UNIVERSITY OF TEXAS ARLINGTON | COLLEGE OF ENGINEERING

ACM Ubicomp '22

CycleGuard: A Smartphone-based Assistive Tool for Cyclist Safety Using Acoustic Ranging

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Motivation

LOCAL NEWS ›

Arlington bicyclist killed in fatal hit-and-run

CBS NEWS DFW

BY ALEX KE

AUGUST 25

Bicyclist killed in Bronx hit and run; driver fled in another car with baby

By Eyewitness News via

Monday, July 4, 2022

SAN JOSE

Cyclist Dies After Crash With Vehicle on Capitol Expressway in San Jose

By NBC Bay Area staff • Published May 2, 2022 • Updated on Ma

COBB COUNTY

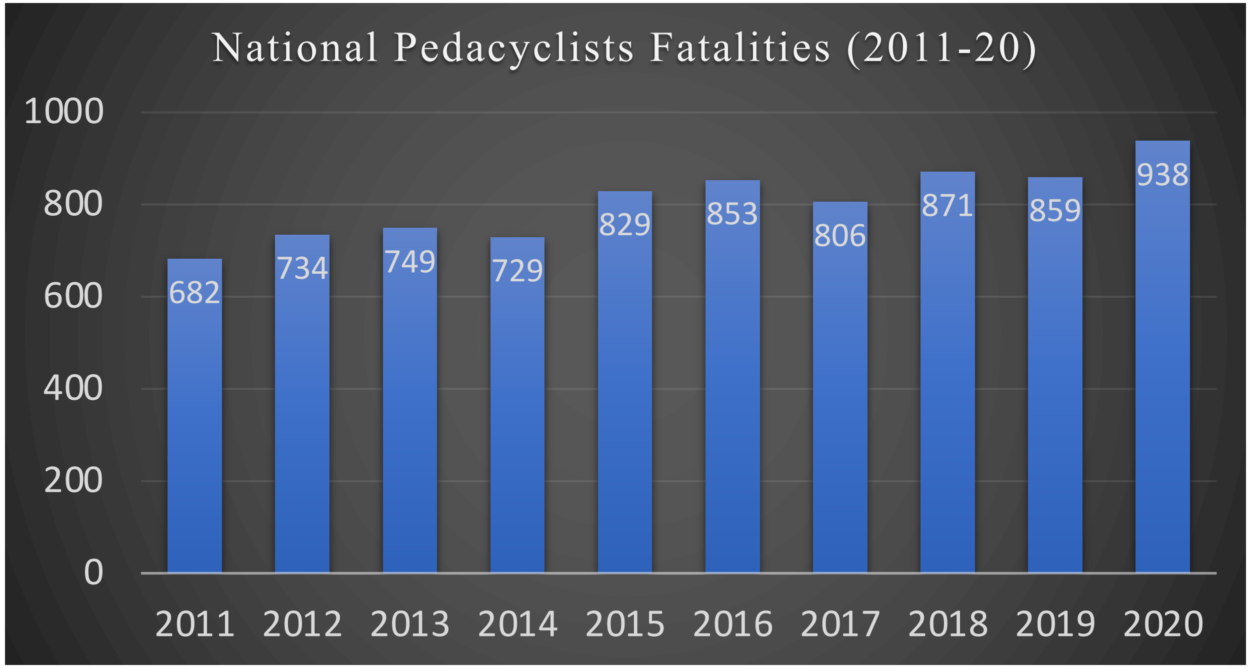
Man riding his bicycle hit and killed by car in Smyrna

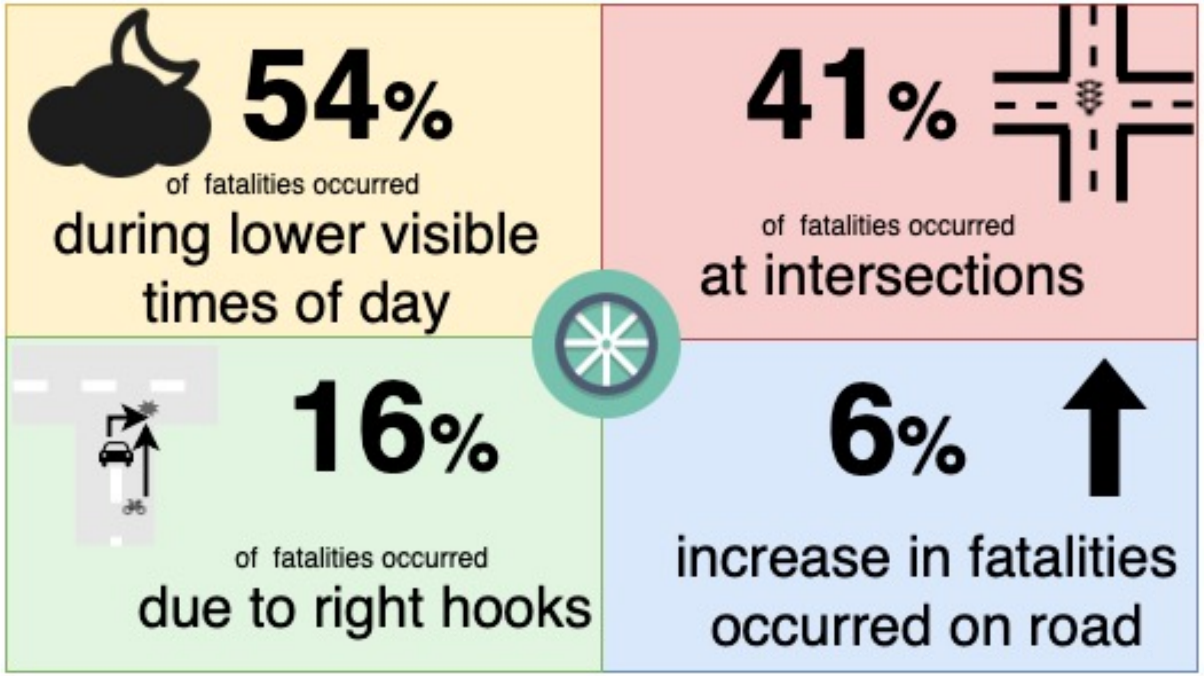
By WSBTV.com News Staff

December 31, 2021 at 4:49 am EST

[1] *CBS News, DFW*
[2] *ABC News, NYC*
[3] *NBC Bay Area*
[4] *WSBTV, GA*

Motivation





Source: National Highway Traffic Safety Administration (NHTSA)

The Right-Hook

- A motorist makes a right turn directly in front of the bicyclist abruptly

**Washington Area Bicyclist Association and The District Department of Transportation*

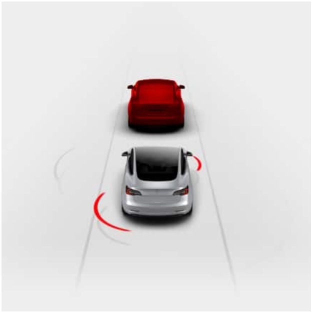
The Right-Hook

- A motorist makes a right turn directly in front of the bicyclist abruptly
  - Not within bicyclist Field-of-view
  - Uncontrolled/partially controlled intersections
    - Worser in lower light scenarios

