Intelligent Intersection Management with Non-Connected and Non-Autonomous Motorcycles

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Introduction

- Intelligent intersection management is a very representative application of connected and autonomous vehicles
  - Many existing works address the problem from different perspectives
    - Centralized approaches
    - Distributed approaches
    - Connected, non-connected, and mixed-type vehicles
    - Autonomous, non-autonomous, and mixed type vehicles
- However, motorcycles have not yet been considered in intelligent intersection management
  - Do motorcycles really matter? Can we regard motorcycles as vehicles, as many countries' policies?

Waterfall of Motorcycles

https://www.taiwannews.com.tw/en/news/3501986

A Left-Turn Accident

https://www.youtube.com/watch?v=7jGPtAEd9yY

Key Features

❑ Designated rightmost lane

- The rightmost lane is for motorcycles only, and the other lanes are for vehicles
- Besides going straight and turning right, a motorcycle on the rightmost lane may intend to turn left
  - This is very different from existing intelligent intersection management, as the left-turn motorcycles will block more traffic than left-turn vehicles

❑ Non-autonomy and non-connectivity

- Connected and autonomous vehicles are more likely to mature before connected and autonomous motorcycles
  - Due to the existing technology, customer willingness, and relative cost

❑ High density

- Regarding the number of motorcycles and vehicles per unit area, motorcycles can move with a higher density

Related Work

- Centralized intelligent intersection management
- Distributed intelligent intersection management
- Intelligent intersection management with mixed traffic
- Motorcycles in transportation

Contributions

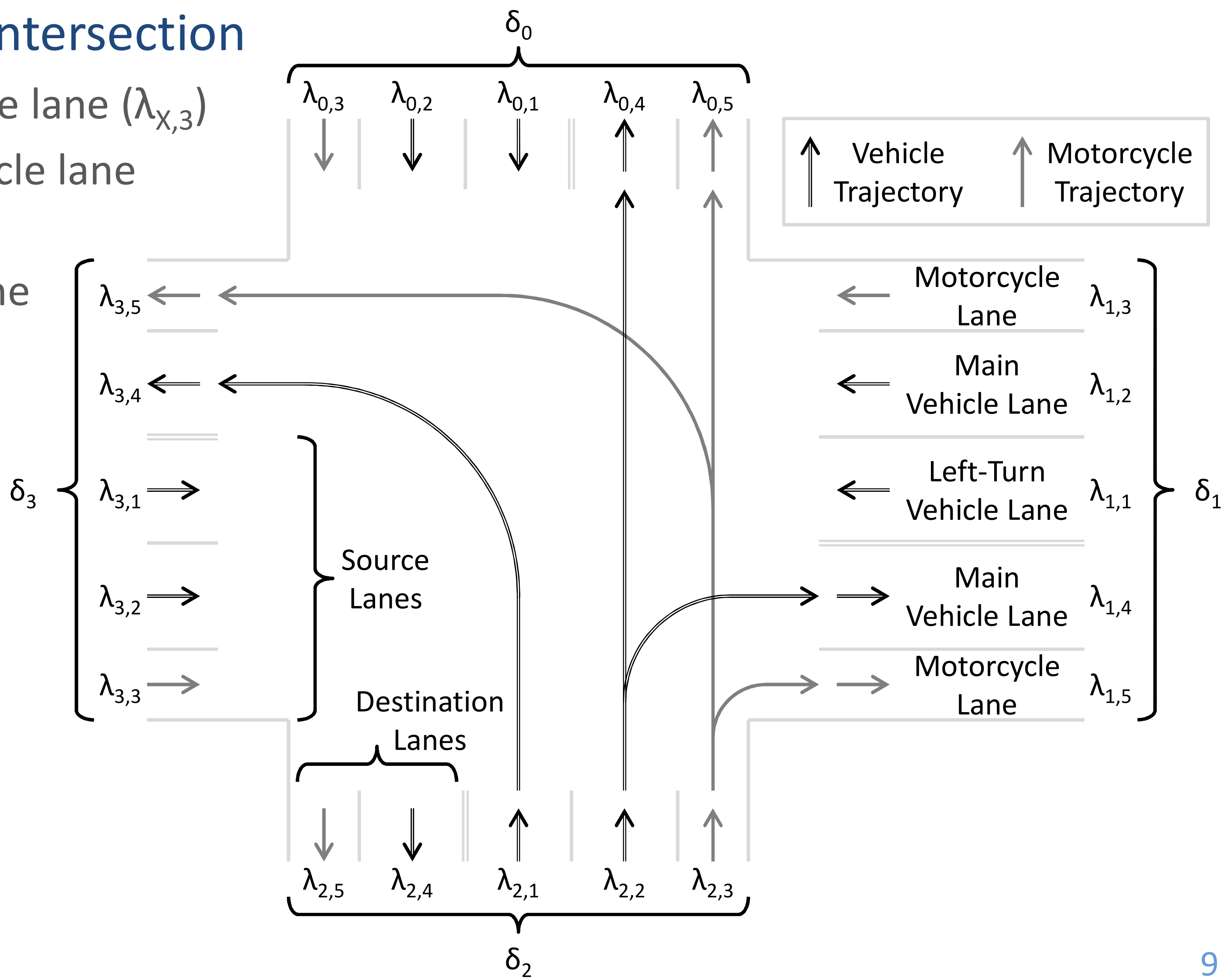
- Model and study the intelligent intersection management with motorcycles
- Use **grouping** and **two-phase left turns with waiting zones** for motorcycles to improve the traffic efficiency of an intersection
  - Vehicles are connected and autonomous
  - Motorcycles are non-connected and non-autonomous
- Demonstrate essential trade-offs and insights for designing intelligent intersection management with motorcycles

