Passengers' Safety Matters: Experience of Deploying a Large-Scale Indoor **De**livery **Mo**nitoring System

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Indoor Delivery in a Subway Station

- **Hong Kong subway stations**
  - Looks like small malls (1,500+ station shops, 300+ brands)
  - Extremely busy (4.7M+ daily passengers)
  - Daily goods deliveries to shops

Retail location ( ) in stations

Example of an indoor delivery

Why Monitor Delivery Process?

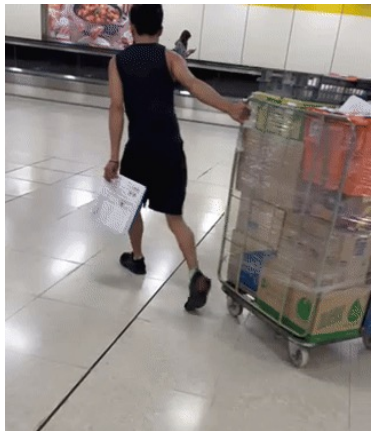
- **Indoor delivery accidents are common**
  - E.g., Collided with passengers
- **HK government propose to regulate the delivery process**
  - Protect passengers' safety

Delivery trolley collided with passengers

Crowded with passengers

Categories of Delivery Violations

Violations	Potential Hazards
Speeding (over 1.5m/s)	Goods falling, collision with passengers
Unauthorized use of passenger lifts	Goods falling, collision with passengers
Non-designated delivery path	Unregulated
Delivery during peak hours	Crowding caused by blocked passageways

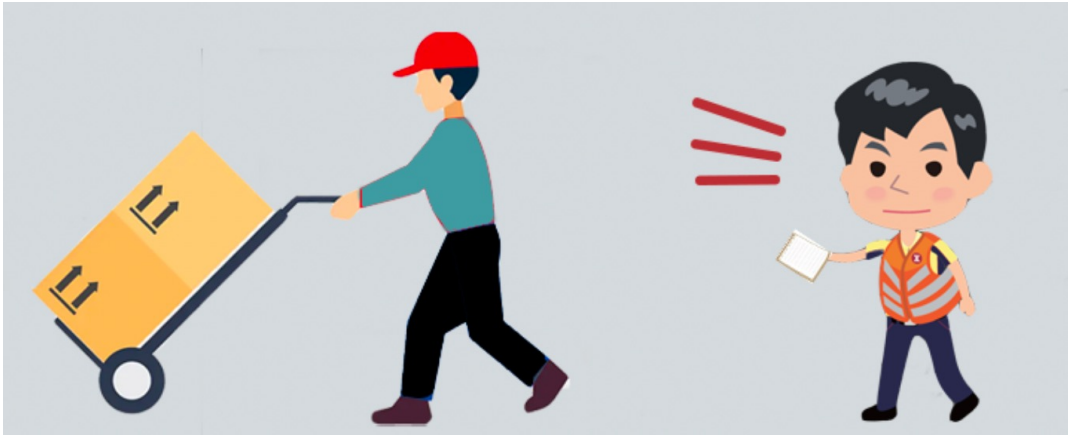


Speeding

Non-designated delivery path

Manual Delivery Supervision

- **Safety staff accompany deliveries, observe, record, and intervene violations**
- **Limitation:**
  - Speeding is difficult to accurately assess
  - One staff can only accompany one trip at a time
  - Labor cost



