METRO

Magnetic Road Markings for All-weather, Smart Roads

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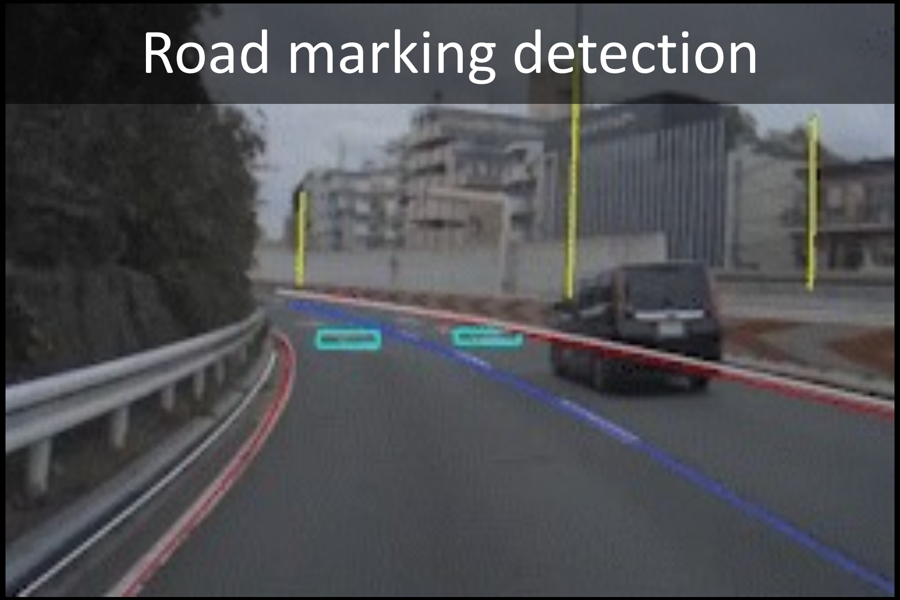
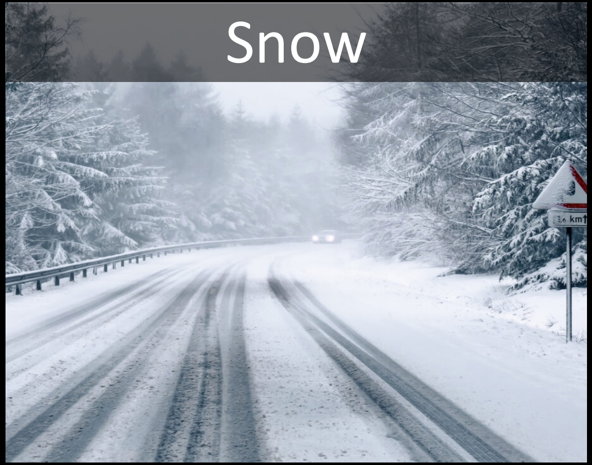
Background and Motivation



Road surface markings are **safety-critical** traffic infrastructure

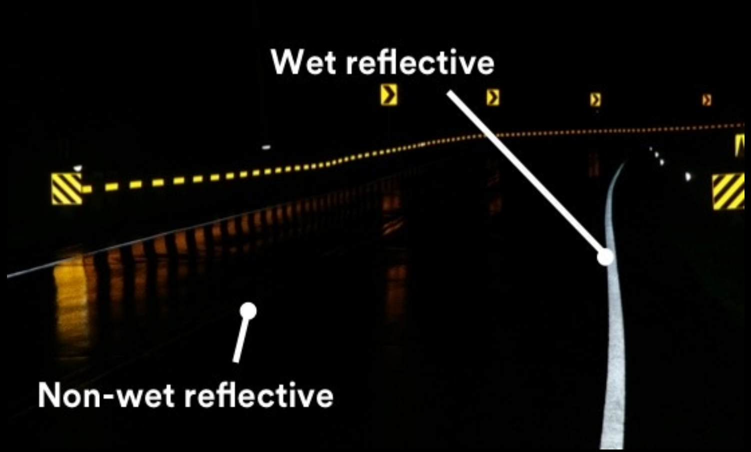


Adverse weather conditions

Wear and tear

The **poor visibility** of road markings is the major hurdle for driving safety and efficiency

Current Paradigm is Limiting



Reflective road marking

Raised pavement marker

Down-pointing arrow

These markers only convey **limited information** and may still be occluded by adverse conditions

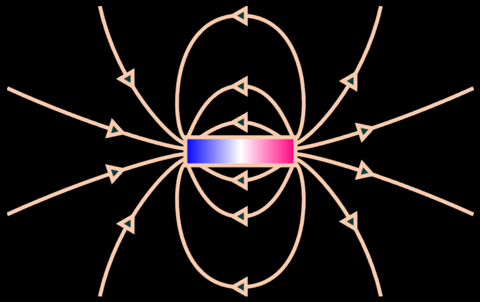
Occlusion-free Solutions

- Radio frequency identification (RFID)
  - High cost (>$1,000)
  - Multi-path effect
- Millimeter wave
  - Obstacle occlusion
  - Multi-path effect
- Near-field communication (NFC)
  - Short range (<10 cm) and low speed (<1 m/s)
- Magnetic sensing
  - **Robust, cost-effective and highly accurate**

