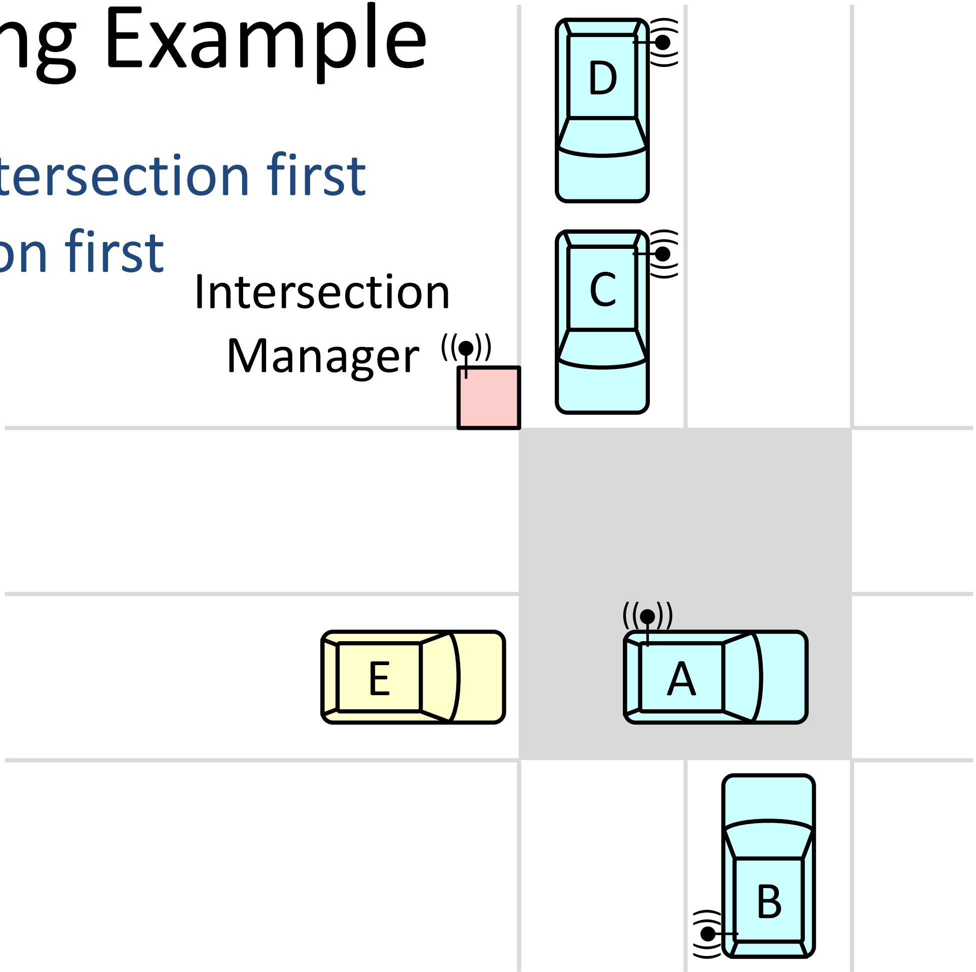
- There are 4 CAVs and 1 HV
  - CAVs: A, B, C, and D
  - HV: E