Outline

- **System Modeling**
- System Design
- Case Study
- Summary

Intersection and Trajectory

- Four-way intersection
  - Motorcycle lane ($\lambda_{X,3}$)
  - Main vehicle lane
  - Left-turn vehicle lane



Vehicles, Motorcycles, and Manager

- Vehicles: connected and autonomous
  - Send information to the intersection manager
  - Receive instructions from the intersection manager
- Motorcycles: non-connected and non-autonomous
  - Be tracked by road-side units
  - Follow traffic lights
- Intersection manager
  - Receive information of vehicles and provide instructions to vehicles via communication
  - Collect motorcycles' information from road-side units and use traffic lights to control motorcycles

Objective

- Travel time
  - The time length
    - From the time that a vehicle or a motorcycle enters the range of the intersection
    - To the time that it leaves the range of the intersection
- Non-delay travel time
  - Assume that there is no interference by any vehicle, motorcycle, or traffic light
- Delay = travel time – non-delay travel time
- Objective
  - Minimize the average delay of all vehicles and motorcycles

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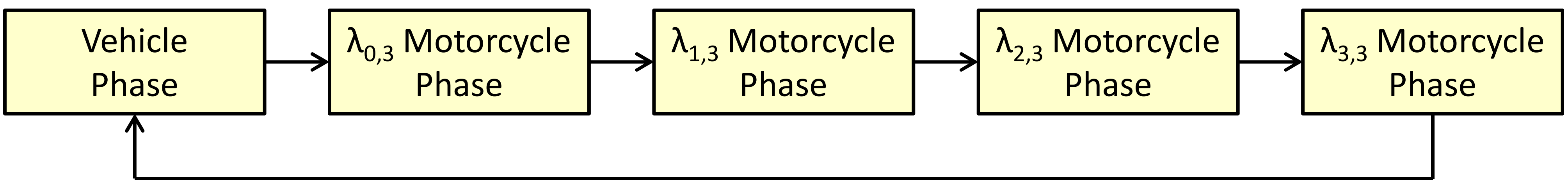
Basic Setting

- Separated phases for vehicles and motorcycles
- Vehicle phase (control of vehicles)
  - First-come-first-go policy
    - All vehicles share the vehicle phase
- Motorcycle phase (control of motorcycles)
  - Control by time-length
  - Control by grouping motorcycles
  - Two-phase left turns with waiting zones