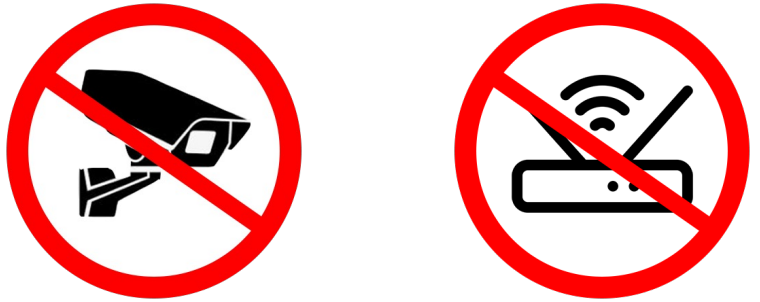
Example of monitoring delivery manually

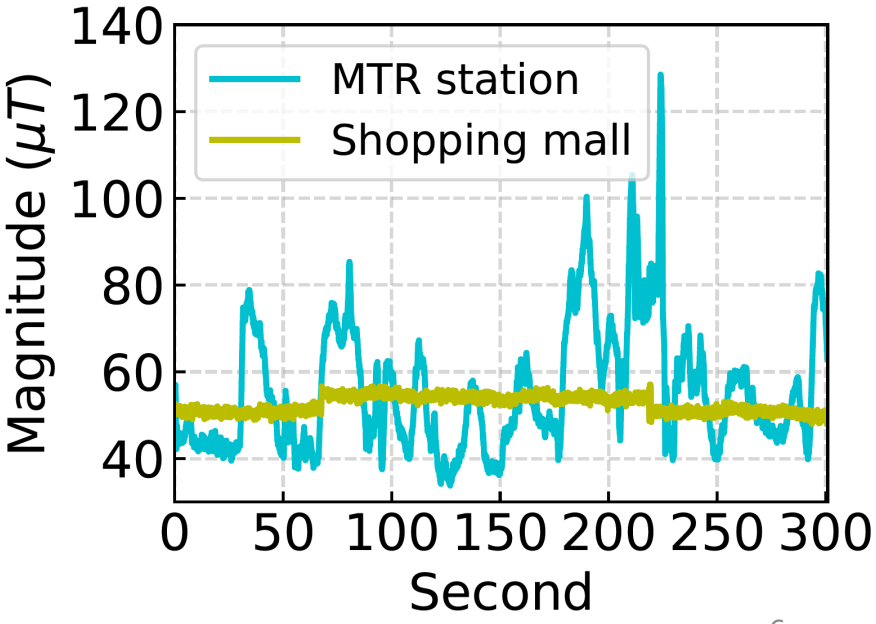
Challenges

- **Requirements from subway corporation**
  1) Privacy protection
  2) No additional power or networking cables
  3) Limited preparation & maintenance overhead
  4) Aesthetic considerations

- **Environmental challenge**
  - Unstable geomagnetic field

- **Uncertain human behavior**
  - Different sensor placement



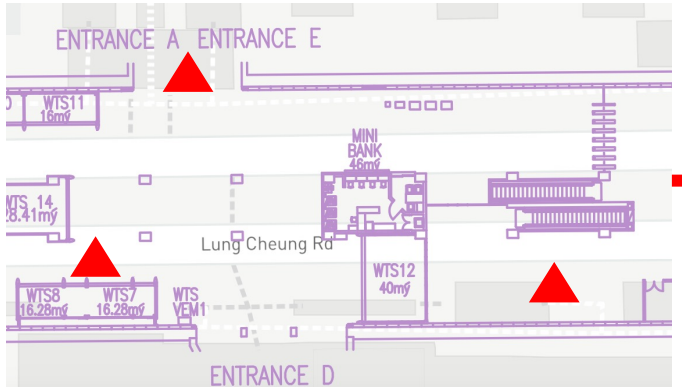


DeMo Overview

- **Indoor Delivery Monitoring System**
  - Bluetooth Low Energy and Inertial Measurement Unit (IMU) readings
  - IMU for speed detection
  - RSSI-distance model for positioning
  - Deployed in 12 subway stations in Hong Kong
  - Covered 200+ shops with 40k+ deliveries

Why RSSI-Distance Model

- **Limitations of fingerprint localization**
  - Training the fingerprint database involves considerable labor costs
  - Updating the per-site fingerprint database is time-consuming
- **RSSI-distance model**
  - Easy to deploy on a large scale at low cost
  - Stable and accurate enough for monitoring deliveries