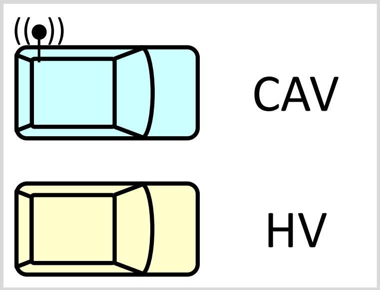




Motivating Example

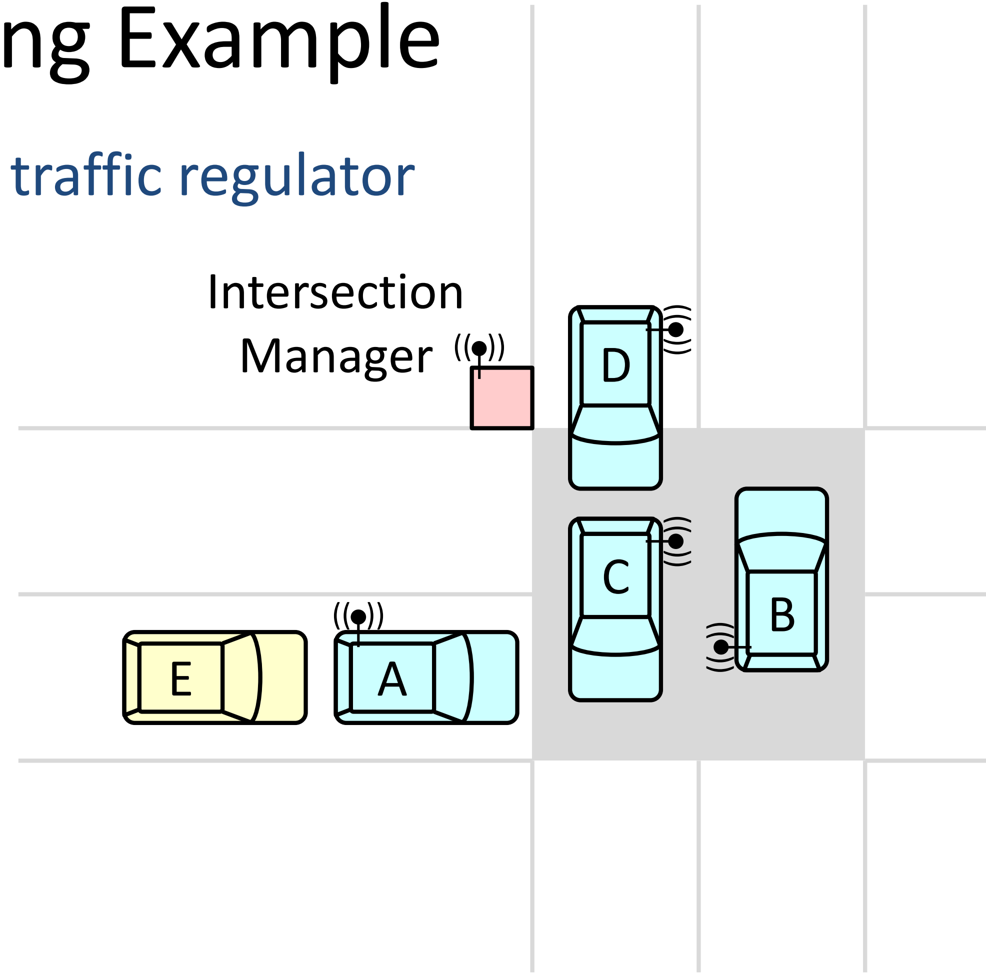
- CAV A passes through the intersection first as it arrives at the intersection first
  - Leave CAVs B, C, and D to pass through the intersection with the presence of HV E
  - Result in performance loss

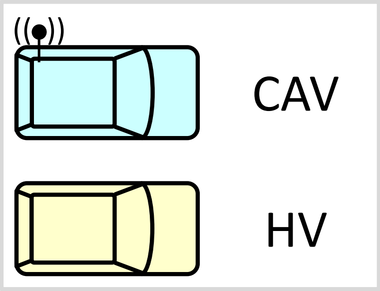




Motivating Example

- CAV A can play the role as a traffic regulator
  - CAV A blocks HV E
  - CAVs B, C, and D can pass through the intersection first without the presence of HV E
  - The overall performance can be improved





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Behaviors of CAVs and HVs

- An overtaking-prohibited mixed-traffic intersection
- CAVs behave depending on whether there exists an HV at the head (as the first vehicle) of any lane
  - If yes, CAVs go slower due to the uncertain behaviors of HVs
  - Otherwise, CAVs may use a more efficient CAV protocol and go faster
- CAVs follow the intersection manager's order to decide when they pass through the intersection
- HVs pass through the intersection as soon as possible