**Washington Area Bicyclist Association and The District Department of Transportation*

Related Work

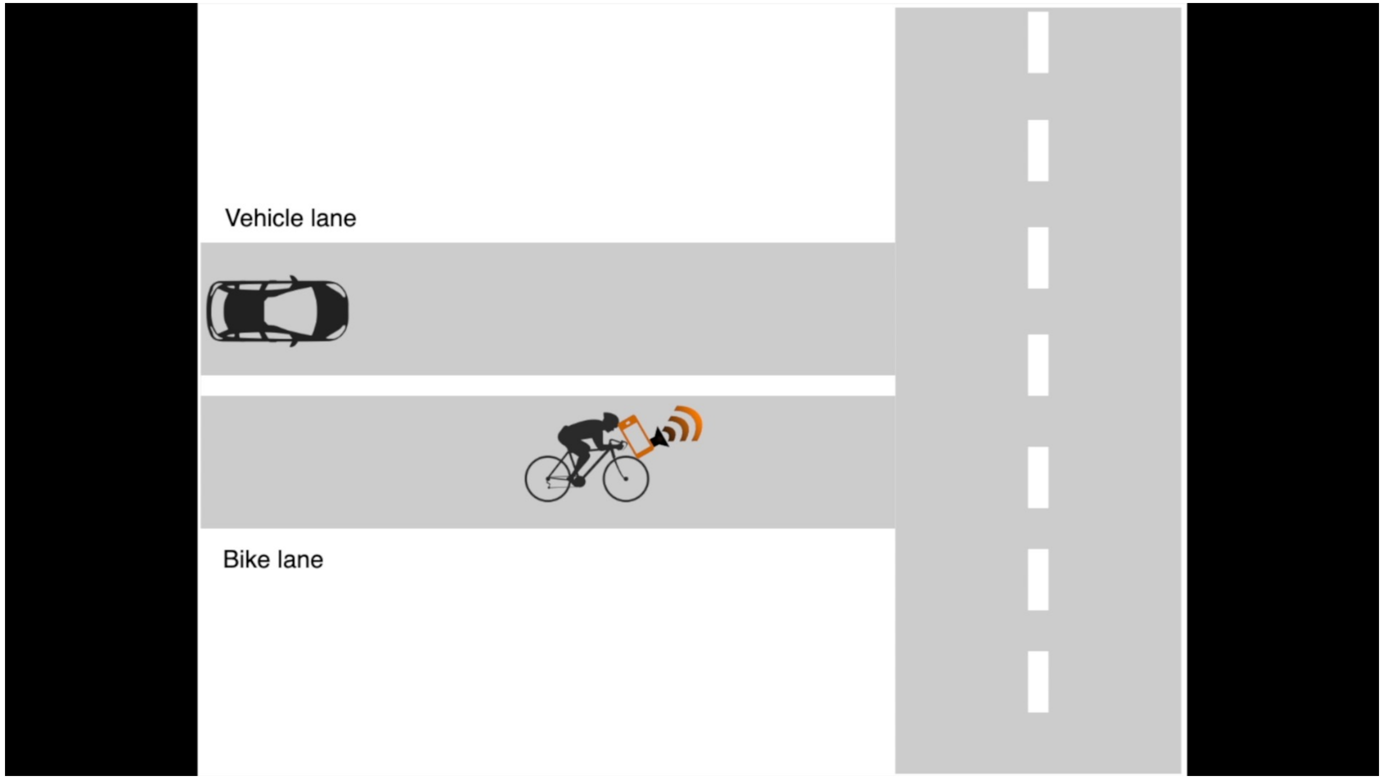
- Cyclist safety Techniques
  - Sophisticated sensors, sensitive to light
  - Expensive
- Collision av
  - Focused t
- Industrial sc
  - Sole purp
  - Full functionality requires expensive add-ons



A portable, cost-efficient system is needed to enhance the safety of cyclists.

Design Rationale

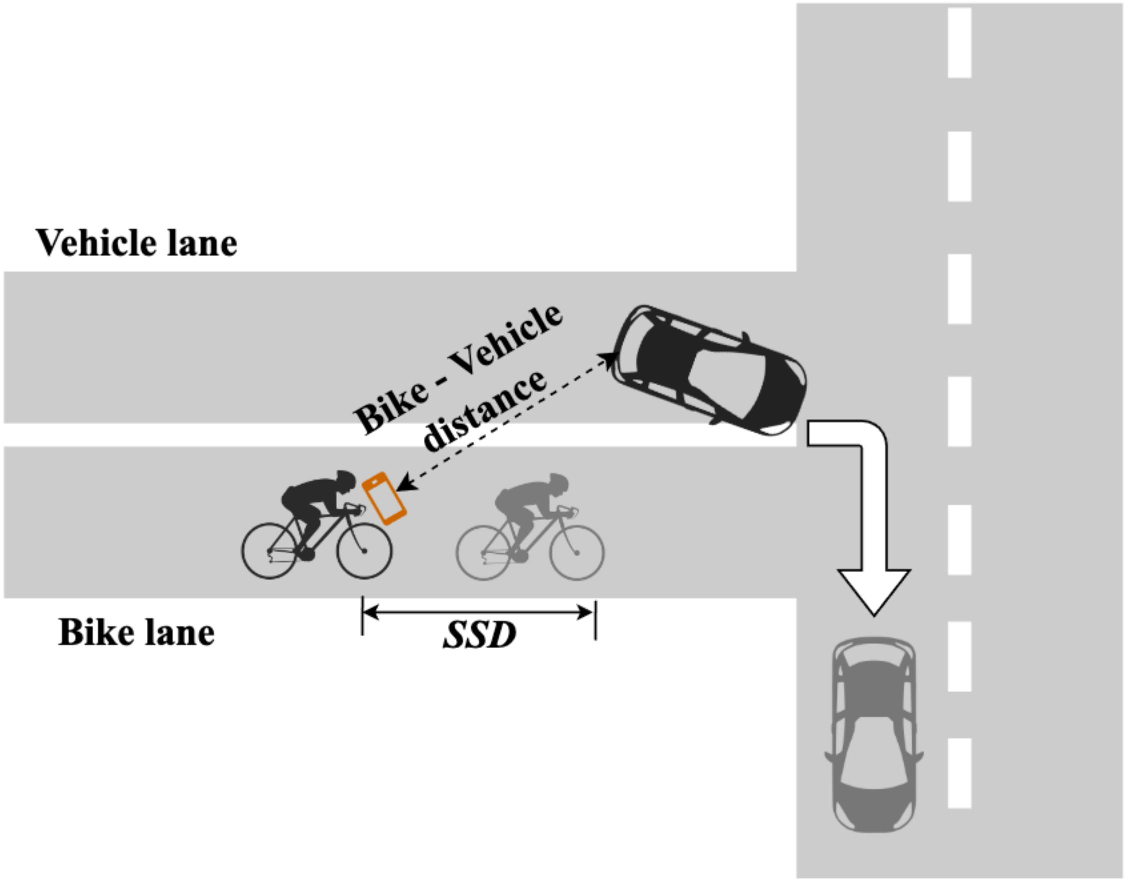
- Key Idea:
  - Alert the cyclist if the car is making a right-turn too close



Design Rationale

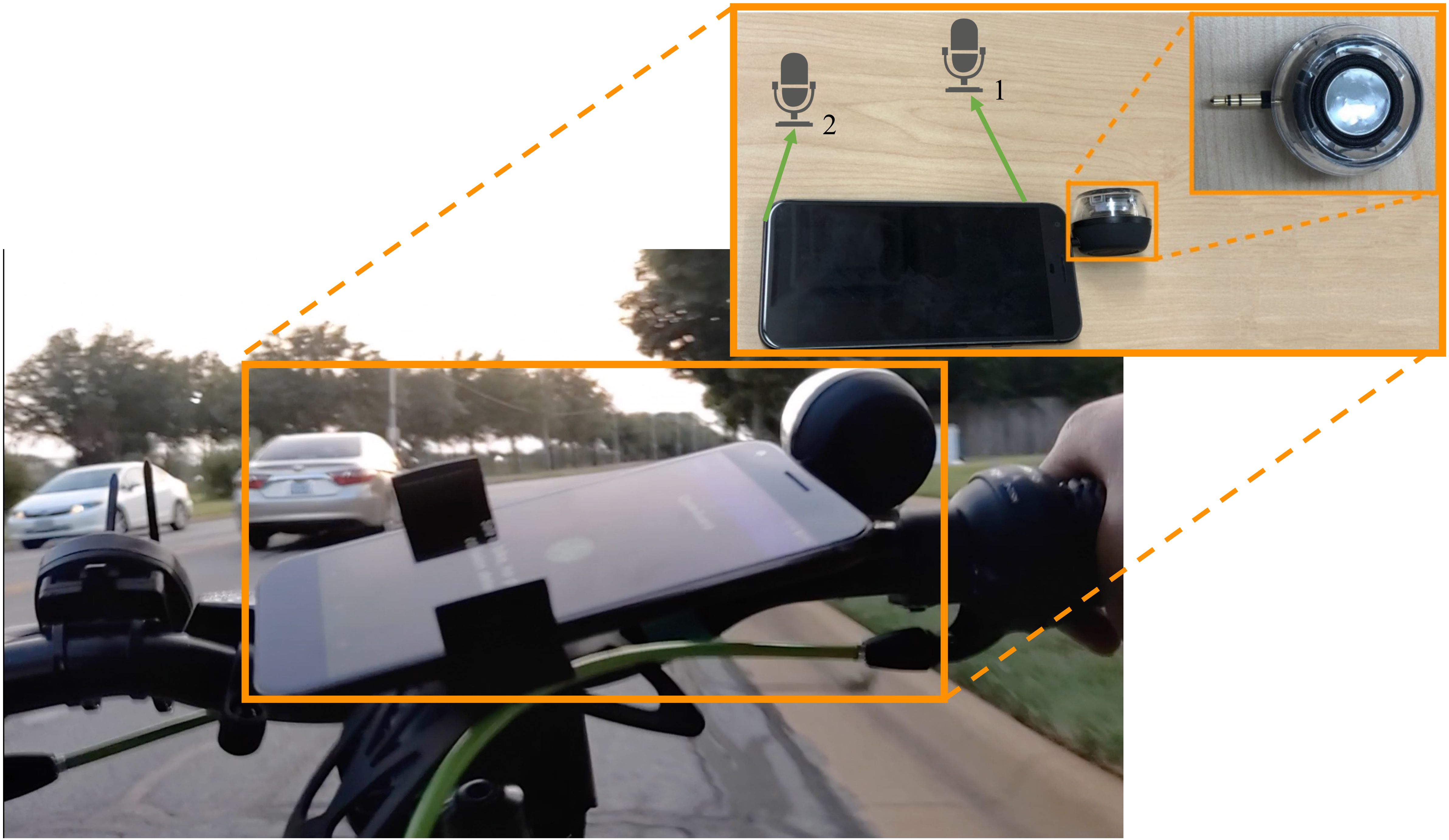
- Collision detection criteria:
  - Bike-Vehicle Distance ≤ *SSD*
  - Vehicle making a right turn

- SSD: Stopping-sight distance
  - Near worst-case distance the cyclist needs to be able to see, react, and brake to have room to stop before colliding with the vehicle.