Collected training data in one station

Validated

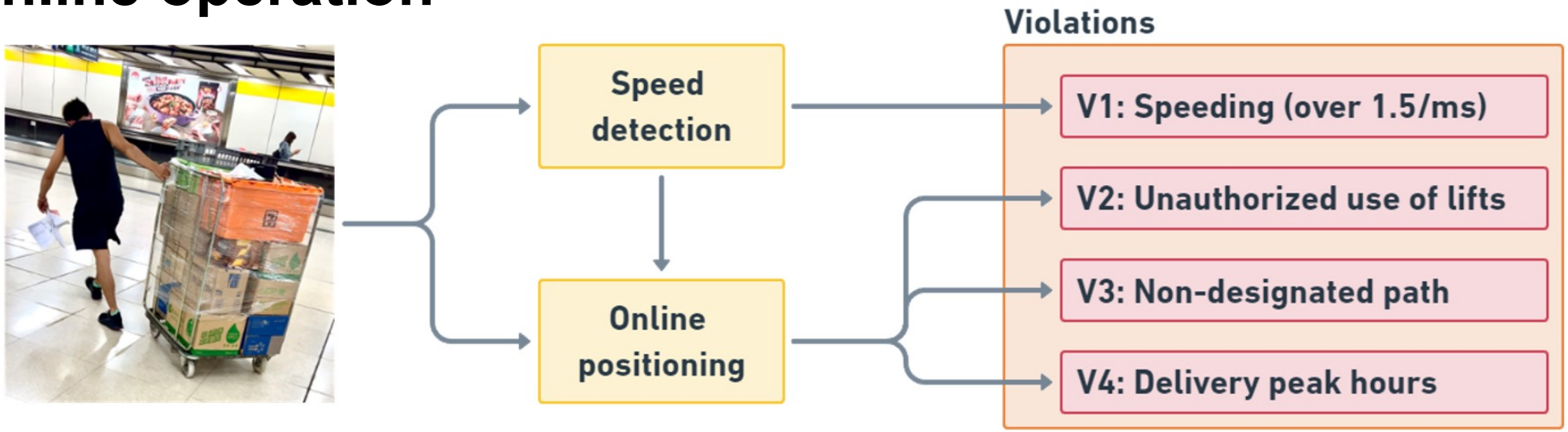
Stations	1	2	3	4	5	6
Accu (m)	2.81	2.55	2.93	2.62	2.99	3.39
Stations	7	8	9	10	11	12
Accu (m)	2.82	2.42	3.68	3.83	2.45	2.51