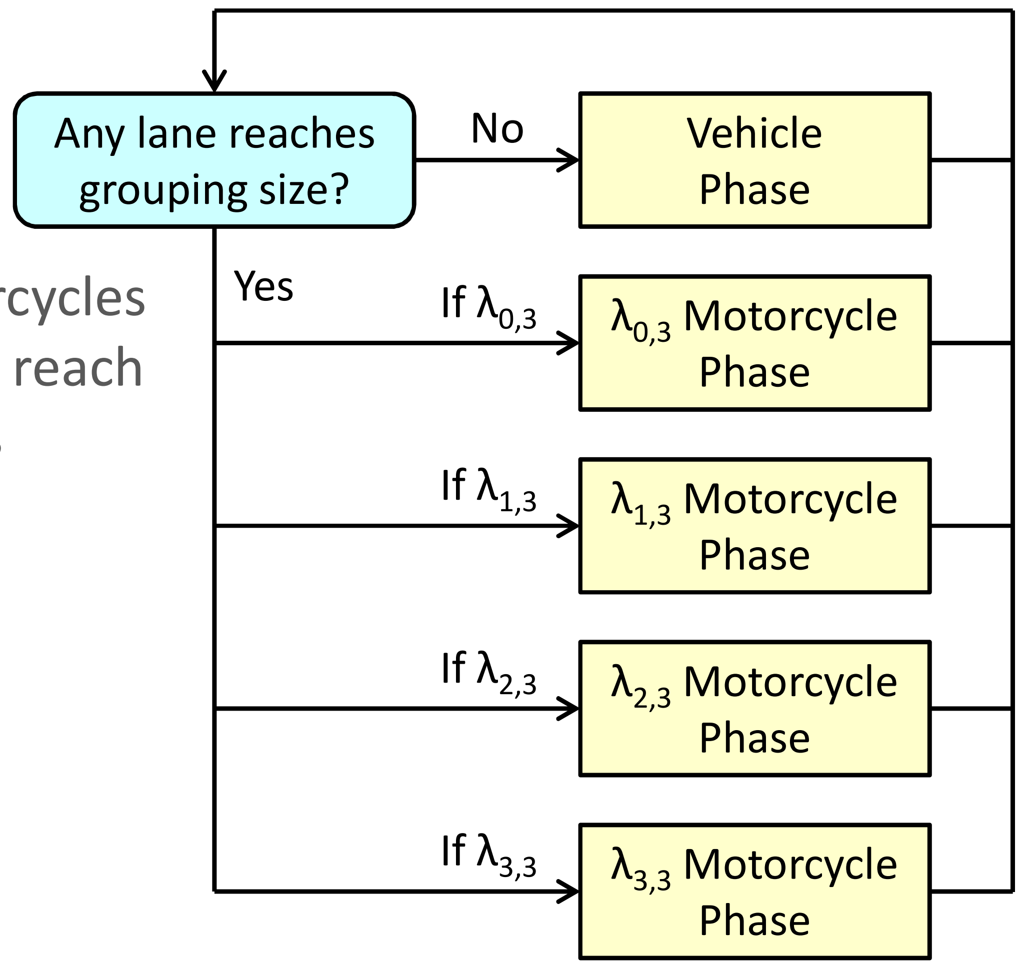
Control by Time-Length

- One phase for vehicles
  - Vehicles from all directions and all lanes can share the phase as they are connected, autonomous, and following the **first-come-first-go policy**
- One phase for motorcycles on each motorcycle lane
  - Motorcycles on other lanes and all vehicles cannot enter the intersection
- Five design parameters
  - Time-lengths of the vehicle phase and the four motorcycle phases



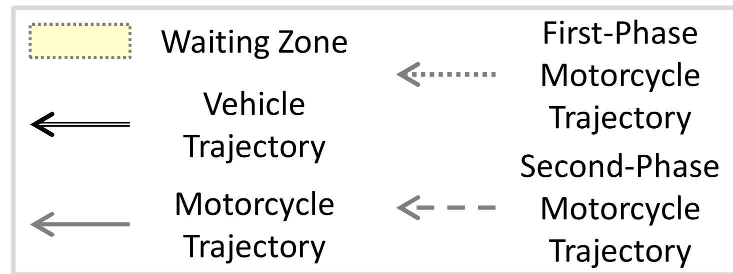
Control by Grouping Motorcycles

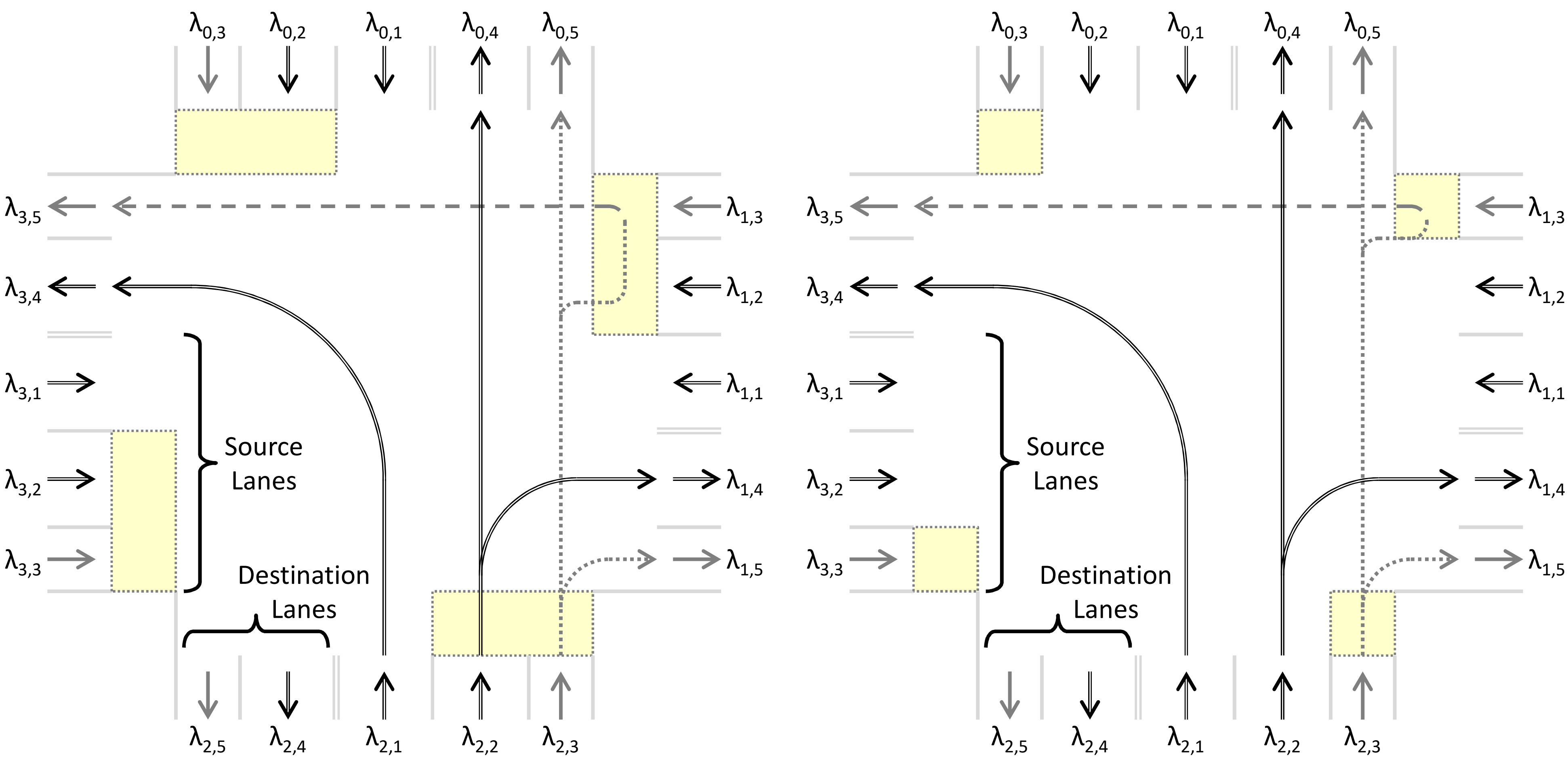
- Motorcycles on one lane can enter the intersection if
  - The number of waiting motorcycles on the lane reaches the pre-defined grouping size
- Vehicles can enter the intersection if
  - The numbers of waiting motorcycles on all motorcycle lanes do not reach the pre-defined grouping sizes
- Four design parameters
  - Grouping sizes of the four motorcycle lanes