System setup

- Smartphone, installed with application
- External speaker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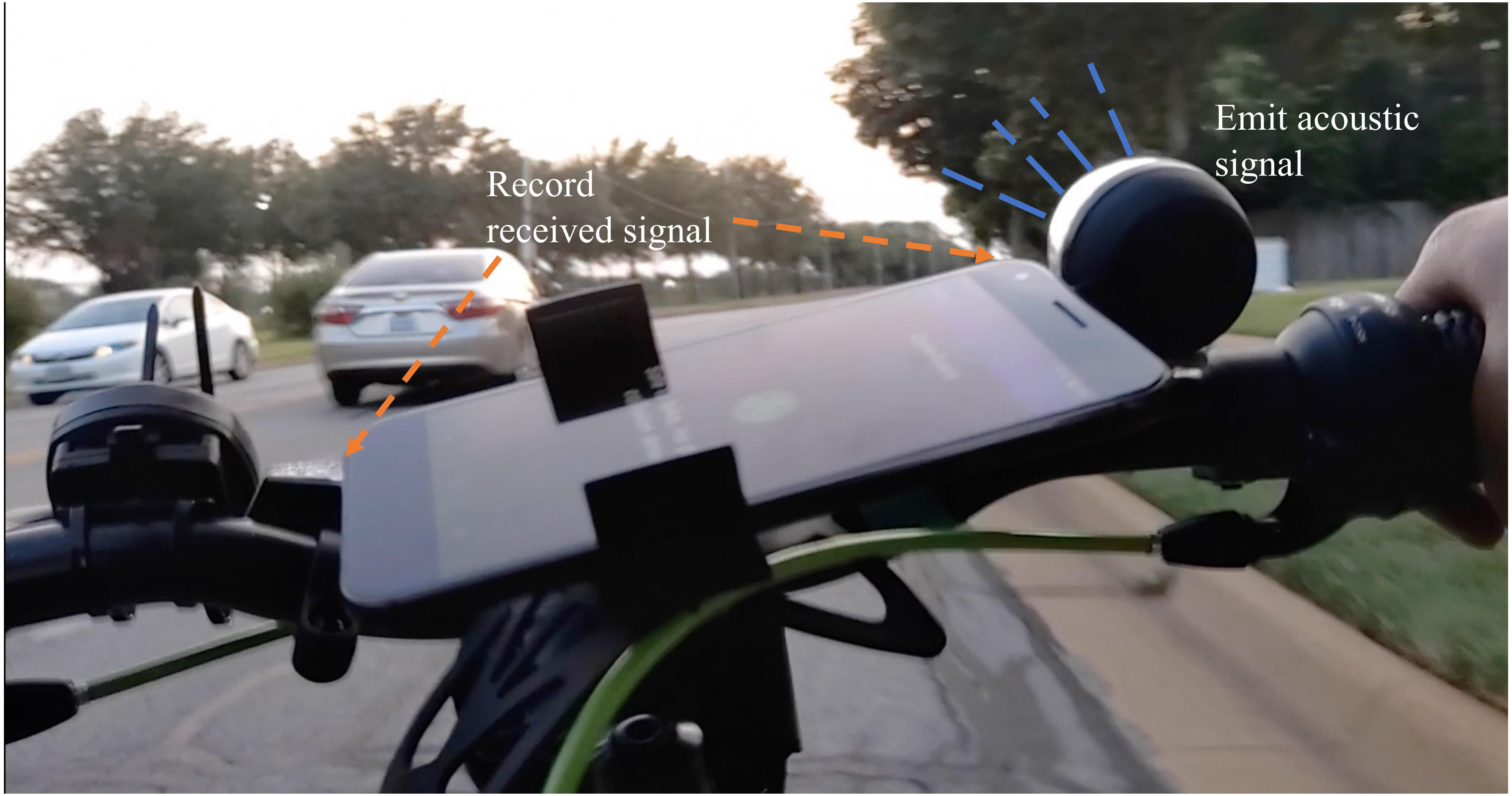
System setup



Practical challenges

- Interference from cyclist’s surrounding objects

Practical challenges

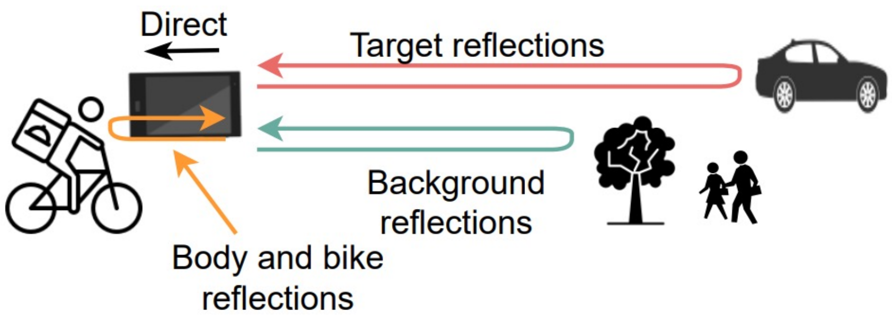
- Interference from cyclist's surrounding objects
- Estimate position correctly

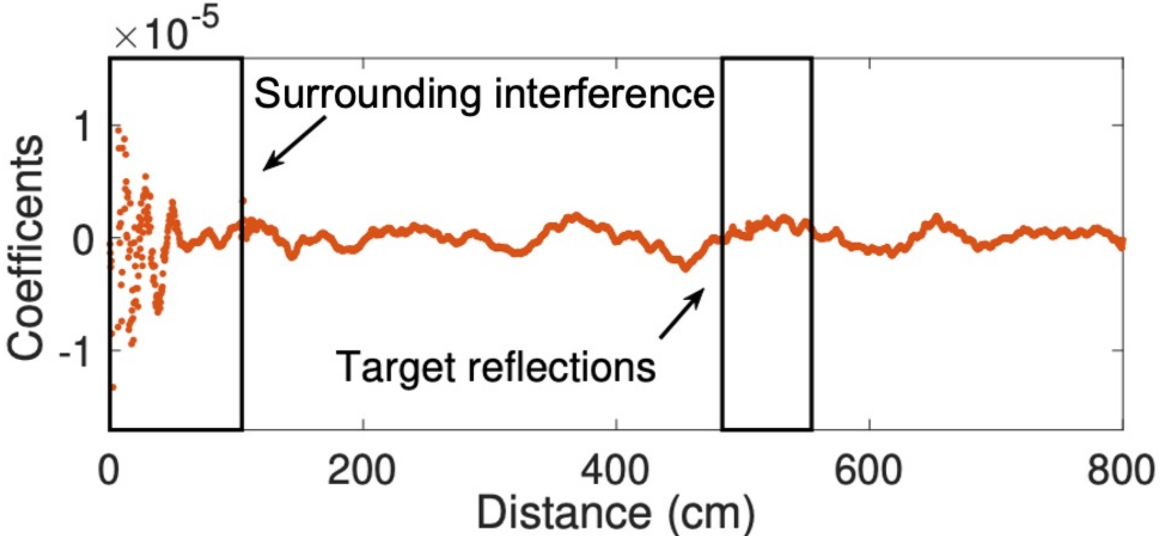
Practical challenges

- Interference from cyclist’s surrounding objects
- Estimate position correctly
- Identify right-turn vehicle from other static and non-static objects

Challenge 1: Interference from cyclist's surrounding objects

- Received signal:
  - $R(t) = \sum_{i \in U_1} h_i S_C(t - \tau_i) + \sum_{i \in U_2} h_i S_C(t - \tau_i)$
- Cleaning of Signal:
  - $min_{h_i} = \sum_t \left[R(t) - \sum_{i \in U_1 \cup U_2} h_i S_C(t - \tau_i) \right]$