Positioning accuracy in 12 stations

DeMo System Design

- **Offline preparatory**

- **Online operation**



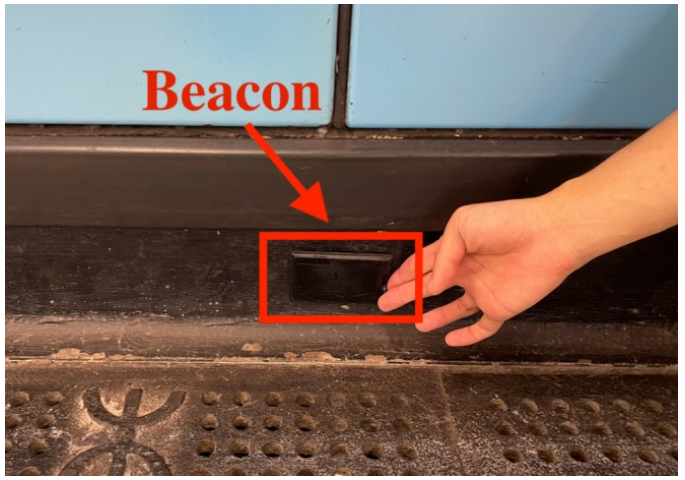
1. Attach a sensor to the trolley

2. Detect trolley's speed and location

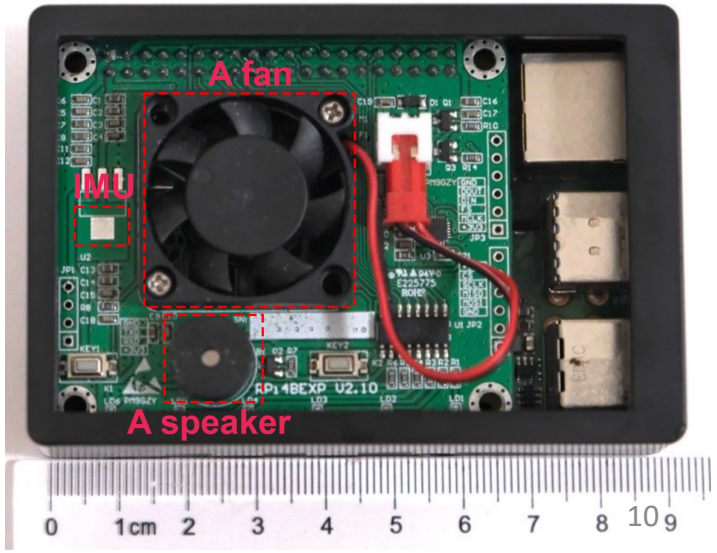
3. Detect violations

Offline Preparatory - Hardware

- **Broadcaster: BLE Beacons**
  - Small-sized
  - Battery-powered (~2 years)
  - Low cost (≤ 9 USD each)