Impinj R420 RFID reader

Millimeter-wave radar

NFC-enabled payment



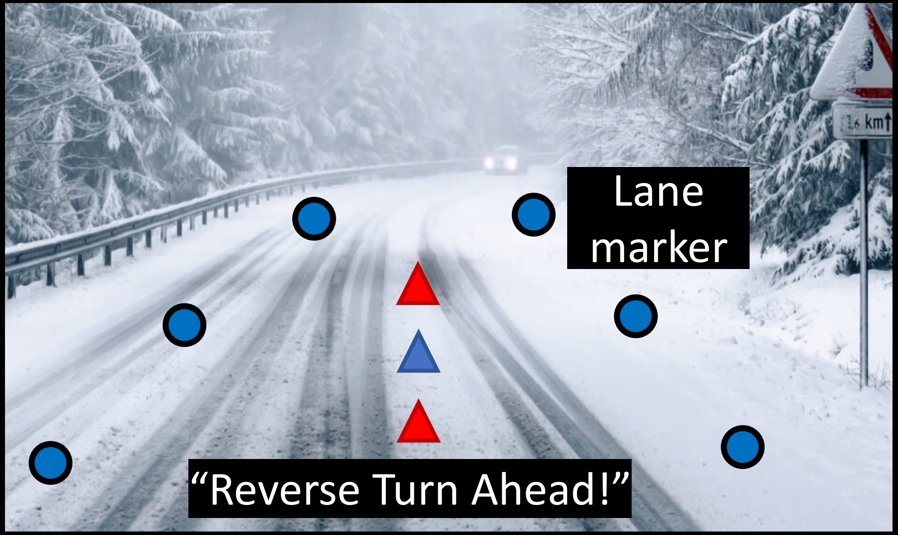
Magnetic field

Technical Challenges

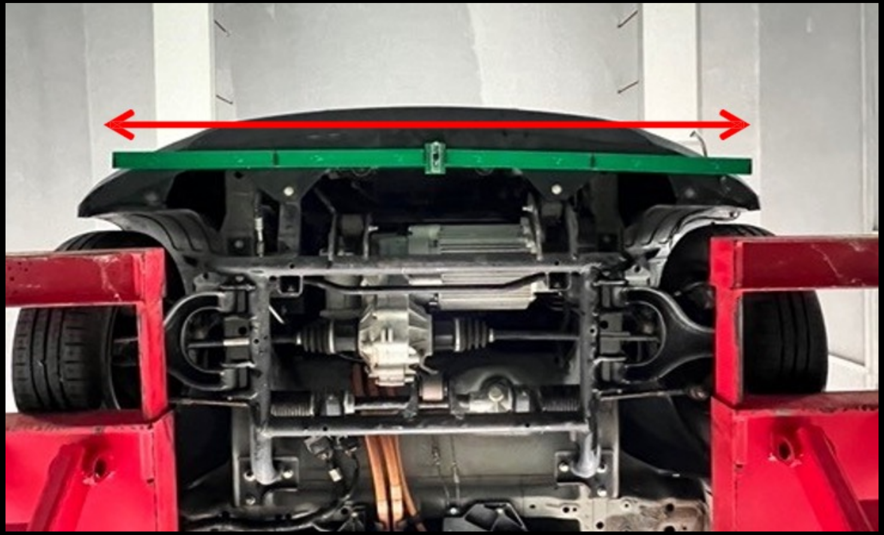
1. How to encode diverse road information with passive magnets?
    - High encoding capacity
2. How to achieve robust sensing in harsh on-road scenarios?
    - Varying speed/headings
    - Real-world disturbances
3. How to deploy METRO in real-word road environments?
    - High durability
    - Low cost

Our Solution: METRO

- A novel all-weather road marking infrastructure utilizing passive magnets and an automotive-grade magnetic sensing framework

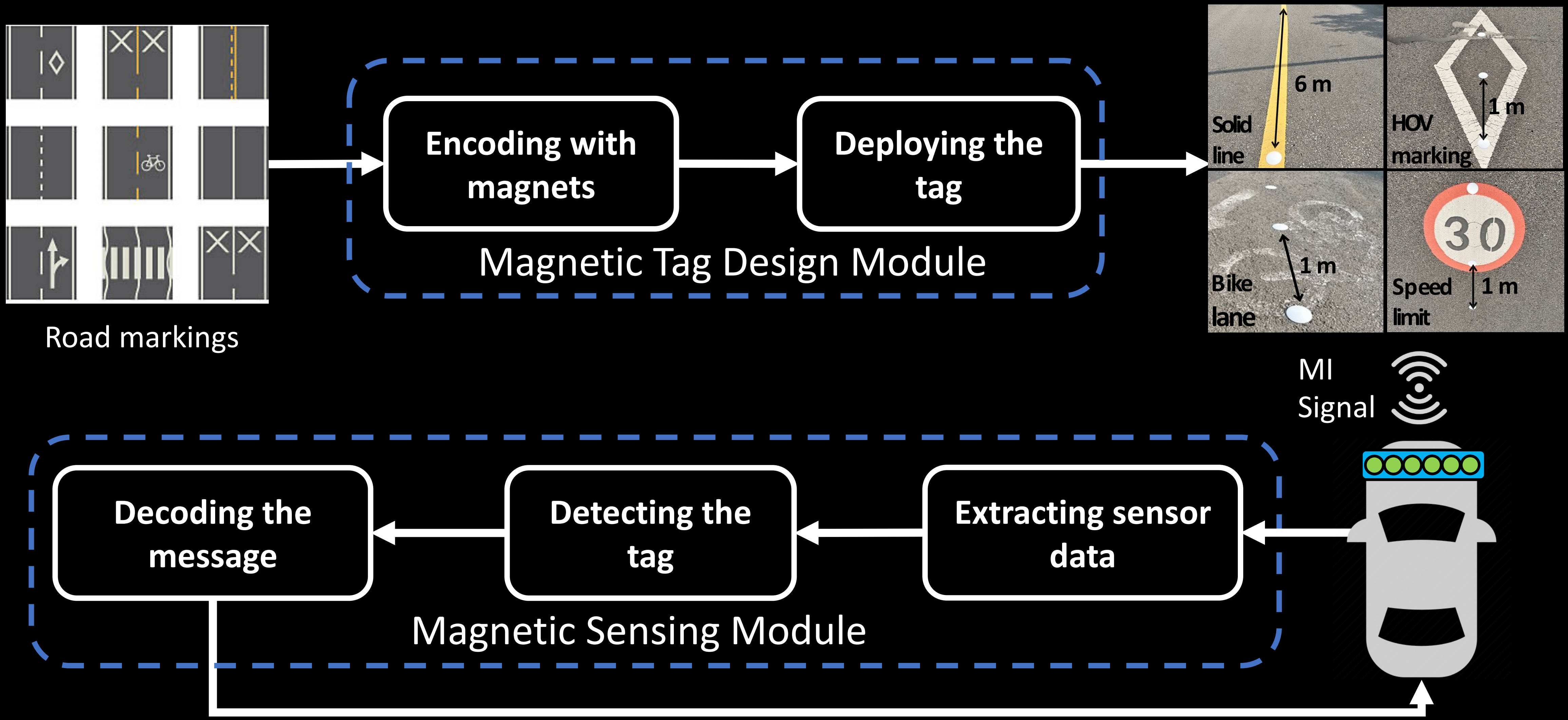


On-road magnetic dots



Sensor array attached in car's bumper

The Overview



Encoding Scheme of METRO

- Two types of road surface markings [1]

Longitudinal markings (e.g., lane lines)

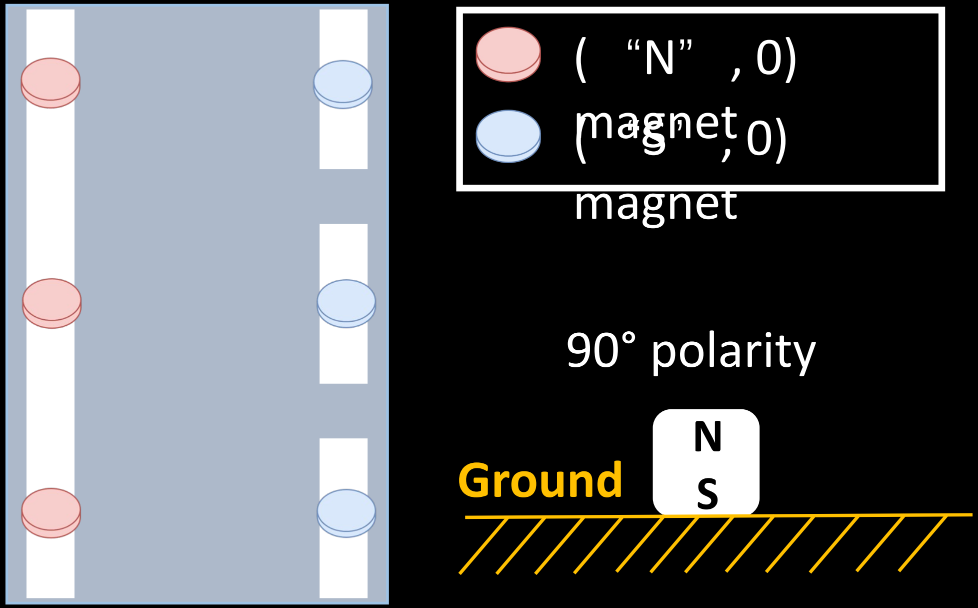
Transverse markings (e.g., arrow markings)

[1] Federal Highway Administration. 2022. Manual on uniform traffic control devices. https://mutcd.fhwa.dot.gov/. (2022).