Intersection Models

- Based on how the vehicles are allowed to enter the conflict zone, we have two intersection models
- Single conflict zone model
  - Only a vehicle can enter the intersection (conflict zone) at a time
- Trajectory-based model
  - As long as all the trajectories of the vehicles in the conflict zone do not conflict with each other, vehicles can enter the conflict zone

Problem Formulation (1/2)

❑ Problem input parameters

- $V_{l,i}$: the i-th vehicle on lane l
- L: the number of lanes
- N_l: the number of vehicles on lane l
- $H_{l,i}$: 1 / 0 if $V_{l,i}$ is an HV / CAV
- $A_{l,i}$: the estimated arrival time of $V_{l,i}$
- G: the time gap for the next passing vehicle if there is no HV at the head on each lane
- G^+: the time gap for the next passing vehicle if there exists an HV at the head on a lane

Problem Formulation (2/2)

- Given the input parameters, the problem is to decide the time when each vehicle enters the intersection
  - $t_{l,i}$: the entering time of $V_{l,i}$
- The objective is to minimize the entering time of the last passing vehicle
  - min $\max_{1 \leq l \leq L,\ 1 \leq i \leq N_l} t_{l,I}$
    - It also represents the performance of the intersection processing all vehicles

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- **Our Approaches**
  - Dynamic Programming Approach
  - MILP Formulation
  - MILP-Based Approach
- Experiments
- Conclusion

Our Approaches

- Dynamic programming approach
  - Optimal to the single conflict zone model
- MILP formulation
  - Optimal to the trajectory-based model
- MILP-based approach
  - Efficient and real-time-applicable

Dynamic Programming Approach (1/2)

- In the single conflict zone model, we can represent the system as the number of vehicles passed through each lane
  - State $\Theta = (\theta_1, \theta_2, \ldots, \theta_L)$
- Given a state Θ, the previous state Θ' must be the same as Θ except for one lane having exact one less passed vehicle
  - $\theta'_l = \theta_l - 1$ for exact one l, and the objective only depends on the time gap for v_{l,θ_l}
  - Therefore, the optimality holds with the subproblems
- Given a state, the passing time of the next vehicle is also known since the head vehicle of each lane is known

Dynamic Programming Approach (2/2)

- $OBJ(\Theta) = \min_i (\max (A_{i,\theta_i}, OBJ(\Theta'_i) + TimeGap(\Theta'_i, I)))$
  - Θ'_i indicates that Θ is the state derived from Θ' where the vehicle from lane i pass through next
  - TimeGap() is the passing time of the next vehicle depending on the state of the intersection
- Return an optimal solution to the single conflict zone model with a polynomial time complexity

MILP Formulation

- Convert the trajectory-based model and the constraints into MILP formulation
  - Overtaking is prohibited
  - Time gap must be large enough (for safety)
  - HVs are non-schedulable
- Return an optimal solution to the trajectory-based model with an exponential time complexity

MILP-Based Approach

- Divide and conquer
  - Divide the problem
  - Solve the subproblems with MILP
  - Combine them for a solution
- Efficient and real-time-applicable
  - Still keep good solution quality, though without guarantee of optimality
- With a given subproblem size, the computation time scales linearly with the problem size