Two-Phase Left Turns with Waiting Zones

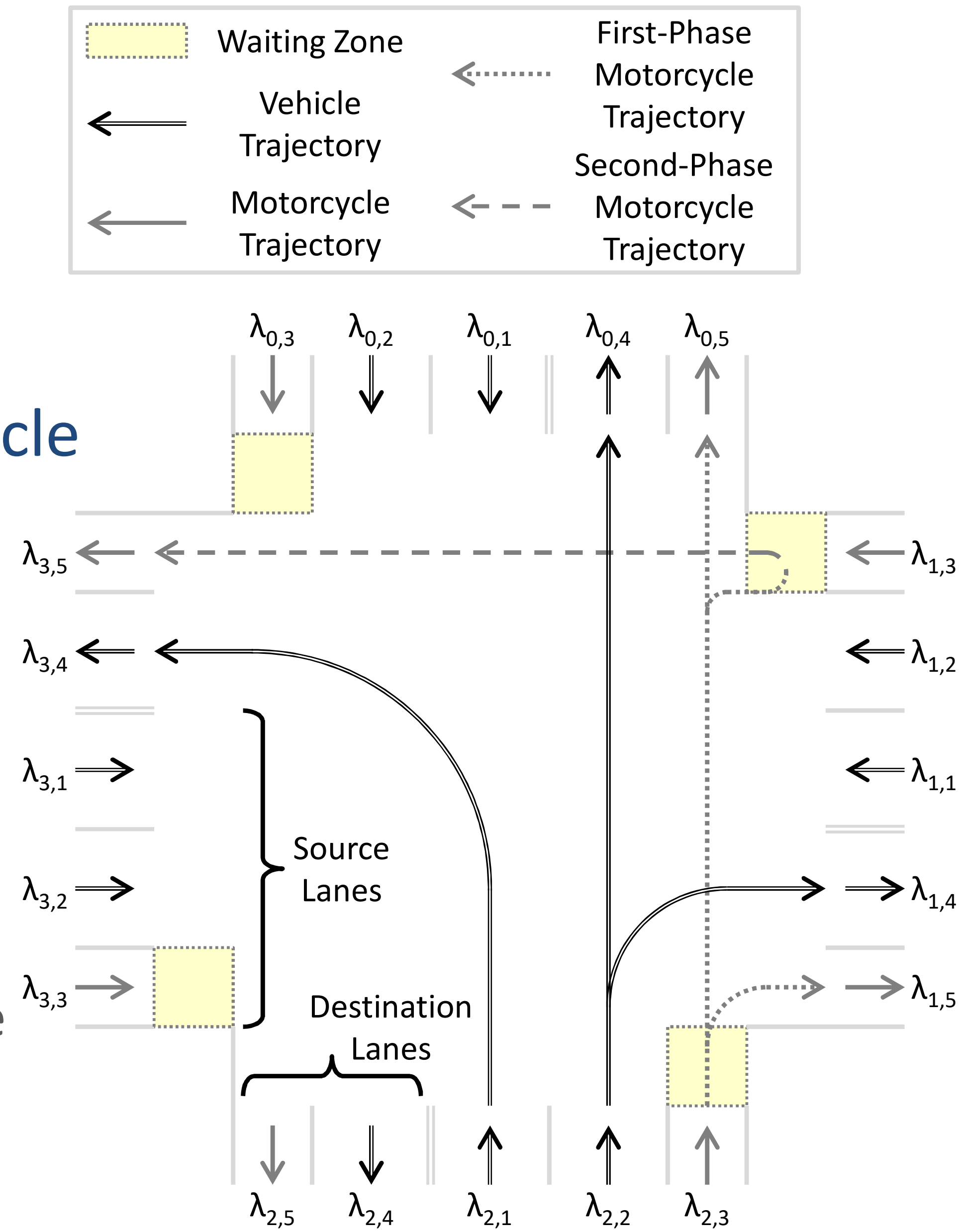
- ❑ **Waiting zones**
  - ➢ Traditional design vs. our design