Encoding Longitudinal Markings

- N/S polarity for the upside
  - Solid line: {“N”, 90°}
  - Dashed line: {“S”, 90°}

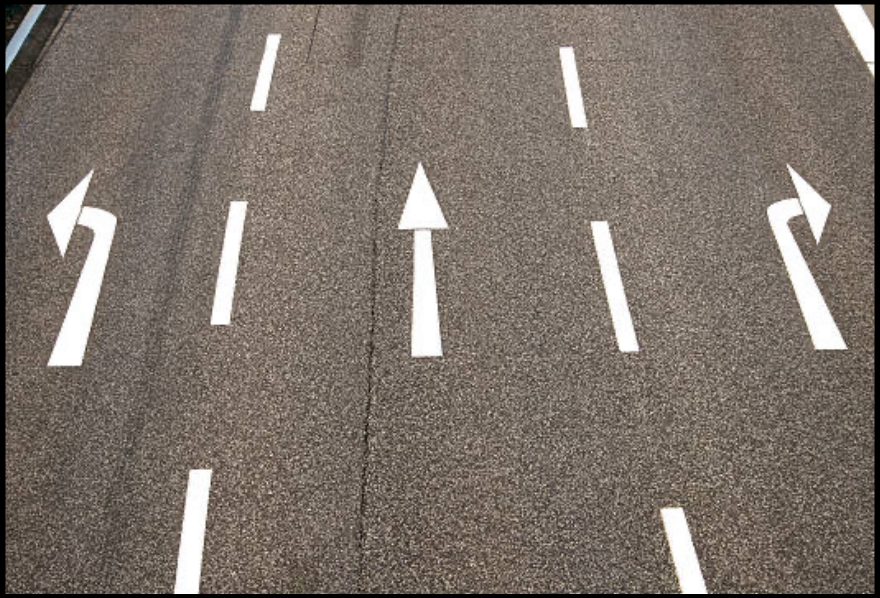
Longitudinal markings (e.g., lane lines)



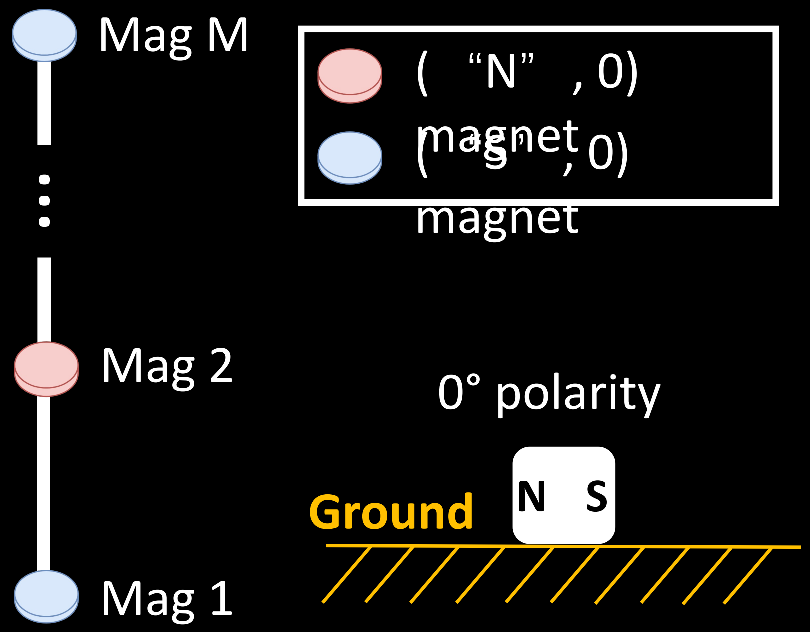
Longitudinal markings encode by METRO

Encoding Transverse Markings

- N/S polarity for the forward

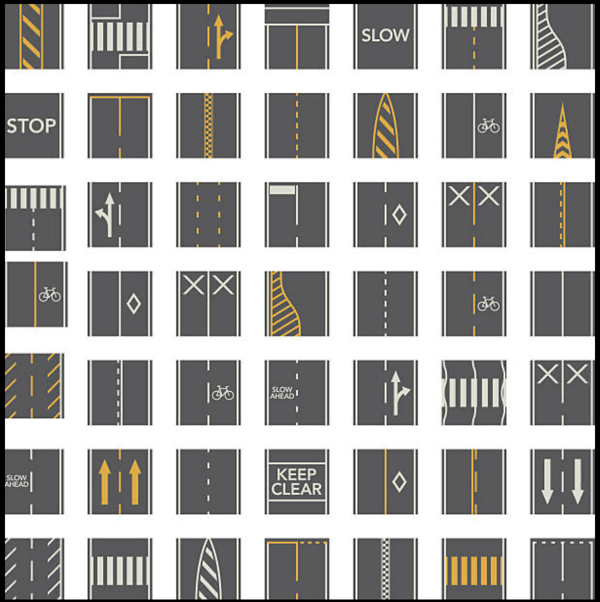


Transverse markings (e.g., arrow markings)

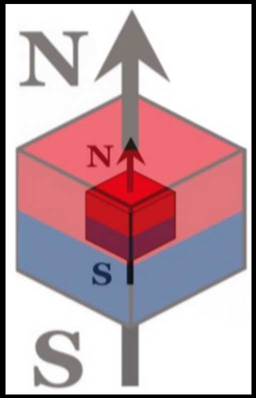


Transverse marking encoded with polarity

How to Encode Diverse Transverse Markings?