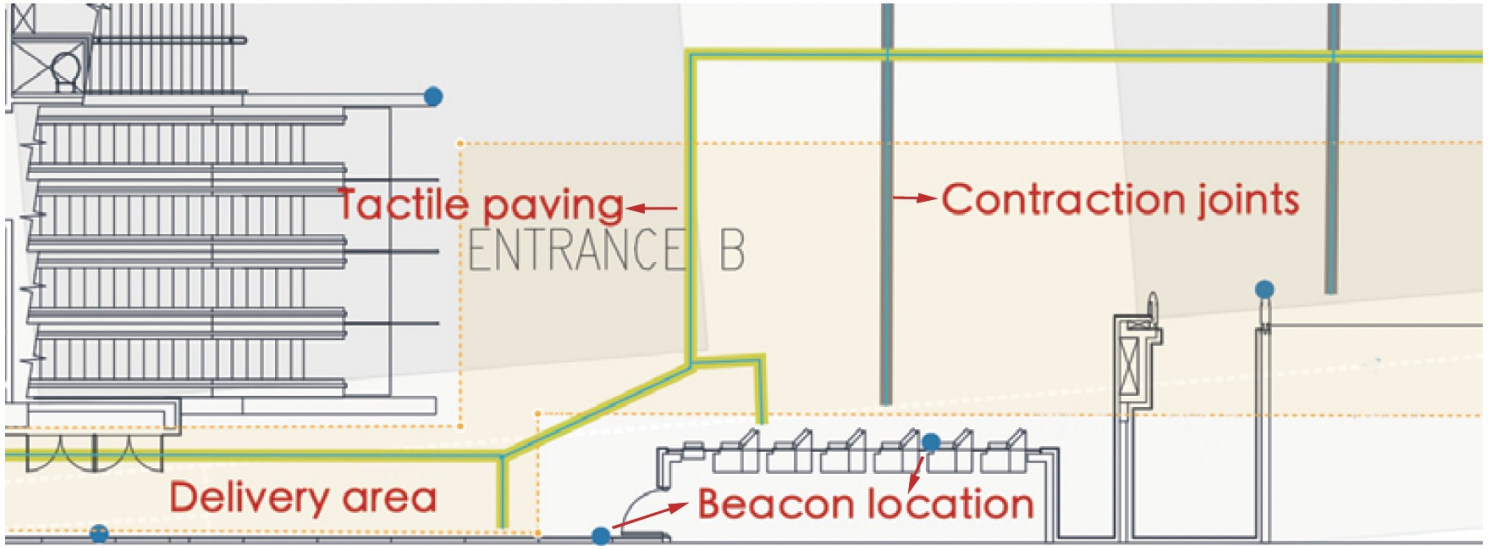


- **Receiver: Customized Raspberry Pi 4B**
  - Battery-powered
  - Customized hardware attached on top (HAT)
  - Placed on trolleys to accompany the deliveries



Offline Preparatory– Floor Plan Processing

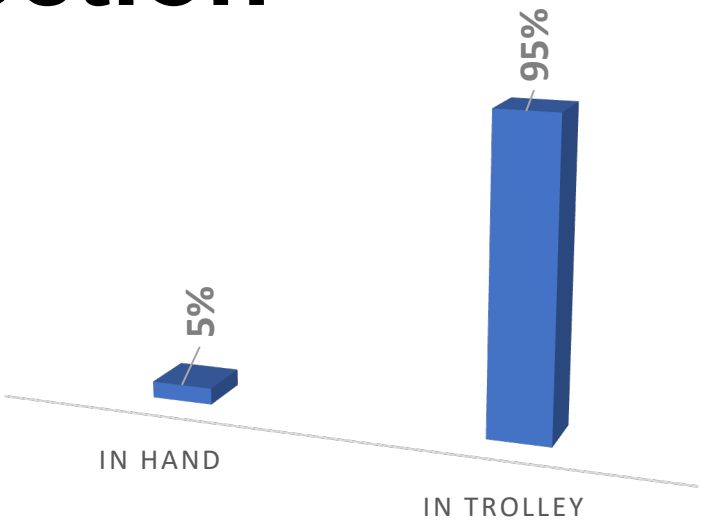
- Specify the installation positions of the beacons
- Demarcate the allowed delivery zone
- Mark road surfaces to enhance speed detection performance



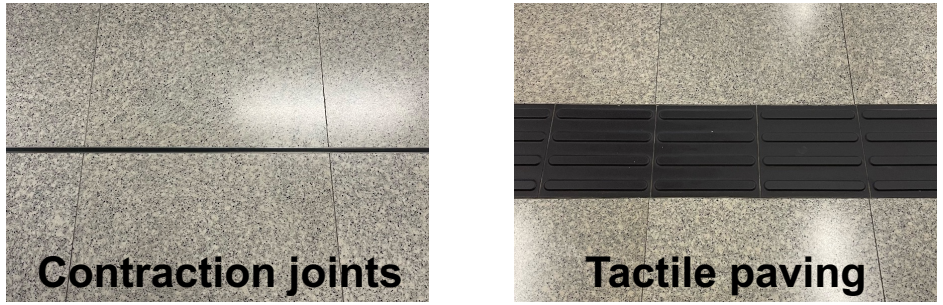
Example of a pre-processed floor plan

Online Operation - Speed Detection

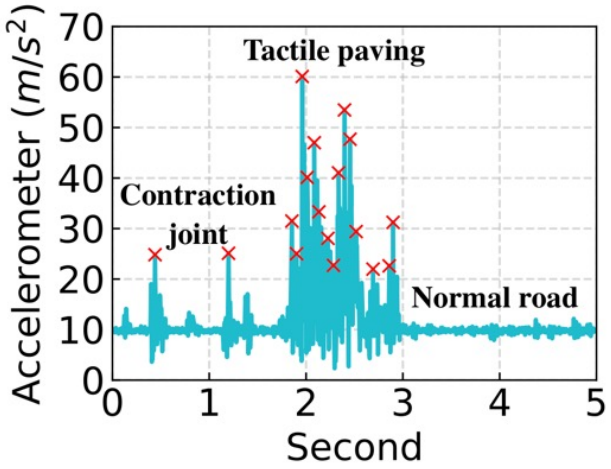
- **Challenges**
  - Uncertain sensor placement
  - Special roads show high fluctuations in readings
- **Solution**
  - Identify person or trolley placement through IMU
  - Filter IMU readings from certain road surfaces