Challenge 2: Position estimation

Step 1: Bike-Vehicle Distance estimation

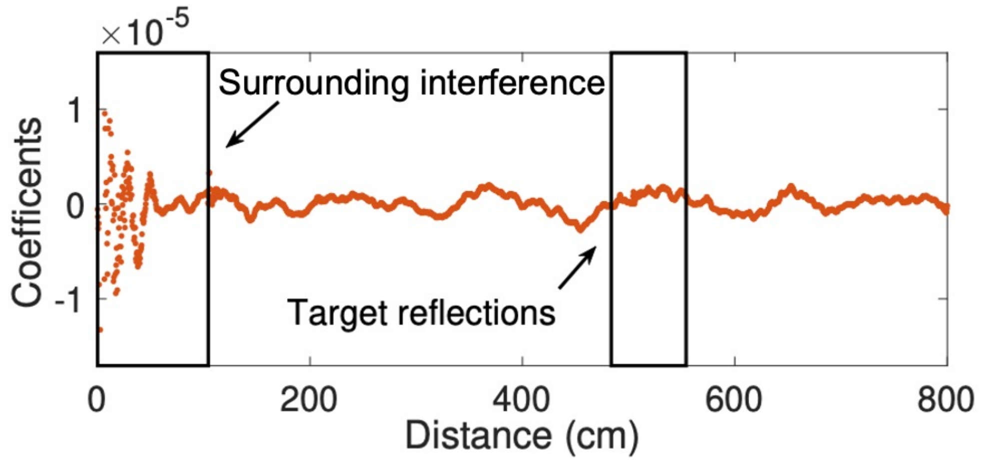
Challenge 2: Position estimation

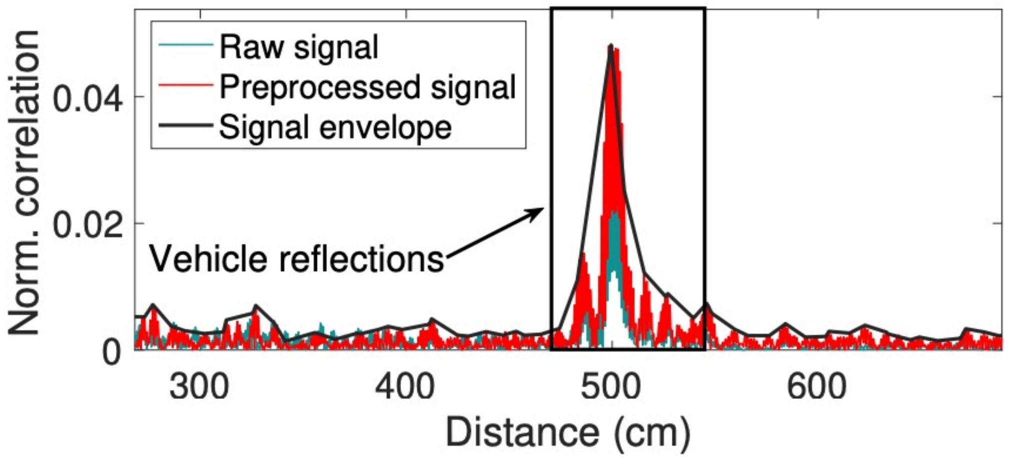
Step 1: Bike-Vehicle Distance estimation

Step 2: Bike-Vehicle Angle estimation

Challenge 2: Position estimation

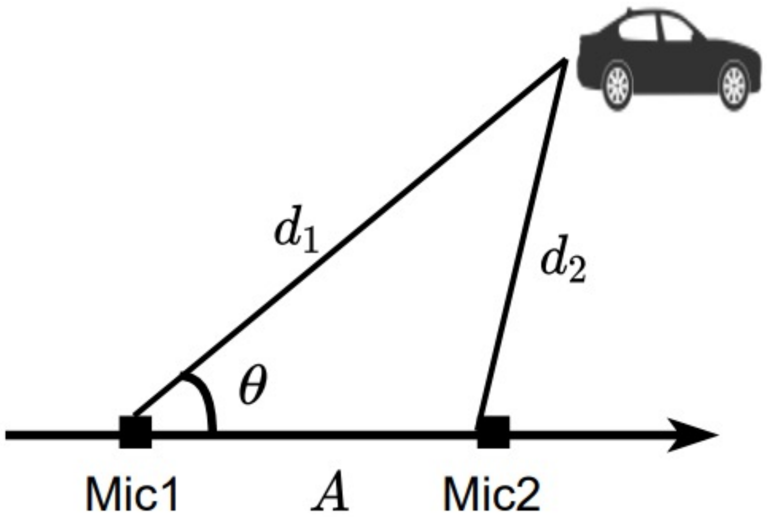
- Estimation of Bike-Vehicle Distance:
  - $C(t) = \int_{\tau=-\infty}^{+\infty} S_c(t)R(t-\tau)d\tau$





Challenge 2: Position estimation

- Estimation of Bike-Vehicle Distance:
  - $C(t) = \int_{\tau=-\infty}^{+\infty} S_c(t)R(t - \tau)d\tau$
- Estimation of Bike-Vehicle Angle:
  - $\theta = \arccos(\frac{d_1^2 + A^2 + d_2^2}{2 \times d_1 \times A})$



Challenge 3: Identify right-turn vehicle

Step 1: Remove static objects

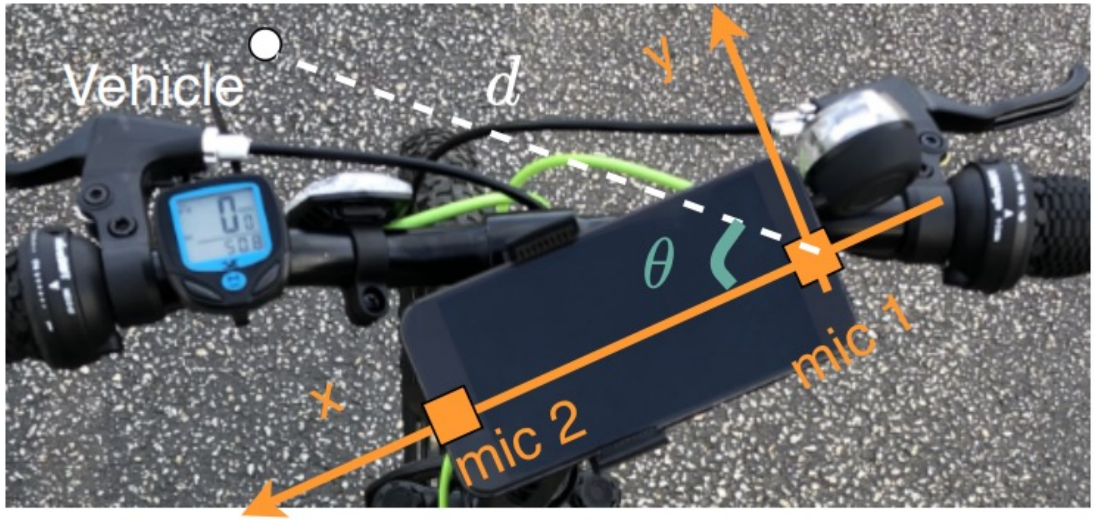
Challenge 3: Identify right-turn vehicle

Step 1: Remove static objects

Step 2: Isolate right turn vehicle from other vehicles

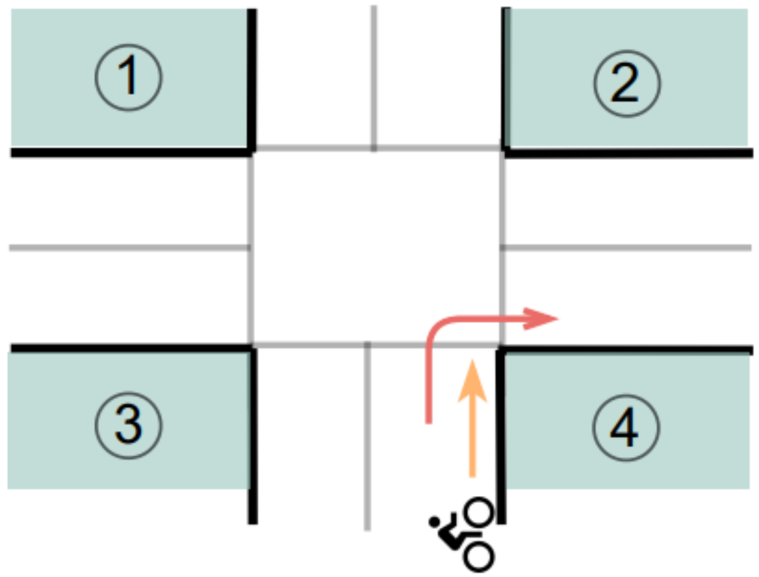
Challenge 3: Identify right-turn vehicle

- Consider smartphone coordinate system on the road



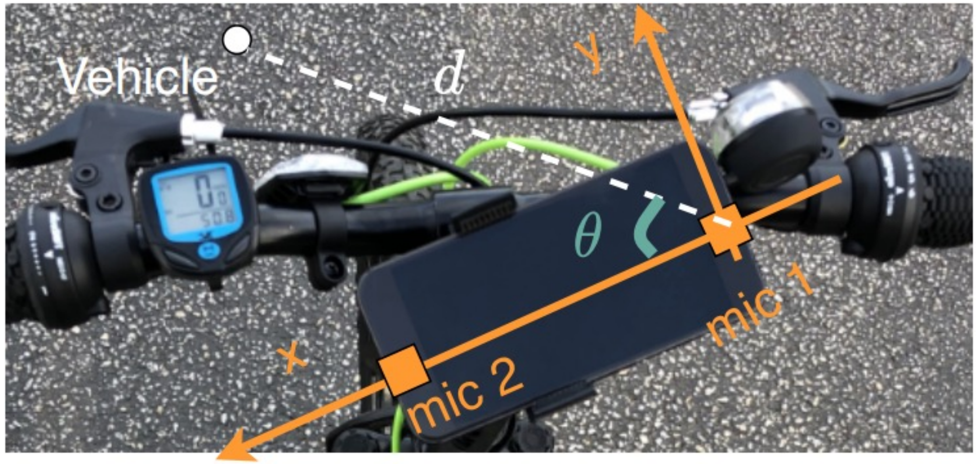
Challenge 3: Identify right-turn vehicle