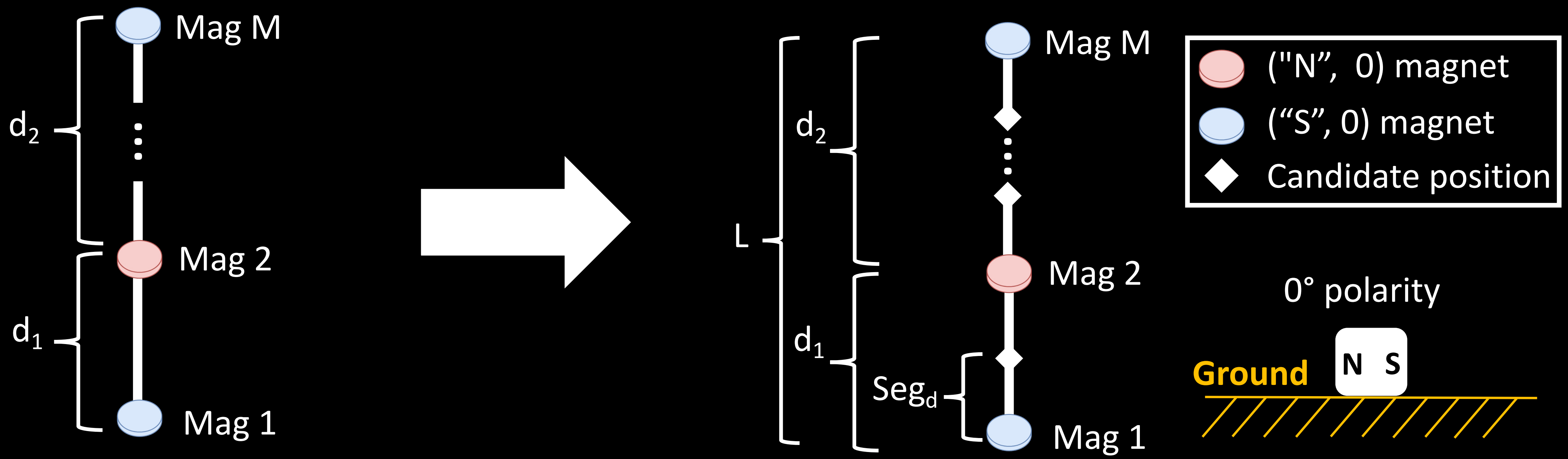
200 types



2 types

Introducing: Inter-magnet Distance

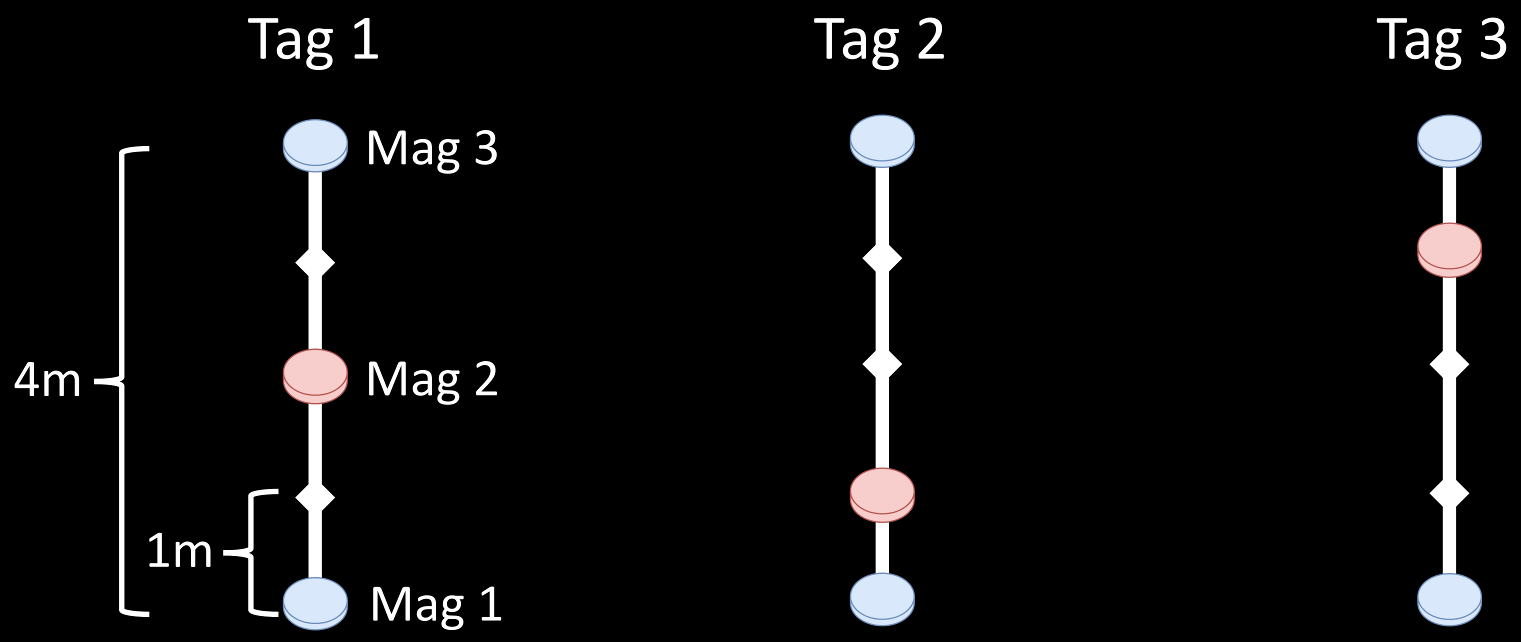
- The calculated distance is inaccurate due to the arbitrary driving trajectory
- METRO introduces **distance ratio** (i.e., ratio of inter-magnet distance)



Transverse marking denoted as {“SNS”, 0°, M, L, Seg_d, d_2/d_1}

Exemplary Transverse Markings

- Given M=3, L=4 m, Seg_d=1 m, METRO can encode **24** unique messages



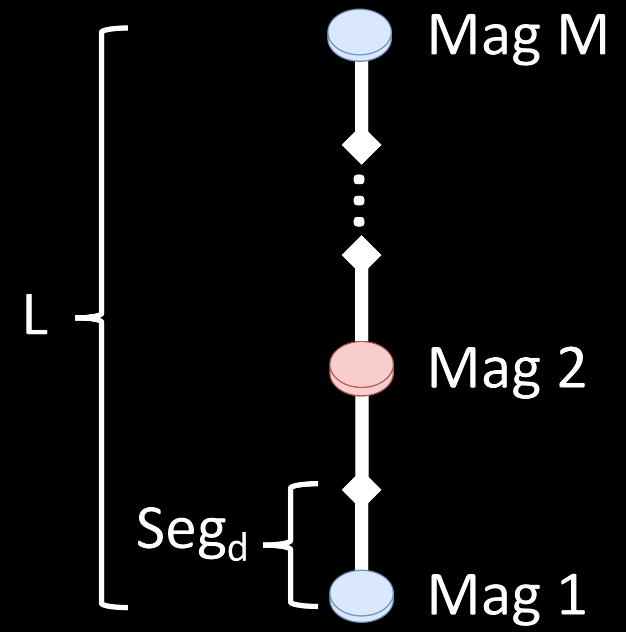
	Tag 1	Tag 2	Tag 3
Polarity:	"SNS"	"SNS"	"SNS"
Distance ratio:	2m/2m=1	3m/1m=3	1m/3m=1/3

Encoding Capacity Analysis

- Encoding capacity

$$C = 2^M \cdot \binom{L/Seg_d - 1}{M - 2}$$

- With M = 3, L = 4 m and Seg_d = 0.1 m, METRO can reliably encode **248** unique messages



How to Achieve Robust Magnetic Sensing?

- METRO needs to tackle unique challenges to facilitate the **harsh on-road scenarios**

High speed (e.g., >50 mph)

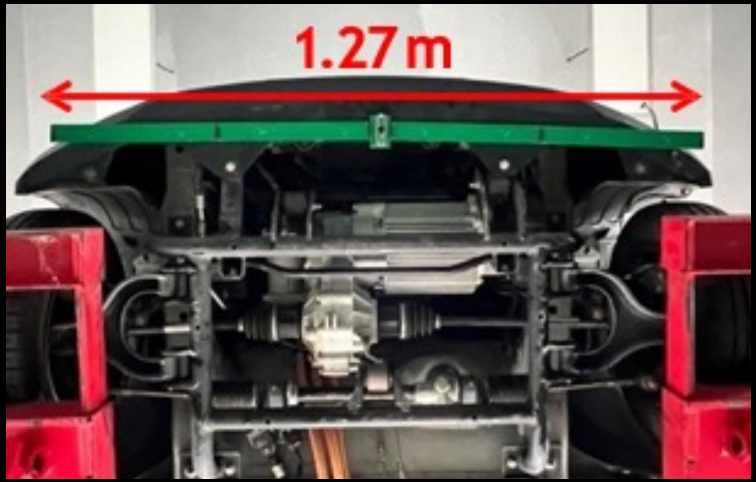
Adverse weather

Rough pavements

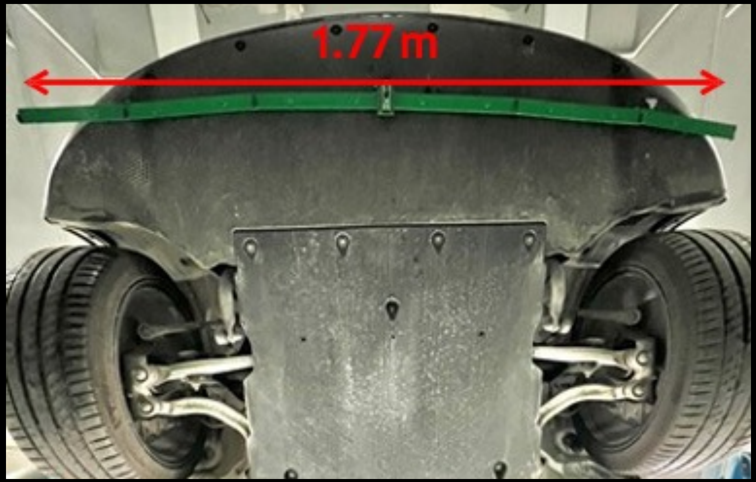
We propose an **automotive-grade magnetic sensing framework** that constitutes novel hardware and software designs