Two-Phase Left Turns with Waiting Zones

- ❑ One phase for vehicles
  - ➢ Vehicles from all directions and all lanes can share the phase
- ❑ One phase for motorcycles on each pair of opposite motorcycle lanes (+ their waiting zones)
  - ➢ Motorcycles on $\lambda_{0,3}$ and $\lambda_{2,3}$ can enter the intersection together
  - ➢ Motorcycles on $\lambda_{1,3}$ and $\lambda_{3,3}$ can enter the intersection together
- ❑ Three design parameters
  - ➢ Time-lengths of the vehicle phase and the two motorcycle phases



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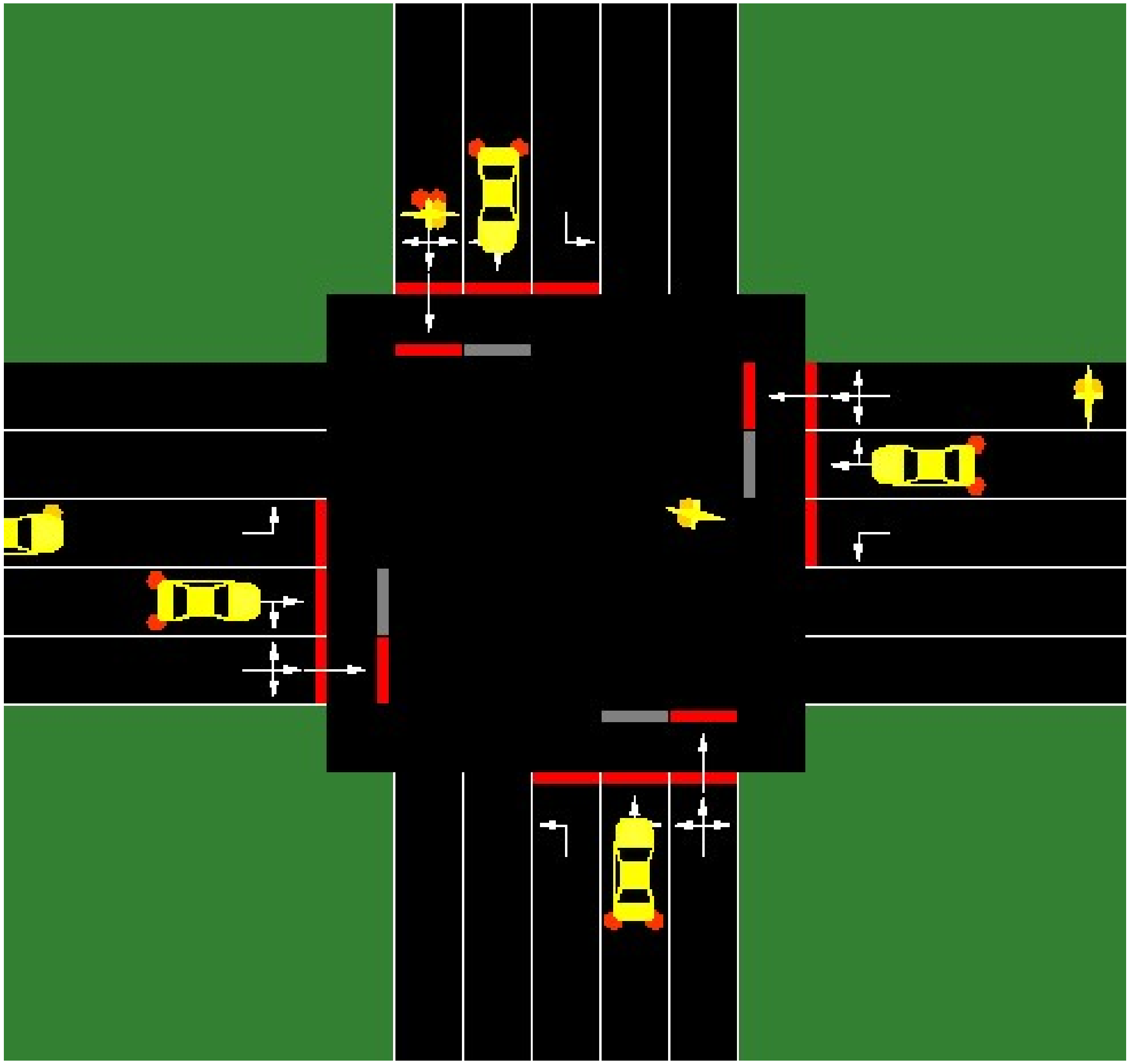
Simulator