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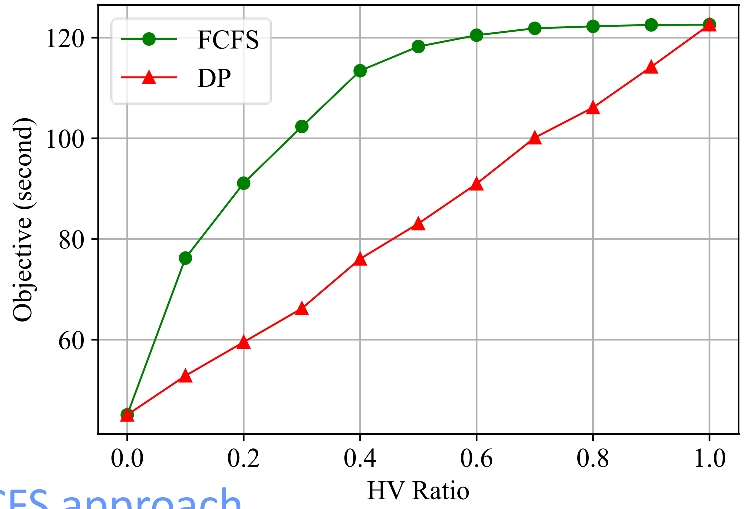
Experimental Setting

- Set the experimental parameters
  - 4 lanes and 5 vehicles on each lane
  - $G = 1$ (second), $G^{+} = 3$ (second)
  - Poisson arrival with $\lambda = 0.5$ vehicle per second
- Run experiments on a laptop with 1.8GHz Intel Core i7-8550U processor and 16GB memory
- Use Gurobi as the MILP solver
- Compare our approaches with the first-come-first-served (FCFS) approach

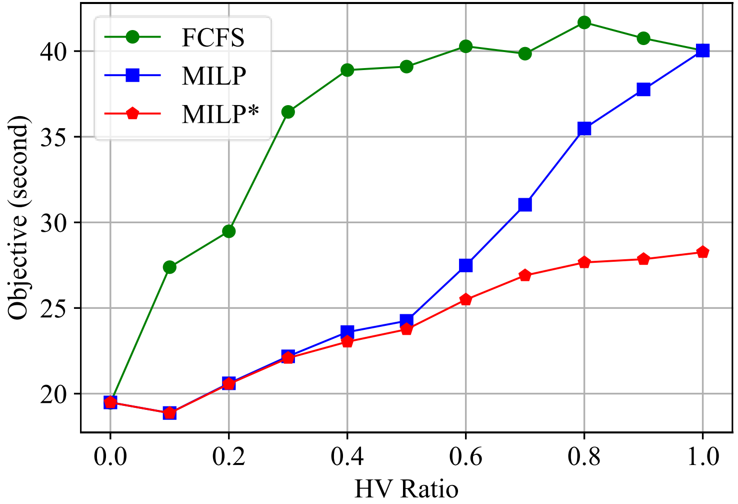
Dynamic Programming Approach

- Comparison between the FCFS approach and the dynamic programming approach for the single conflict zone model
  - When the CAV penetration rate is 0
    - Without controllable vehicles, the two approaches are the same
  - When the CAV penetration rate is 1
    - With all controllable vehicles, the two approaches are the same
  - Otherwise
    - The dynamic approach outperforms the FCFS approach



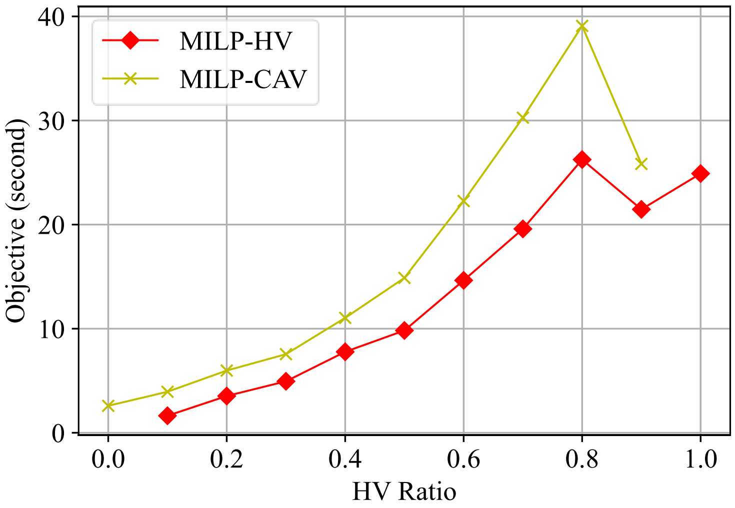
MILP Formulation

- Comparison between the FCFS approach and the MILP formulation for our trajectory-based model
  - MILP* is the case where HVs are assumed to be connected and schedulable
    - Having half vehicles controllable is comparable to having all vehicles controllable
  - Average runtime 0.42 second