Hardware Design

- Modular magnetic sensor array
  - A Teensy 4.1 MCU
  - 12 MLX90393 magnetometers
- Hardware cost: < $85
- The sampling rate: >350 Hz



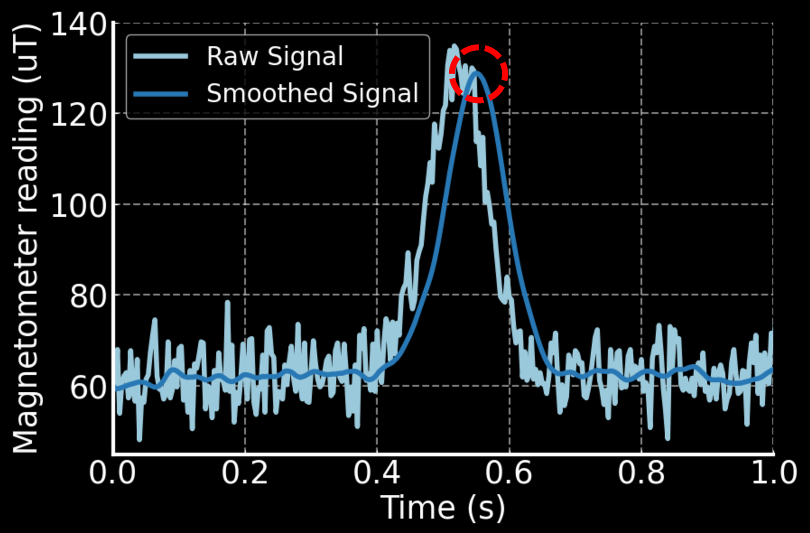
On a smart electric car



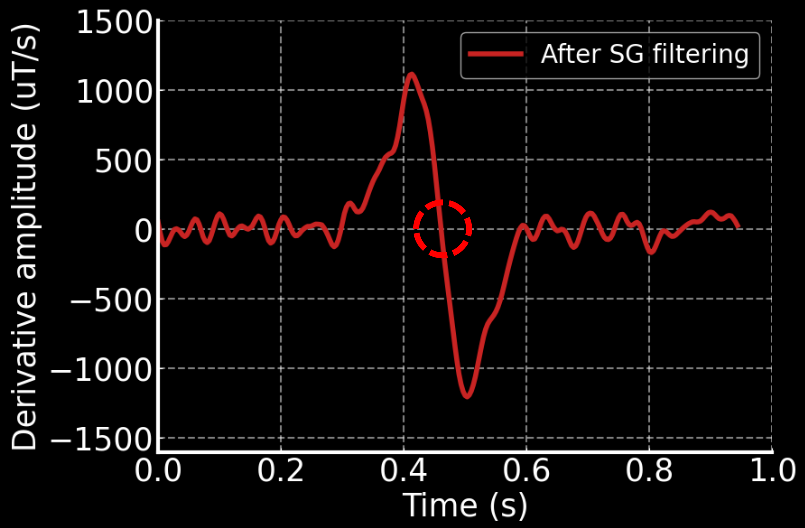
On a Tesla Model Y

Sensing Algorithm

- **Derivative-based** peak detection algorithm
- Three key steps, total time delay <25 ms
  - Preprocessing, derivation, peak/valley detection



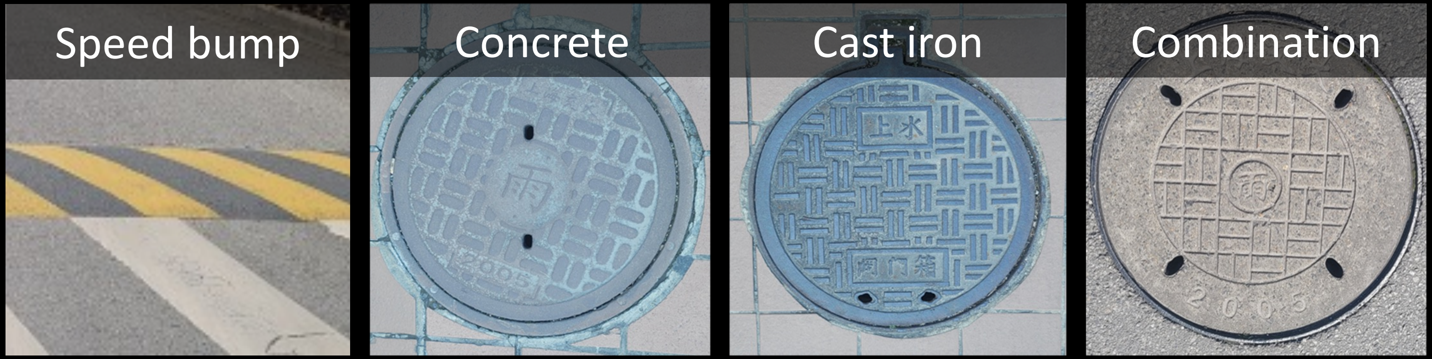
Raw peak signal with "N" polarity



First derivative signal

Integrated Noise Cancellation

- Environmental disturbances can be eliminated by the derivative-based sensing pipeline
  - On-road infrastructures
  - Surrounding vehicles

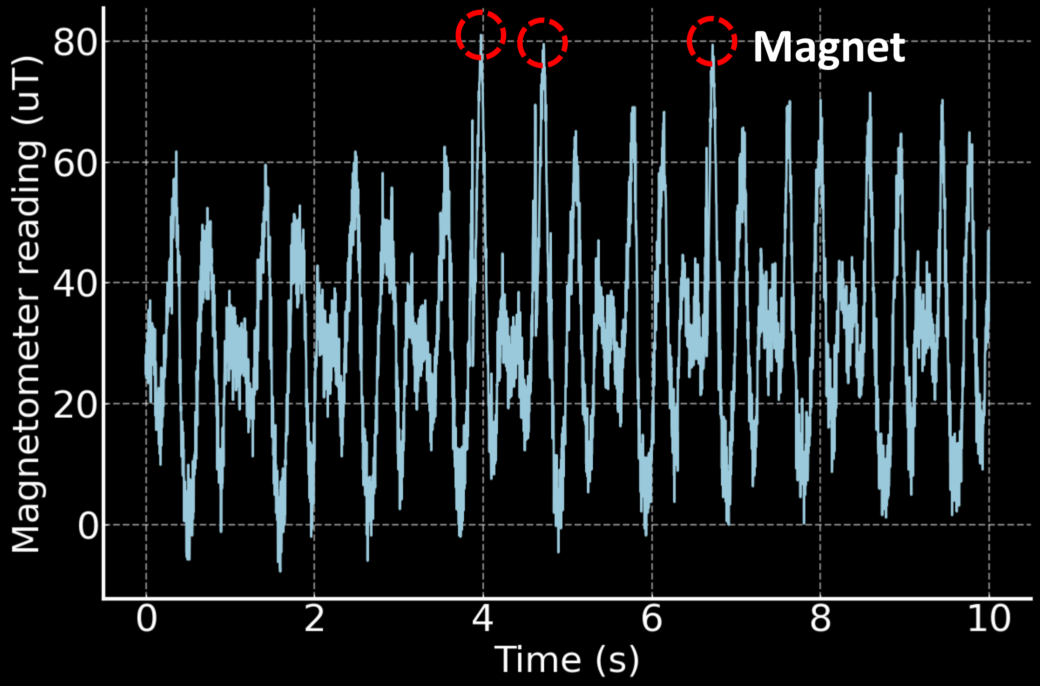


On-road infrastructures

Surrounding vehicles

Integrated Noise Cancellation (Cont.)