- SUMO-0.19.0
  - Low-level control
  - Delay calculation
  - Visualization



Default Setting

Arrivals and directions

- Poisson distribution with 2 arrivals per second (highly congested traffic)
- Probabilities of a motorcycle & a vehicle = P_M & $1 – P_M$
  - P_M is set to 0.1, 0.3, 0.5, 0.7, and 0.9
- Uniform distribution for source direction
- Probabilities of turning left & going straight & turning right
  - 0.25 & 0.5 & 0.25 for vehicles
  - P_L & $2*(1 – P_L) / 3$ & $(1 – P_L) / 3$ for motorcycles
  - P_L is set to 0.1, 0.3, 0.5, 0.7, and 0.9

Will report

- The average delay of all vehicles and motorcycles: Δ_A
- The average delay of all vehicles: Δ_V
- The average delay of all motorcycles: Δ_M

[EXP1] Connectivity: Settings

- Purpose
  - Show the impacts of motorcycles
- Setting 1-1
  - All vehicles and motorcycles are connected and autonomous
  - All follow first-come-first-go policy
- Setting 1-2
  - Mixed-autonomy traffic
  - Control by time-length
  - Total period is set to 90, 120, 160, 250, and 800 seconds
    - Motorcycle phase: 80 seconds
    - Vehicle phase: 10, 40, 80, 170, and 720 seconds --- roughly match the ratio of the number of vehicles to the number of motorcycles (P_M = 0.9, 0.7, 0.5, 0.3, and 0.1)

[EXP1] Connectivity: Results 1-1

- When P_M is fixed, P_L increases → Δ_A increases
  - A left-turn motorcycle has more trajectory conflicts
- When P_L is fixed, P_M = 0.5 → Δ_A is largest
  - There are more trajectory conflicts between a vehicle and a motorcycle
- The impacts of motorcycles, especially left-turn motorcycles, on the traffic efficiency are significant

P_M	P_L				
	0.1	0.3	0.5	0.7	0.9
0.1	46.6	50.8	58.1	57.7	60.6
0.3	65.4	65.3	80.4	97.4	105.0
0.5	81.0	89.8	104.3	122.6	136.2
0.7	66.7	78.4	93.9	111.3	128.6
0.9	58.7	71.4	92.2	109.4	109.7

[EXP1] Connectivity: Results 1-2

- Δ_V is always smaller than Δ_M
  - The vehicle phase uses first-come-first-go policy
- When P_M = 0.1, Δ_M is large and Δ_A is small for each P_L
  - Motorcycles averagely need to wait longer until the next green light
  - Δ_A benefits from a longer vehicle phase and higher ratio of vehicles

		P_L														
	Period	0.1			0.3			0.5			0.7			0.9		
P_M	(second)	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	800	182.4	818.7	248.2	162.7	743.0	215.8	215.0	713.7	256.9	217.8	917.6	293.2	177.3	770.2	236.4
0.3	250	228.0	454.9	292.9	200.4	426.0	266.4	180.9	447.3	263.1	234.5	501.7	315.7	228.6	531.5	326.6
0.5	160	235.5	466.2	356.3	215.4	413.1	313.1	190.7	435.7	319.3	224.5	453.8	341.0	263.6	443.3	349.1
0.7	120	243.7	424.3	372.0	271.3	410.0	365.1	184.5	408.4	347.0	168.7	395.9	329.1	241.4	390.2	341.3
0.9	90	264.5	380.1	367.4	273.8	401.0	386.3	269.9	370.5	359.0	253.2	415.6	399.7	253.1	344.0	334.1

[EXP2] Grouping: Settings

- Control by grouping motorcycles
- Setting 2-1
  - Grouping size is set to 1, 5, 10, and 15
- Setting 2-2
  - All vehicles are from top or bottom, and all go straight
  - All motorcycles are from bottom, and all turn left
- Setting 2-3
  - All vehicles are from bottom, and all go straight
  - All motorcycles are from bottom, and all turn left

[EXP2] Grouping: Results 2-1

- When P_M is 0.3, 0.5, 0.7,and 0.9, the grouping size increases → Δ_A decreases
  - Vehicles and motorcycles are affected frequently without grouping
- When P_M is 0.1, this trend is not clear
  - There are too few going through the intersection or forming a group

P_M	Grouping Size	P_L 0.1	0.3	0.5	0.7	0.9
0.1	1	227.6	140.5	190.0	231.9	177.3
	5	241.9	199.0	237.4	257.7	223.8
	10	—	—	—	—	—
	15	—	—	—	—	—
0.3	1	518.2	507.4	482.6	573.6	586.2
	5	301.0	293.7	297.3	328.2	359.6
	10	250.0	270.0	247.3	293.9	290.0
	15	240.0	235.2	217.3	240.4	285.1
0.5	1	821.9	697.2	765.6	743.3	781.6
	5	392.3	339.5	363.9	353.2	376.8
	10	329.0	287.1	290.7	293.8	319.9
	15	295.1	251.5	290.6	271.8	273.2
0.7	1	900.1	857.6	838.5	813.4	794.7
	5	389.1	382.4	363.2	356.9	348.2
	10	334.6	311.3	301.3	286.8	300.6
	15	305.0	281.1	281.1	264.4	264.9
0.9	1	888.6	919.3	907.2	1025.0	804.0
	5	356.9	375.2	366.2	398.7	339.7
	10	298.4	321.7	301.0	329.7	280.7
	15	278.0	279.8	276.0	318.6	253.4