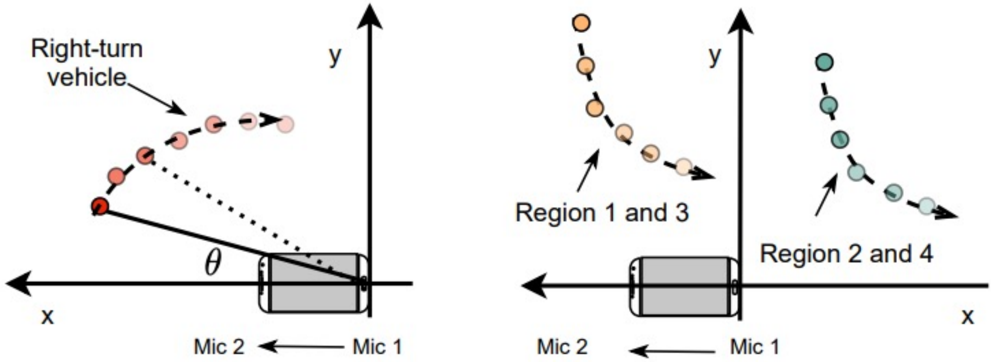
- Consider smartphone coordinate system on the road
- Divide intersection into 4 regions



Challenge 3: Identify right-turn vehicle

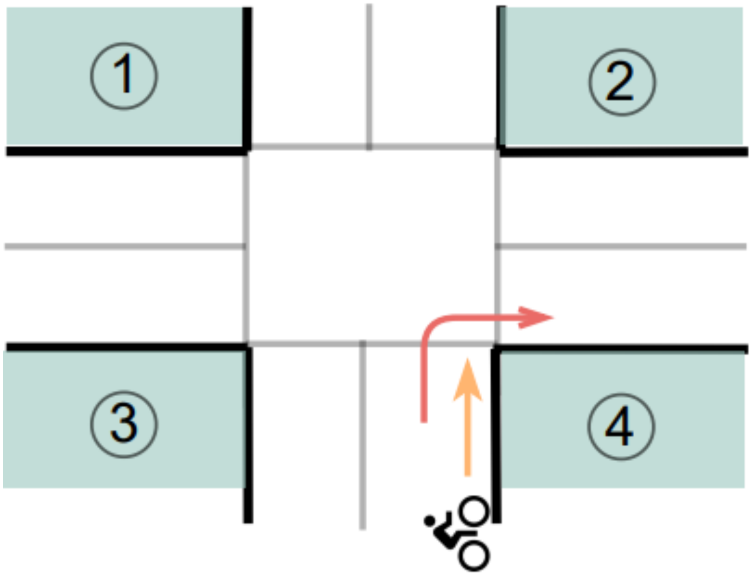
- Consider smartphone coordinate system on the road
- Divide intersection into 4 regions
- Construct position curves for objects
  - Series of distances and angles





Challenge 3: Identify right-turn vehicle

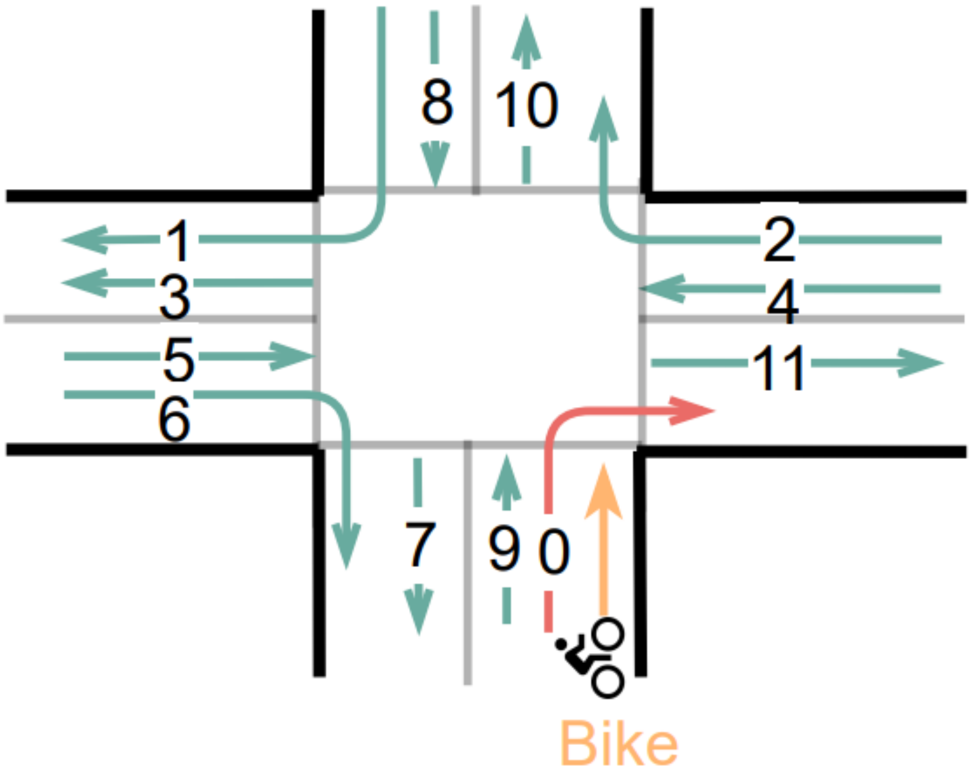
- Right-turn vehicles' curves confined within $[0,\pi/2]$

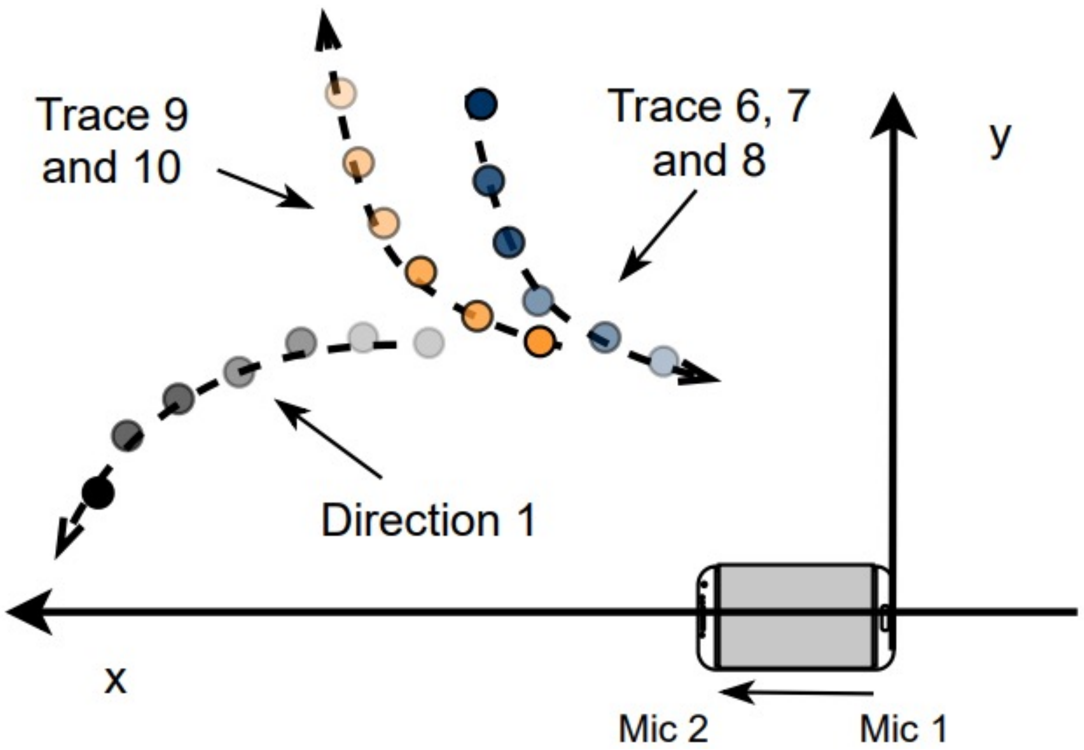


	θ	d	Range of θ
Region 1	↓	↓	$[0, \pi/2]$
Region 2	↑	↓	$[\pi/2, \pi]$
Region 3	↓	↓	$[0, \pi/2]$
Region 4	↑	↓	$[\pi/2, \pi]$
Right-turn vehicle	↑	↓	$[0, \pi/2]$