SENSOR PLACEMENT



Special road surfaces



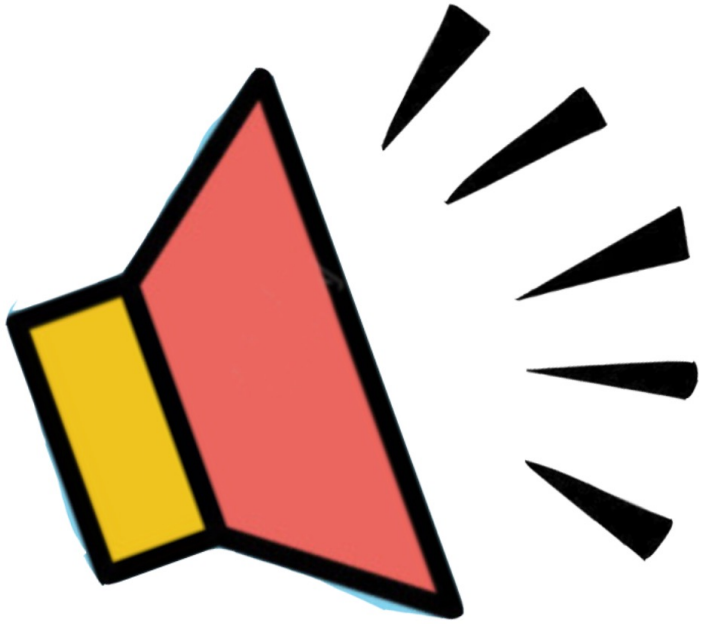
Online Operation - Positioning

- **Challenges**
  - The geomagnetic field strength in subway stations is unstable
  - Miss the accurate direction of the trolley's movement

- **Solution**
  - Particle filter: translating the RSSI model into a probability model
  - Integrating accelerometer and gyroscope readings
  - Utilizing the trolley's historical trajectory

Real-Time Violation Detection

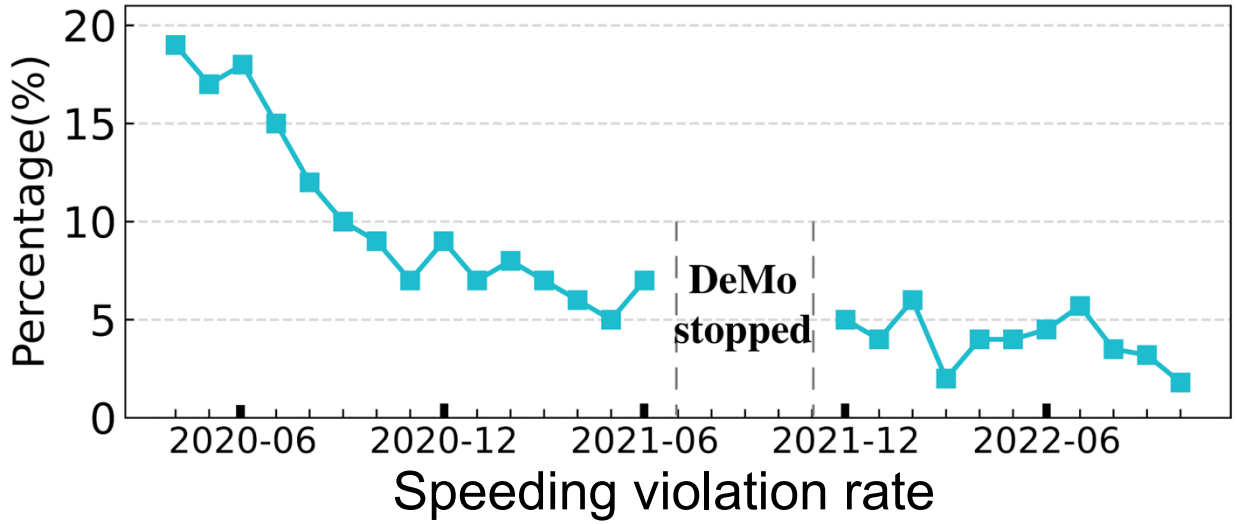
- **Speeding**
  - Sensor's speed consistently exceeds 1.5 m/s
- **Non-designated delivery path**
  - Detect deviation from the pre-determined route
- **Unauthorized use of passenger lifts**
  - Monitor floor changes
  - Geo-Fencing detection
- **Delivery during peak hours**
  - Record delivery times