- Noises from the ego car
  - Observation: the wheel rotation incurs severe periodic magnetic noise



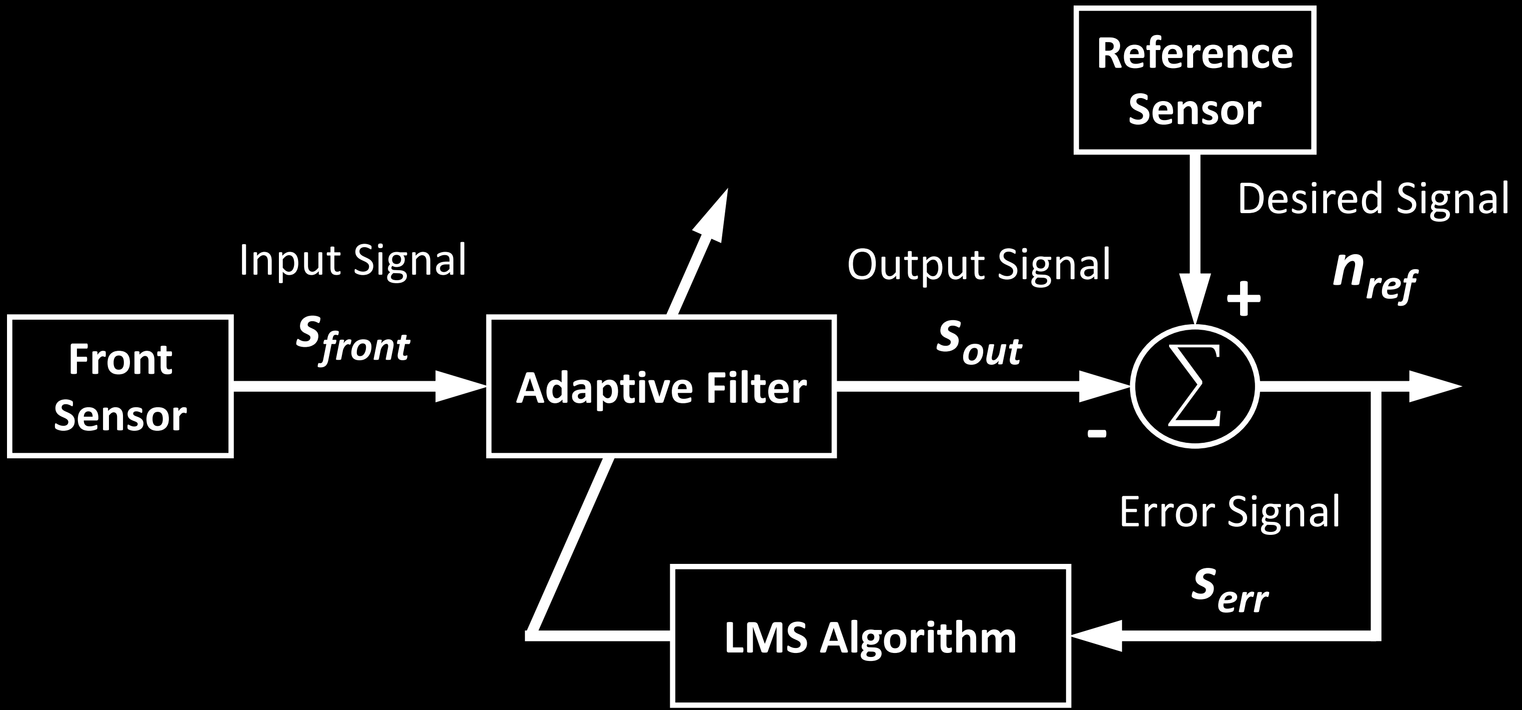
W/ the wheel noise

28.8%

Accuracy

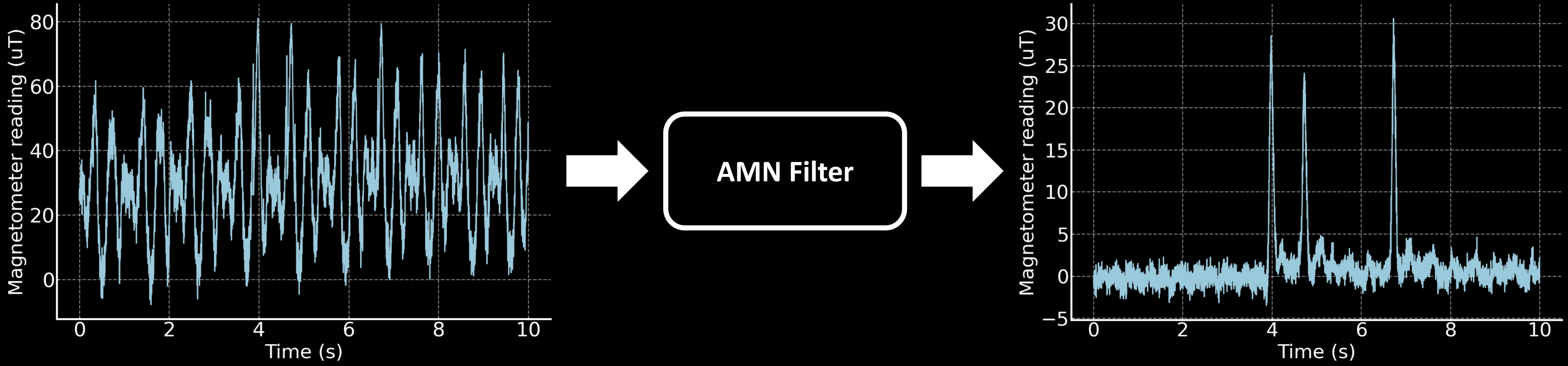
Integrated Noise Cancellation (Cont.)

- Solution: LMS-based *adaptive magnetic field neutralization* (AMN)



Adaptive filter with Least Mean Square

Integrated Noise Cancellation (Cont.)