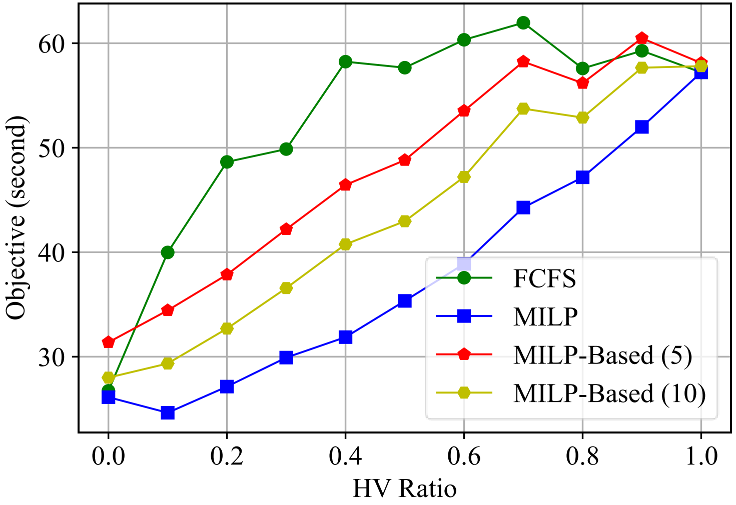
MILP Formulation: CAVs vs HVs

- The waiting time of CAVs is larger than that of HVs
  - Using CAVs to block HVs lets CAVs suffers extra waiting times but improve the overall traffic performance



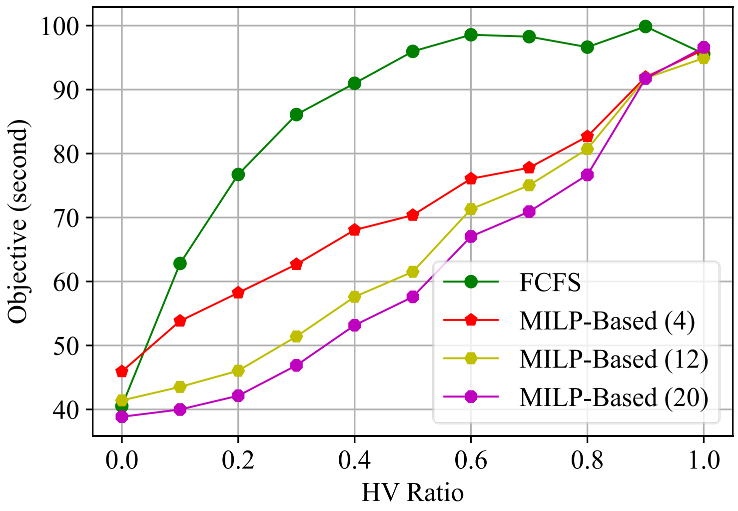
MILP-Based Approach

- When the subproblem size increases
  - The performance improves
- When the subproblem size is the number of vehicles
  - It is equivalent to the MILP formulation which returns an optimal solution