[EXP2] Grouping: Results 2-2

- When P_M is fixed, grouping size increases → Δ_V decreases in most cases, but Δ_M increases
  - Larger grouping size prevents motorcycles from blocking vehicles but increases queuing time of motorcycles
- When grouping size is fixed, P_M increases → Δ_V increases, but Δ_M decreases
- When grouping size is fixed, P_M = 0.5 → Δ_A is largest

P_M	Grouping Size											
	1			5			10			15		
	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	57.5	0.0	51.6	4.4	27.0	6.2	3.6	59.4	6.8	5.5	87.6	12.2
0.3	145.0	0.0	100.8	97.3	9.4	71.4	62.3	18.0	49.6	47.6	42.1	45.9
0.5	318.0	0.0	157.4	201.7	2.6	112.2	145.0	7.6	85.6	129.7	15.3	79.5
0.7	446.2	0.0	116.3	280.0	1.2	88.4	210.6	4.8	72.9	206.2	8.4	72.1
0.9	513.1	0.0	73.4	293.7	1.2	52.2	204.4	3.7	41.3	190.6	7.8	42.9

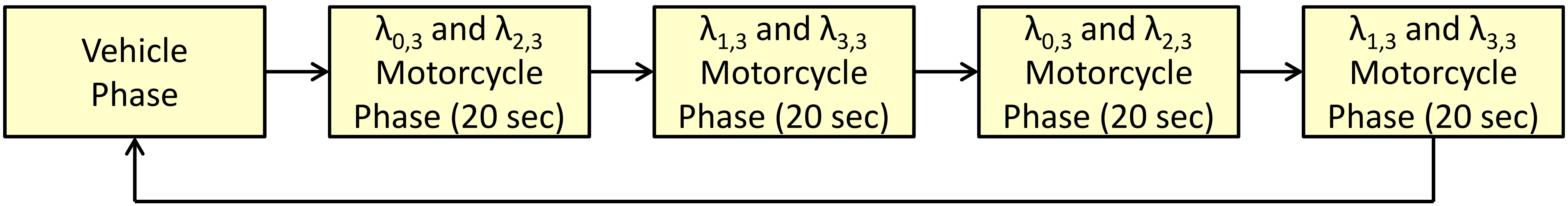
[EXP2] Grouping: Results 2-3

- Most are the same as setting 2-2
- The grouping size 15 is not necessarily better than the group size 10 for Δ_V
  - Motorcycle blocks vehicles from two lanes in setting 2-2, but one lane in setting 2-3, making grouping less effective

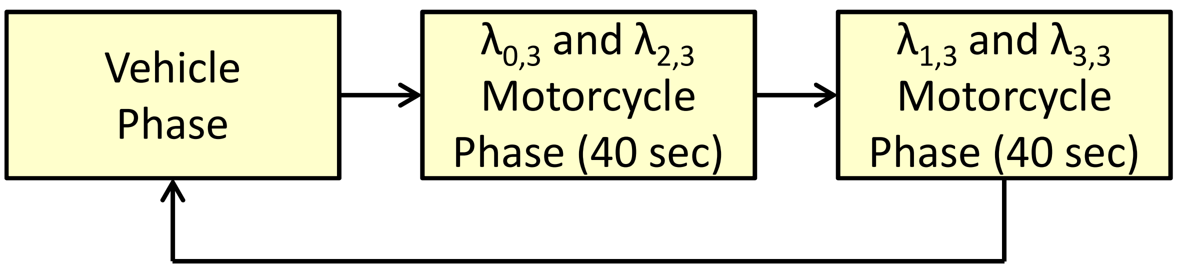
P_M	Grouping Size 1			5			10			15		
	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	56.2	0.0	45.4	4.2	30.9	8.4	3.0	63.8	9.6	5.4	85.9	18.6
0.3	71.5	0.0	48.5	24.8	21.1	23.5	13.7	38.3	18.9	8.1	56.7	17.3
0.5	143.5	0.0	71.8	81.0	10.1	45.9	62.6	27.4	45.0	44.8	37.0	40.9
0.7	187.2	0.0	63.0	102.9	8.9	42.5	66.5	19.4	36.2	70.6	25.8	41.7
0.9	251.0	0.0	20.7	130.1	3.0	15.8	58.6	7.5	12.9	33.9	14.3	16.3

[EXP3] Waiting Zone: Settings

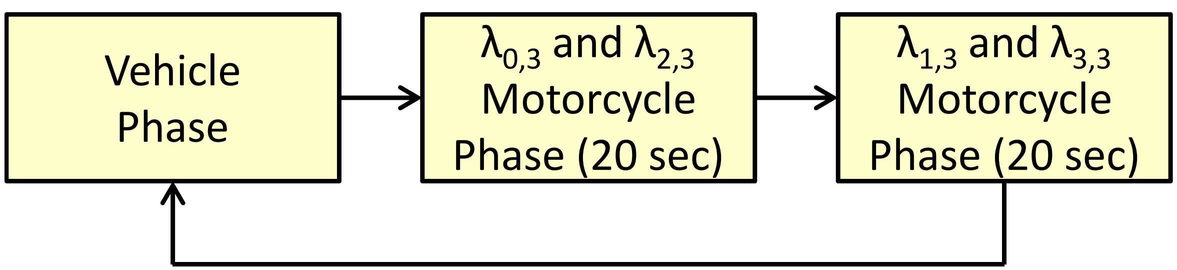
- Control by two-phase left turns with waiting zones
- Setting 3-1