Challenge 3: Identify right-turn vehicle

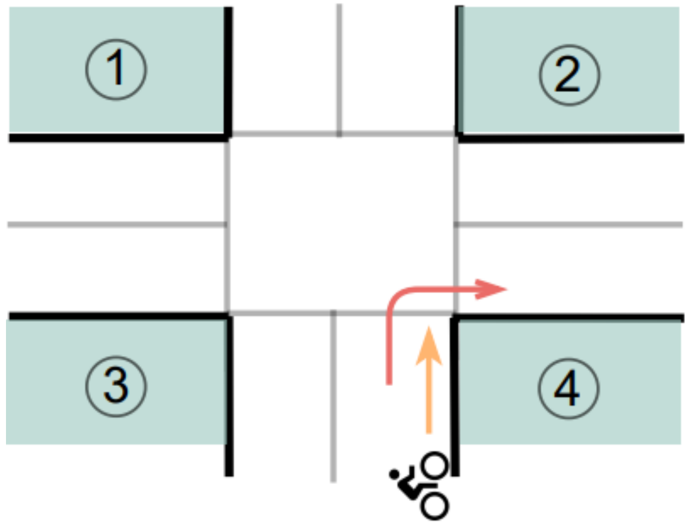
- Construct moving trajectory for all possible vehicle directions





Challenge 3: Identify right-turn vehicle

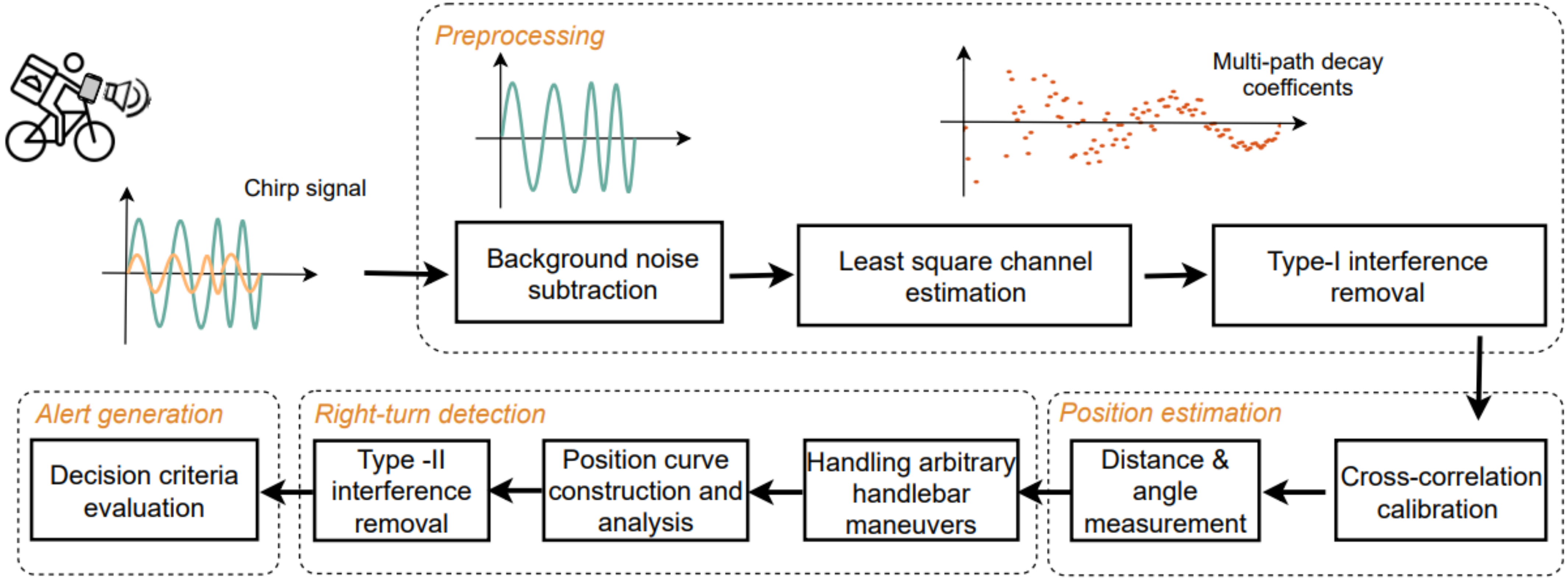
- Right-turn vehicles' curves confined within $[0,\pi/2]$
  - Constantly increasing angle
  - Constantly decreasing distance



Trace	1	2	3	4	5	6	7	8	9	10	11	Right-turn vehicle (0)
θ	↓	↓	↓	↓	↓	↑↓	↓	↓	↑	↑	↑	↑
d	↓↑	↓↑	↑	↓	↓	↓	↓	↓	↑	↑	↑	↓
θ range	Q1	Q2	Q1	Q2	Q1	Q1	Q1	Q1	Q1	Q1	Q2	Q1

Q1: $\theta \in [0, \pi/2]$, Q2: $\theta \in [\pi/2, \pi]$

Piecing all together



Evaluation

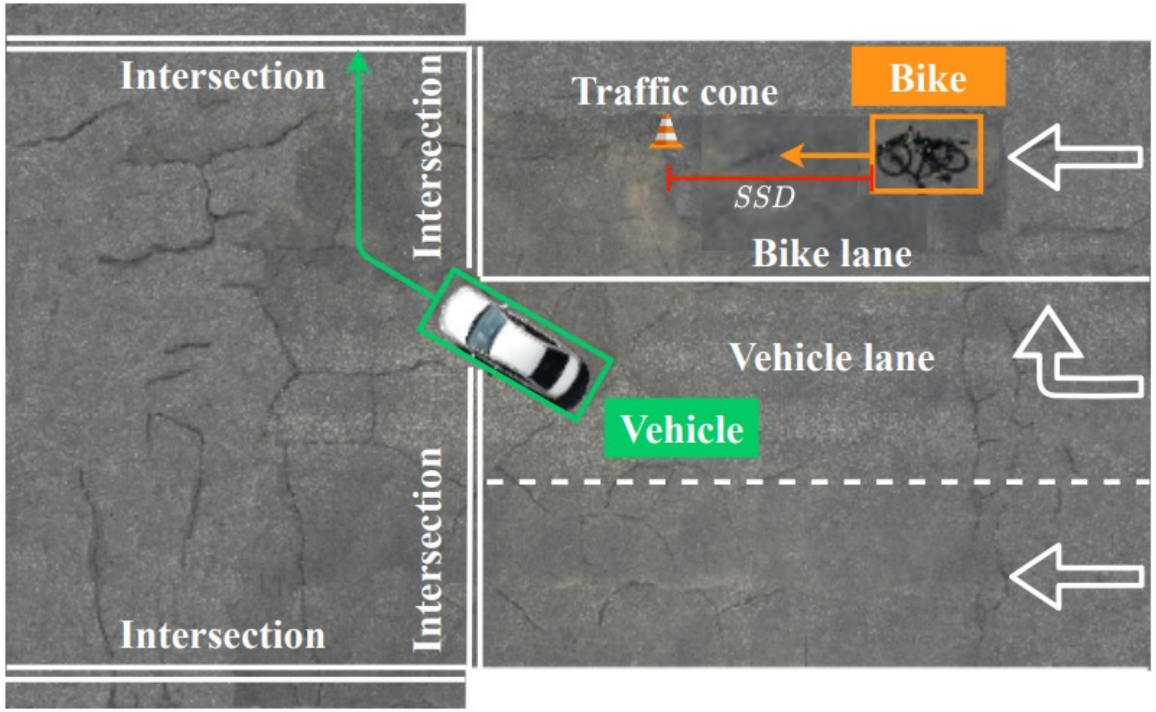
Overview

- System benchmarks
  - Detection in presence of multiple vehicles
  - Impact of on-road obstacles
- Real-world testing (on-road)
  - Different environments
  - Different times of the day
- Micro benchmarks
  - Computation time
  - Energy consumption
  - Device diversity