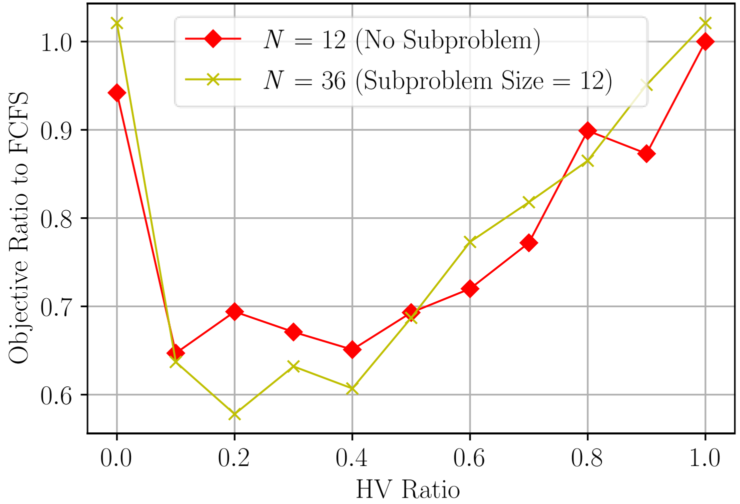
MILP-Based Approach: Computation Time

- ❑ Larger subproblem size
  - ➢ Fewer sub-cases
  - ➢ Better objective value
  - ➢ Longer computation time
- ❑ Tradeoff between solution quality and computation time
  - ➢ The MILP-based approach with subproblem sizes 4, 12, and 20 takes 0.01, 0.08, and 0.42 second, respectively
    - Real-time applicable



MILP-Based Approach vs. MILP Formulation

- Splitting a problem into subproblems (solved by the MILP-based approach) with size 12 gives similar improvement as optimally solving a problem (MILP formulation) with size 12



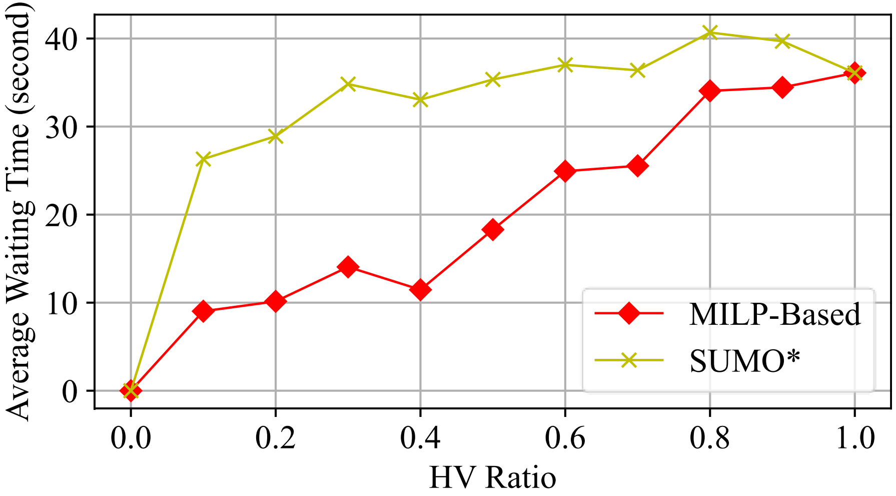
SUMO Simulation Setting

- Simulation of an unsignalized intersection

Type	Parameter	Value
Simulation	Simulation Step	0.1 (s)
	Road Length	500 (m)
Intersection Manager	Sensing Range	100 (m)
	Scheduling Period	1 (s)
Vehicle	Max Speed	16 (m/s)
	Max Acc/Deceleration	3/-4.5 (m/s^2)
	Min Gap	2.5 (m)
	Vehicle-Following Model	Krauss Model

SUMO Simulation Results

- The MILP-based approach significantly outperforms the SUMO unsignalized intersection



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Conclusion

- Target the problem of mixed-traffic intersection management by using CAVs as traffic regulators
  - Dynamic programming approach, MILP formulation, and MILP-based approach
- Controlling CAVs by our approaches is effective to regulate mixed-traffic even if the CAV penetration rate is low
  - This brings incentive to early adoption of CAVs
- Future directions
  - Management with specific lanes for CAVs and HVs
  - Management considering different dynamics of CAVs and HVs

Q&A