- Setting 3-2



- Setting 3-3



[EXP3] Waiting Zone: Results

- Settings 3-1, 3-2, and 3-3

P_M	Period (second)	P_L														
		0.1			0.3			0.5			0.7			0.9		
		Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	800	182.4	646.6	230.4	162.7	733.3	214.9	215.0	709.0	256.5	217.8	1067.8	309.4	177.3	1008.7	260.2
0.3	250	228.0	306.2	250.4	200.4	370.5	250.2	180.9	411.4	252.0	234.5	558.0	332.8	228.6	702.8	382.0
0.5	160	235.5	278.7	258.1	215.4	335.3	274.6	190.7	492.7	349.2	224.5	548.8	389.3	263.6	557.0	403.2
0.7	120	243.7	260.3	255.5	271.3	351.5	325.5	184.5	448.3	375.9	168.7	498.4	401.4	241.4	459.8	388.1
0.9	90	264.5	212.4	218.2	273.8	324.8	318.9	269.9	397.5	382.8	253.2	529.2	502.1	253.1	481.6	456.7

P_M	Period (second)	P_L														
		0.1			0.3			0.5			0.7			0.9		
		Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	800	182.4	668.4	232.6	162.7	788.2	219.9	215.0	818.6	265.7	217.8	1170.2	320.4	177.3	1125.5	271.9
0.3	250	228.0	259.0	236.9	200.4	324.6	236.8	180.9	350.0	233.1	234.5	481.5	309.5	228.6	609.8	351.9
0.5	160	235.5	232.9	234.1	215.4	261.9	238.4	190.7	365.5	282.4	224.5	409.8	318.6	263.6	480.3	366.7
0.7	120	243.7	196.6	210.2	271.3	261.2	264.5	184.5	338.8	296.4	168.7	357.1	301.7	241.4	397.0	345.9
0.9	90	264.5	171.5	181.7	273.8	255.6	257.7	269.9	296.0	293.0	253.2	382.2	369.5	253.1	371.4	358.5

P_M	Period (second)	P_L														
		0.1			0.3			0.5			0.7			0.9		
		Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A	Δ_V	Δ_M	Δ_A
0.1	800	182.4	877.1	254.2	162.7	1009.6	240.1	215.0	1070.3	286.8	217.8	1722.8	380.0	177.3	1576.0	316.8
0.3	250	183.5	591.9	300.3	159.7	718.7	323.2	143.4	775.6	338.5	189.7	987.7	432.2	186.3	1209.7	517.4
0.5	160	146.7	569.9	368.2	142.8	624.8	381.1	118.3	883.0	519.8	137.9	942.3	546.8	162.6	1038.7	579.2
0.7	120	89.3	564.4	427.0	107.0	696.7	505.6	72.5	858.4	642.8	78.7	874.0	640.1	96.0	937.8	661.4
0.9	90	31.3	514.2	461.3	28.1	693.5	616.7	22.3	777.9	691.1	29.8	1006.7	910.7	23.3	896.3	801.0

[EXP3] Waiting Zone: Results

- Comparison among Setting 1-2, 3-1, 3-2, and 3-3
  - When $P_M = 0.1$ and P_L ranges from 0.1 to 0.5 → Setting 3-1 has the smallest Δ_A
    - Theory in scheduling
  - When P_M ranges from 0.3 to 0.9 and P_L ranges from 0.1 to 0.7 → Setting 3-2 has the smallest Δ_A
    - More transitions between phases, forcing approaching motorcycles to decelerate (similar to yellow lights)
  - In the remaining scenarios (P_L is even larger) → Setting 1-2 has the smallest Δ_A
    - Waiting zones benefit straight and right-turn motorcycles

Design Insights

- When there are about the same number of vehicles and motorcycles, Δ_A has the largest value
  - Trade-off between Δ_V and Δ_M
  - Left-turn motorcycles which have more trajectory conflicts with other vehicles or motorcycles need to be taken care of
- In general, Δ_A benefits from grouping motorcycles
  - Still, trade-off between Δ_V and Δ_M
- In general, Δ_A also benefits from two-phase left turns with waiting zones
  - Good separations for vehicles and motorcycles
- The design can also be applied to system with non-connected and non-autonomous **vehicles**
  - A potential solution to mixed-traffic scenarios

Outline

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- **Summary**

Summary

- Modeled and studied the intelligent intersection management with motorcycles
- Used **grouping** and **two-phase left turns with waiting zones** for motorcycles to improve the traffic efficiency of an intersection
- Demonstrated essential trade-offs and insights for designing intelligent intersection management with motorcycles

Q&A

Thank You!

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