Evaluation

Testing Scenario

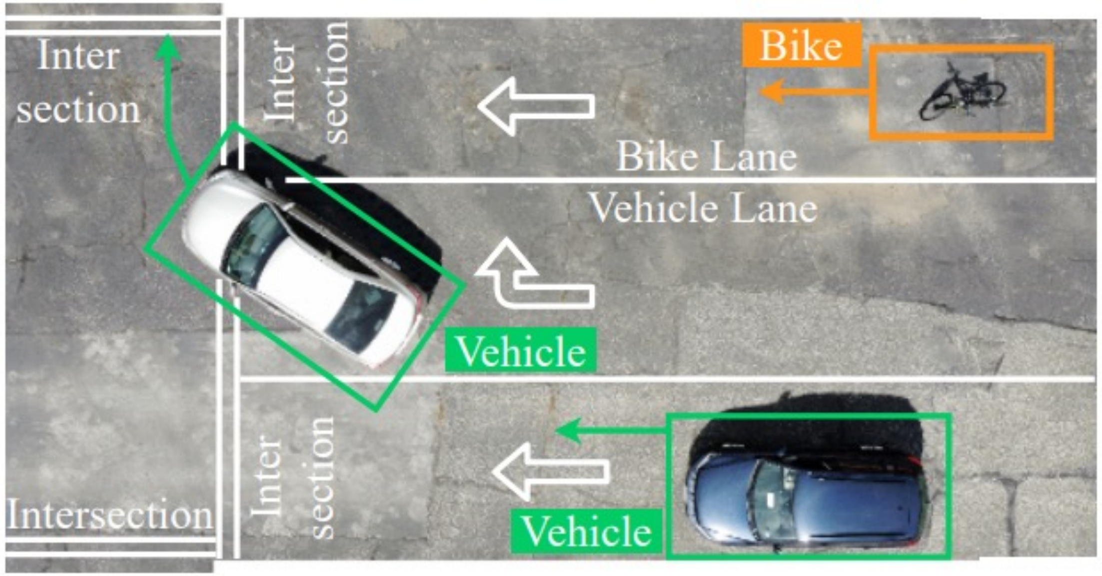
- Evaluation metrics:
  - True Positive Rate (TPR):
    - System successfully detects target vehicle before collision
  - True Negative Rate (TNR):
    - No false alarms in the absence of target vehicles



Evaluation

System benchmarks

- Impact of Multi-vehicles
  - Bike riding speed

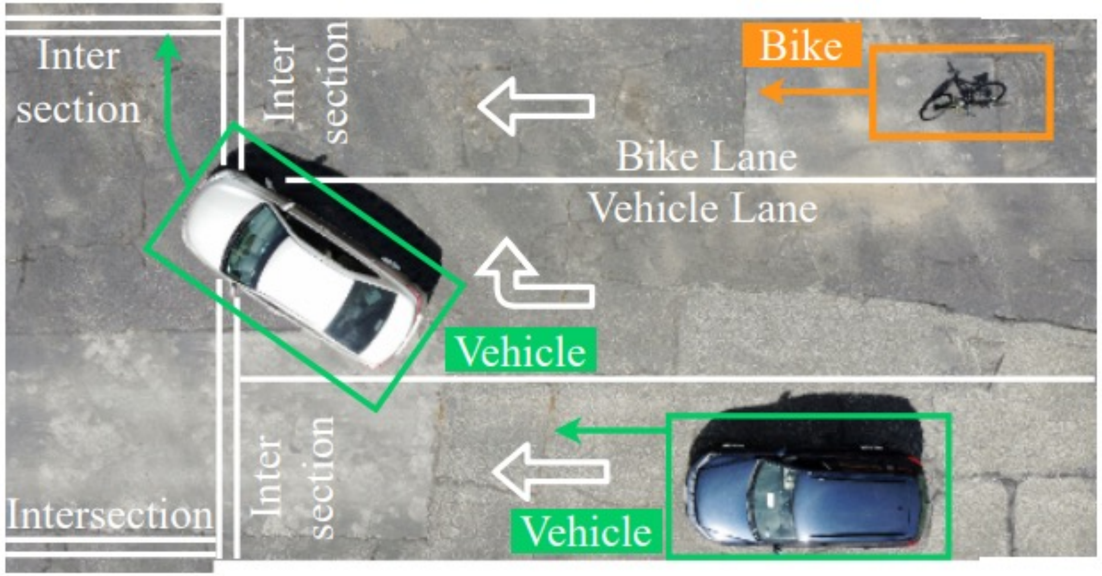


Metric	Bike riding speed (m/s)					Vehicle speed (mph)				
	2	3	4	5	6	5	7	10	12	15
TPR	98%	98%	96%	94%	93%	98%	98%	94%	92%	92%
TNR	90%	88.8%	88%	87.5%	86.95%	90%	88.8%	87%	86.6%	85%

Evaluation

System benchmarks

- Impact of Multi-vehicles
  - Bike riding speed
  - Vehicle speed



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TNR	90%	88.8%	88%	87.5%	86.95%	90%	88.8%	87%	86.6%	85%

Successfully detect the correct vehicle 92% of the time

Evaluation

System benchmarks

- Impact of maneuver changes
  - Bike riding speed

Metric	Bike riding speed (m/s)					Relative b-v distances (m)				
	2	3	4	5	6	10	15	20	25	30
TPR	98%	96.8%	95.83%	93.75%	92.3%	96.6%	96%	94.73%	93.9%	93.1%
TNR	90%	89.2%	88.57%	87.5%	87.5%	90.9%	88.4%	88%	86.9%	86.2%

Evaluation

System benchmarks

- Impact of maneuver changes
  - Bike riding speed
  - Relative distances between bike and vehicle

CycleGuard achieves a minimum of 92.3% TPR and 86.2% TNR

Metric	Bike riding speed (m/s)					Relative b-v distances (m)				
	2	3	4	5	6	10	15	20	25	30
TPR	98%	96.8%	95.83%	93.75%	92.3%	96.6%	96%	94.73%	93.9%	93.1%
TNR	90%	89.2%	88.57%	87.5%	87.5%	90.9%	88.4%	88%	86.9%	86.2%

Evaluation

Real-world testing

- Real-world environment:
  - Parking lot

Metric/Setting	Parking lot			Campus areas			Residential areas		
	Relative b-v distances (m)			Relative b-v distances (m)			Relative b-v distances (m)		
	10	20	30	10	20	30	10	20	30
TPR	98%	96%	92%	96.15%	93.9%	92.3%	95.45%	93.54%	91.83%
TNR	92%	89.7%	88%	91.66%	85.71%	80.55%	90.32%	84.31%	78.84%

Evaluation

- Real-world environment:
  - Parking lot
  - Campus areas

Metric/Setting	Parking lot			Campus areas			Residential areas		
	Relative b-v distances (m)			Relative b-v distances (m)			Relative b-v distances (m)		
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Evaluation

- Real-world environment:
  - Parking lot
  - Campus areas
  - Residential areas

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TNR	92%	89.7%	88%	91.66%	85.71%	80.55%	90.32%	84.31%	78.84%

Evaluation

- Real-world environment:
  - Parking lot
  - Campus areas
  - Residential areas

Acceptable real-world performance

Metric/Setting	Parking lot			Campus areas			Residential areas		
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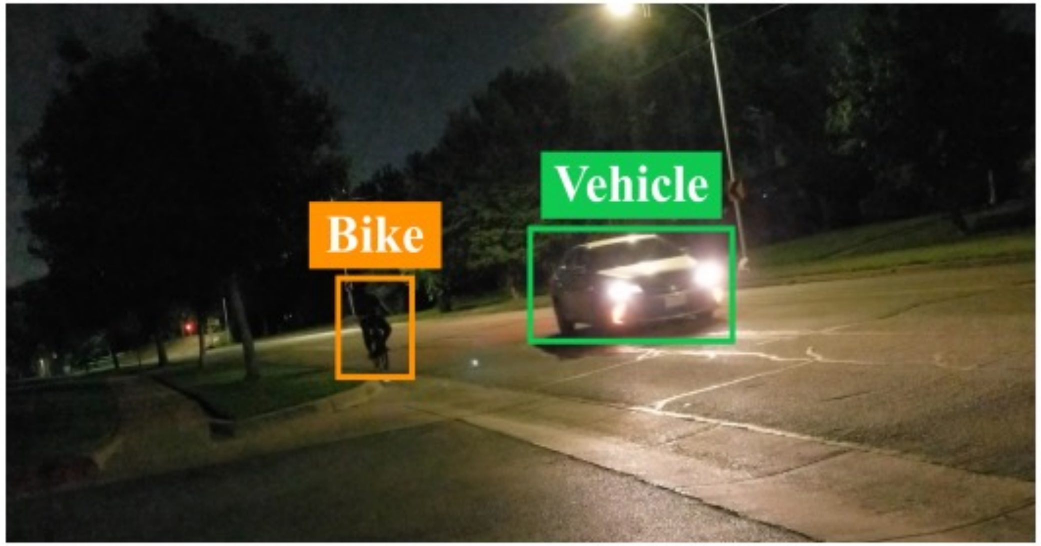
TPR	98%	96%	92%	96.15%	93.9%	92.3%	95.45%	93.54%	91.83%
TNR	92%	89.7%	88%	91.66%	85.71%	80.55%	90.32%	84.31%	78.84%