W/ the wheel noise

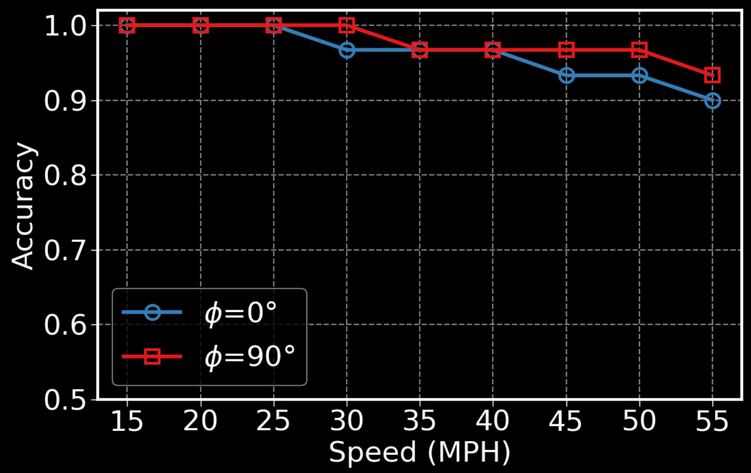
Filtered by AMN

96.7%

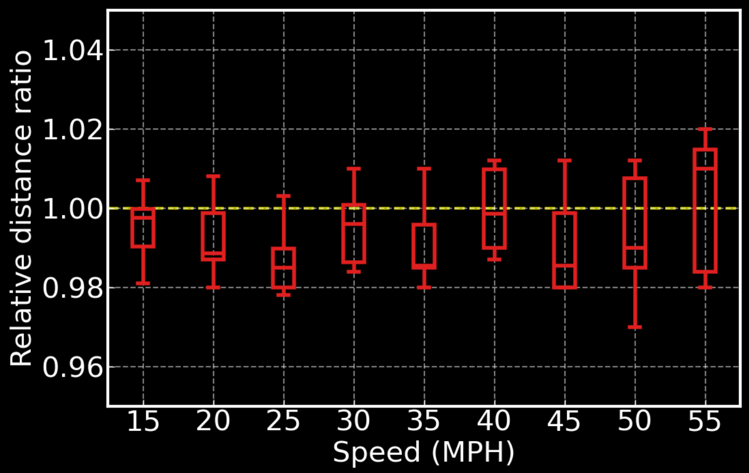
Accuracy with AMN

Evaluation: Vehicle Speed

- Speed: 15-**55** mph (24-**88** km/h)
  - Test tags: tag {“N”, 90°} and tag {“NNN”, 0°, 3, 4m, 1m, 3/1}
- Results
  - The accuracy of detecting 90° and 0° magnets exceeded **93%** and **90%** at **> 50** mph
  - Overall detecting accuracy over **97%**



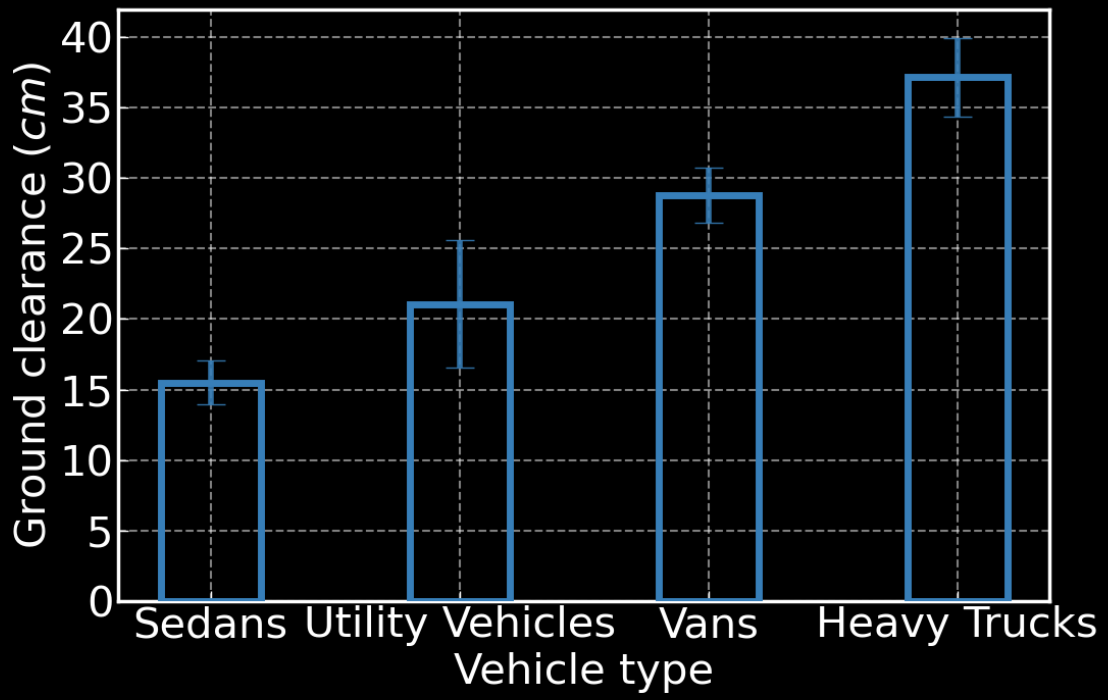
Accuracy w/ different polarities



Distance ratio result

Evaluation: Ground Clearance

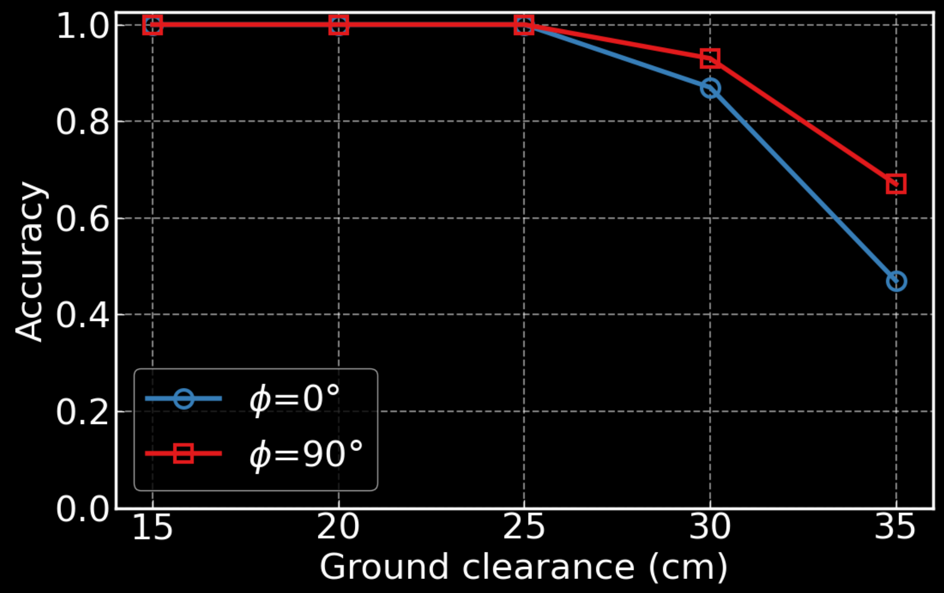
- Measure four types of real-world vehicles
- Ground clearance: 15-35 cm



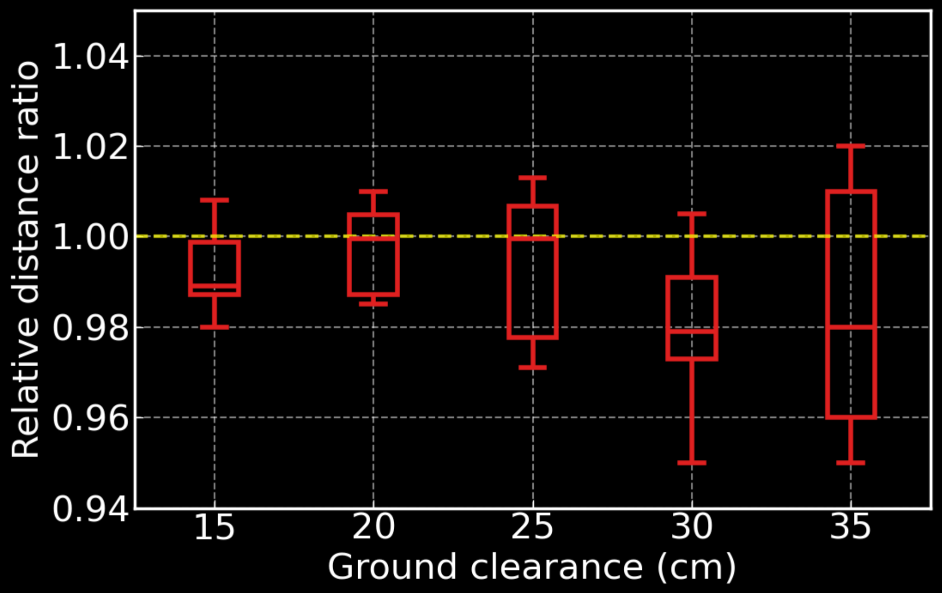
Ground clearances of different cars

Evaluation: Ground Clearance (Cont.)