Alarm upon violation detection

Large-Scale Operation Result

- **Witness a significant decrease in speeding (19% to 2.7%)**
- **Other violations reduced from 1% to 0.5%**



- **Exclude placebo effect**
- **Lesson**
  - Accurate detection and real-time alerts contribute to altering delivery behavior

Large-Scale Operation Result

- **DeMo vs. manual monitoring**
  1. Cost reduction: >8X
     - One-time deployment & maintenance vs. ongoing manpower costs
  2. Monitoring efficiency
     - 88% vs. 53% of total delivery activities
  3. Delivery behavior change: violation reduction
  4. Full coverage of violation type

- **Lesson**
  - DeMo outperforms manual monitoring in detecting violations

Large-Scale Operation - Maintenance

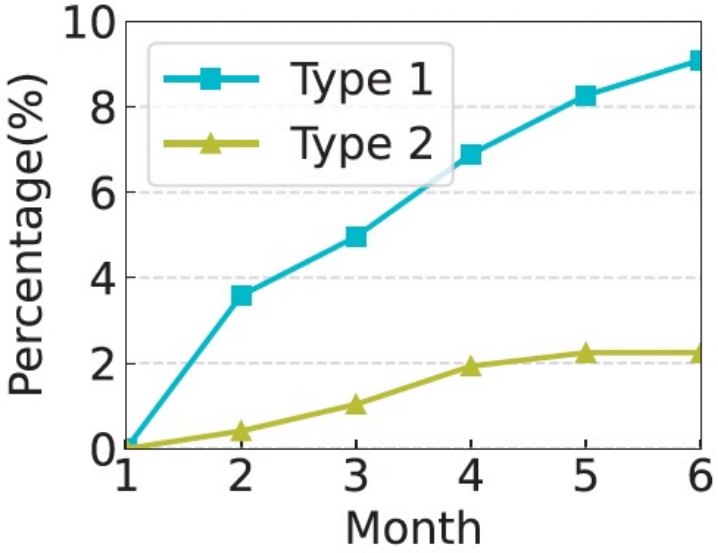
- **Types of beacon**
  - Different shapes influence the failure rate of beacons
- **Failed beacon location**

Location	Store	Entry/Exit	Corridor	Others
Failure rate (%)	5.3	3	1	0.6

- **Lesson**
  - Strategic beacon deployment could alleviate system maintenance costs