Evaluation

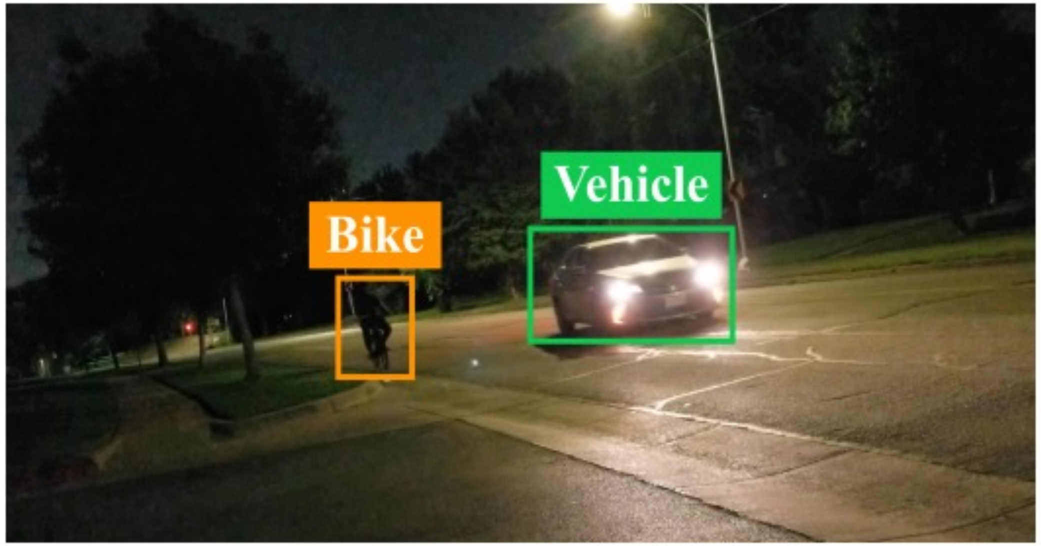
- Testing during night-time:
  - Parking lot



Metric/Setting	Parking lot Relative b-v distances (m)			Campus roads Relative b-v distances (m)		
	10	20	30	10	20	30
TPR	98%	96.67%	92.3%	96.55%	94.1%	92.85%
TNR	93.9%	91.66%	90.9%	91.89%	86.36%	81.48%

Evaluation

- Testing during night-time:
  - Parking lot
  - Campus roads



Metric/Setting	Parking lot			Campus roads		
	Relative b-v distances (m)			Relative b-v distances (m)		
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TNR	93.9%	91.66%	90.9%	91.89%	86.36%	81.48%

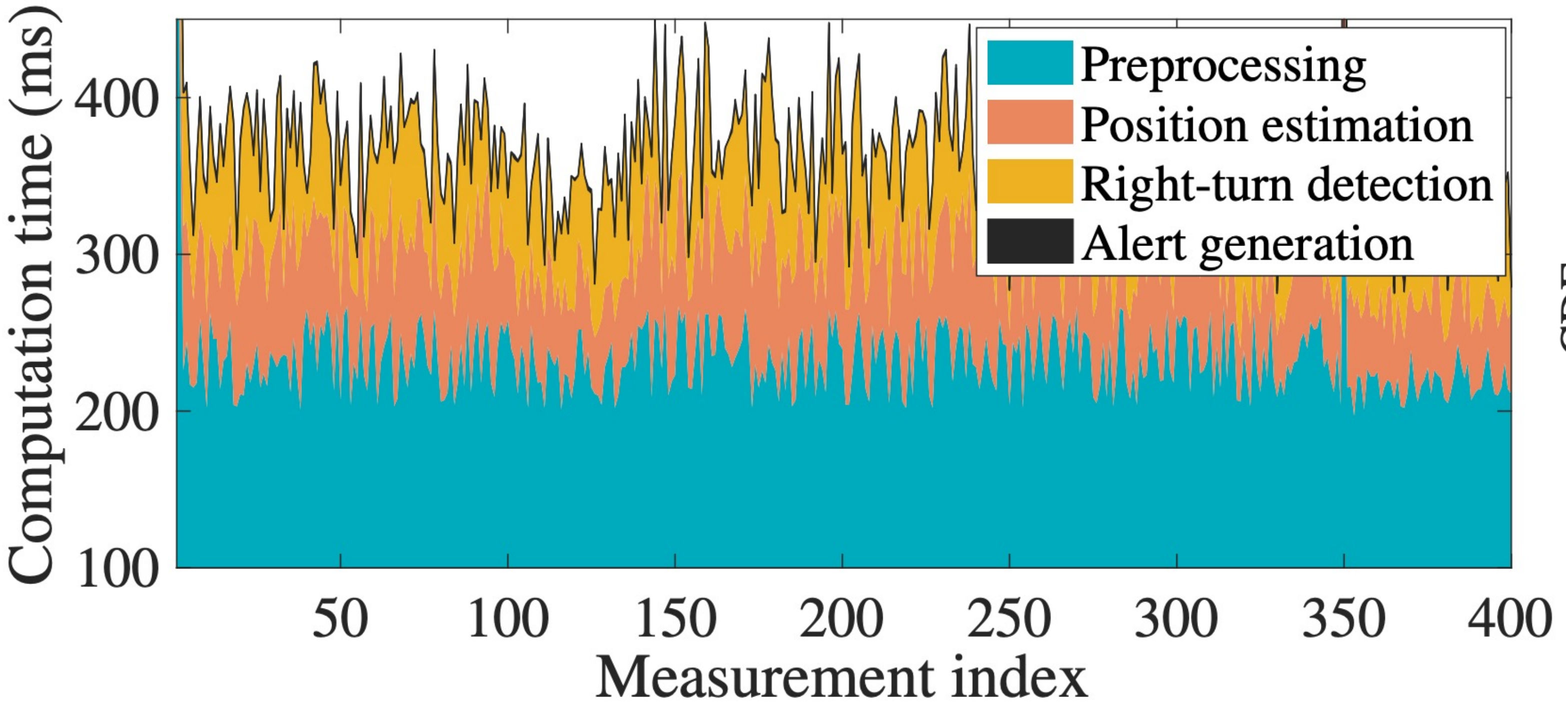
Acceptable real world performance at night

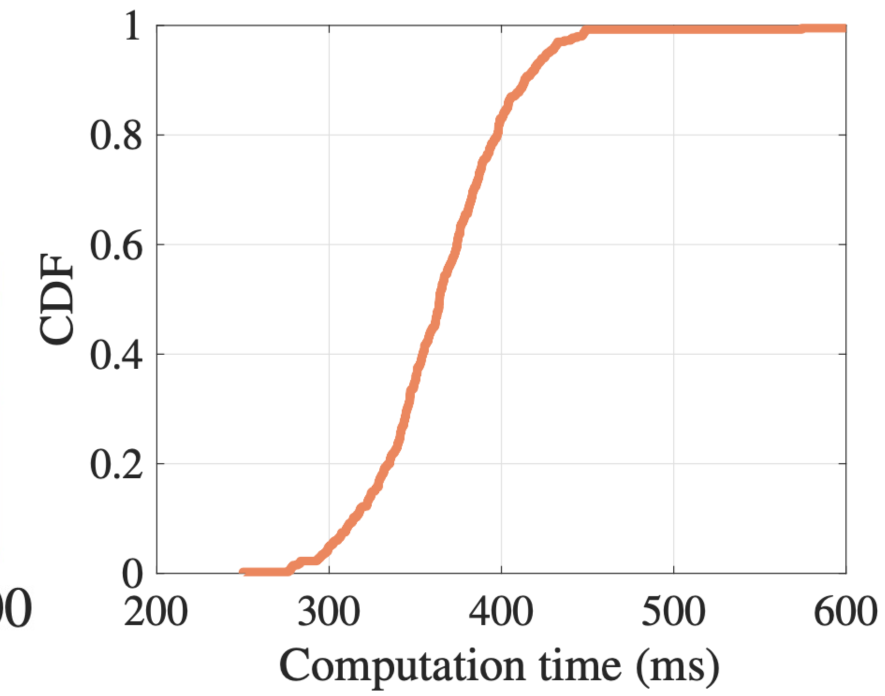
Evaluation

- Micro benchmarks
  - Computation time

Acceptable time consumption:

- Average : 365ms
- 90% measurements ≤ 414ms





Evaluation

- Micro benchmarks
  - Computation time
  - Energy consumption

Acceptable power consumption:
- 30-min usage: 242mAh

Application	CycleGuard	Video calling	Video streaming	Web browsing
Energy consumption	242 mAh	563 mAh	422 mAh	242 mAh
Percentage	7%	16%	12%	7%

Evaluation

- Micro benchmarks
  - Computation time
  - Energy consumption
  - Different devices

Portable to other devices

Phone	Battery capacity	Energy consumption	Percentage
Pixel XL	3450 mAh	242 mAh	7%
Galaxy S8	3000 mAh	270 mAh	9%

Conclusion

- We presented a low-cost, accurate, portable system to continuously detect potential right-hook collisions
- Our solution relies on emitting ultrasonic signals via a cheap external speaker to analyze the vehicular reflections, which cannot affect human hearing, but can be captured by standard smartphone hardware
- We conduct extensive experiments in both controlled parking lots and on real-roads in low-light conditions
- Our system achieves up to 95% real-world accuracy and is energy friendly

Thanks for your attention!

For more details, please refer to our paper

For Demo video: https://bit.ly/3BbsPRE