- Results
  - Even at 30 cm, the performance of 90° and 0° magnets are **93%** and **87%**
  - The overall accuracy exceeded **97%** within the clearance of **30** cm



Accuracy w/ different polarities



Distance ratio result

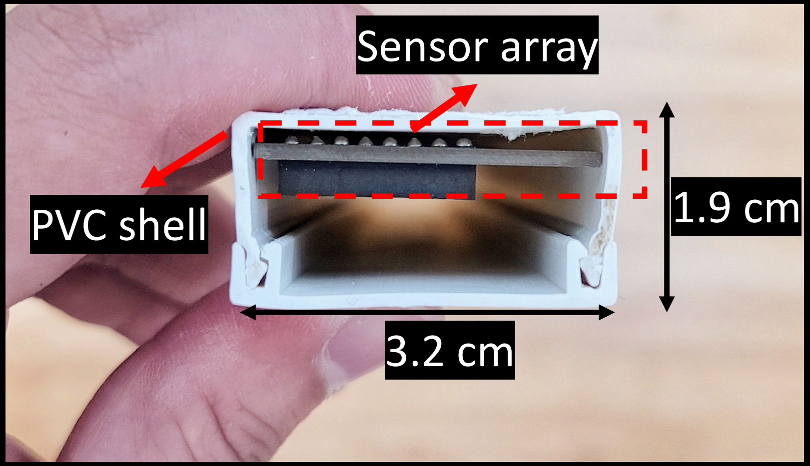
How to Deploy METRO in Real-world Roads?

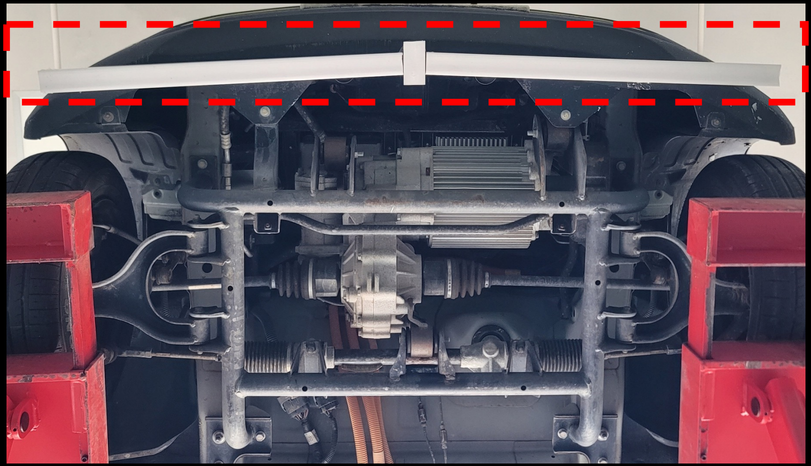
Achieve **highly durable** and **cost-effective** deployment for

- METRO’s sensor array and magnetic tag

Deployability of METRO’s Sensor Array

- Protect the sensor array with a PVC shell
- Installed the sensor array under the front bumper of a compact EV for a month
  - A total travel distance of over **150** km

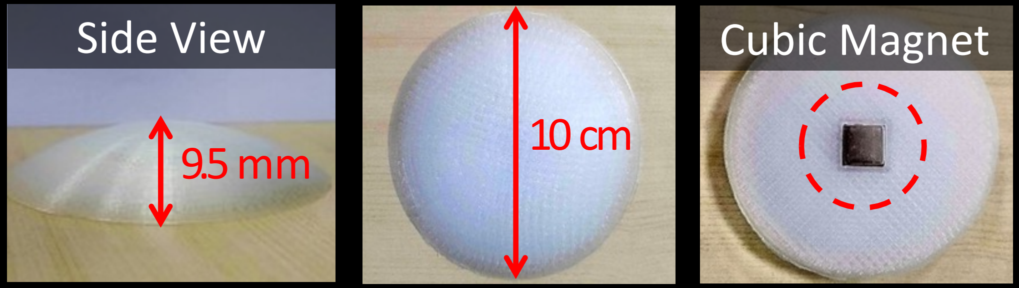




No sensor malfunctions/anomalies to METRO’s sensor array

Deployability of METRO's Tag

- High durability
  - Use cubic N52-grade passive magnets
  - With a 3D-printed protective shell
- Low cost
  - Each magnet: **$1**
  - Line marking: **$0.17** per meter
    - Traditional line marking: $0.21-7.70 per meter [2]
  - Transverse marking: **$3** per tag

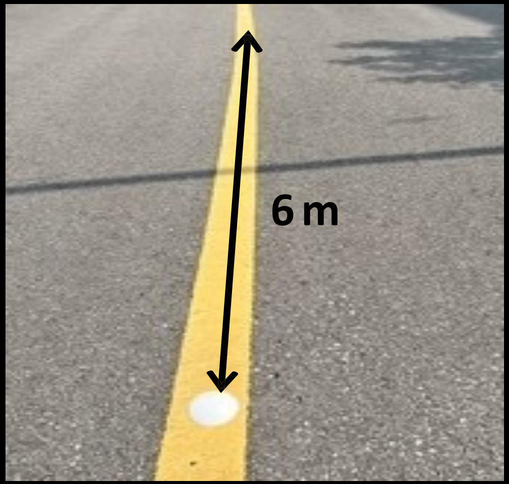


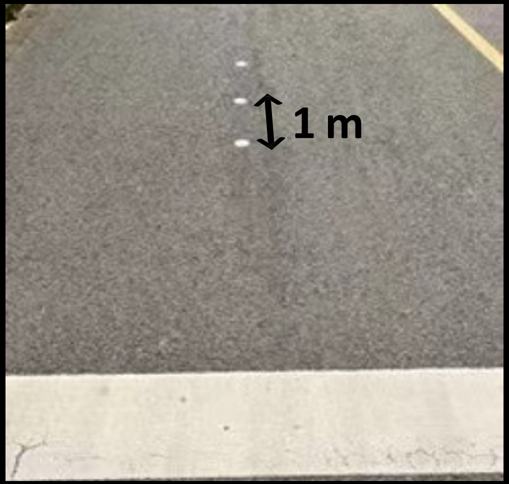
METRO tags in all-weather conditions

[2] 2005. Cost-Benefit Analysis. https://www.fhwa.dot.gov/publications/ research/safety/humanfac/04142/costest.cfm. (2005)

Deployability of METRO's Tag (Cont.)

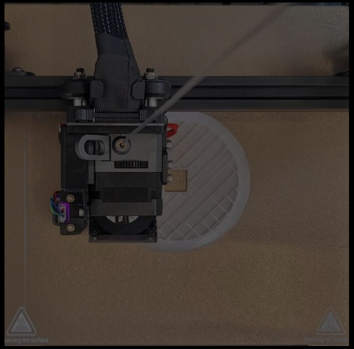
- Deployed the tags on a busy public road for one month
  - An average daily traffic volume exceeding **2,200** vehicles





No damage or demagnetization to METRO's magnetic tags

Manufacture and Deployment of METRO’s Tag



1. Print the protective

3. Add adhesive

4. Deploy the tag

6. One-month deploy

Conclusion

- METRO is a novel **all-weather** road marking infrastructure. It leverages magnetic sensing to achieve **accurate**, **robust**, and **cost-efficient** perception of road markings.
- METRO is tested and verified on REAL-WORLD ROADS!

Yes, METRO is Open-source!

open source hardware

https://github.com/wjk5117/METRO

Thanks!
Q&A

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IIOT
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Interactive Sensing
& Computing Lab