Beacon type 1

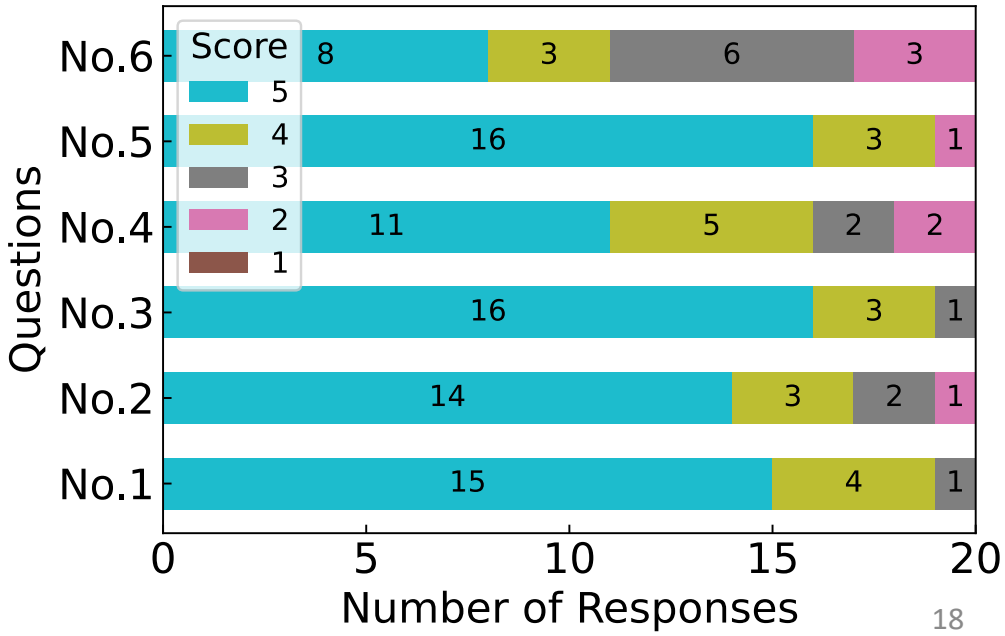
Beacon type 2



Feedback from Subway Station Staff

- **Over 95% of interviewees gave DeMo a high rating**
  - From 20 safety staff in 12 subway stations

- **Questionnaire survey**
  1. Satisfaction with DeMo
  2. Low complexity of device usage
  3. Effect on violation reduction
  4. Speed detection accuracy
  5. Decrease of workload
  6. Frequency of sensor damage

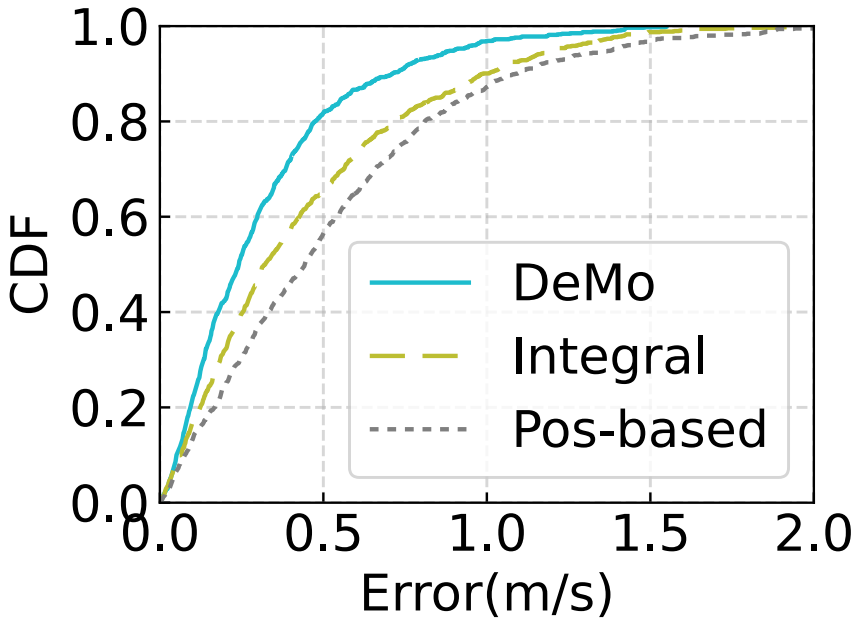


Evaluation via Controlled Experiment

- **Small-scale evaluation**
  - Selected 3 stations (552, 1105, and 3,003 m^2)
  - Collection of simulated delivery and ground truth data
    - Including delivery time, speed, trajectory and destination

Small-Scale Evaluation

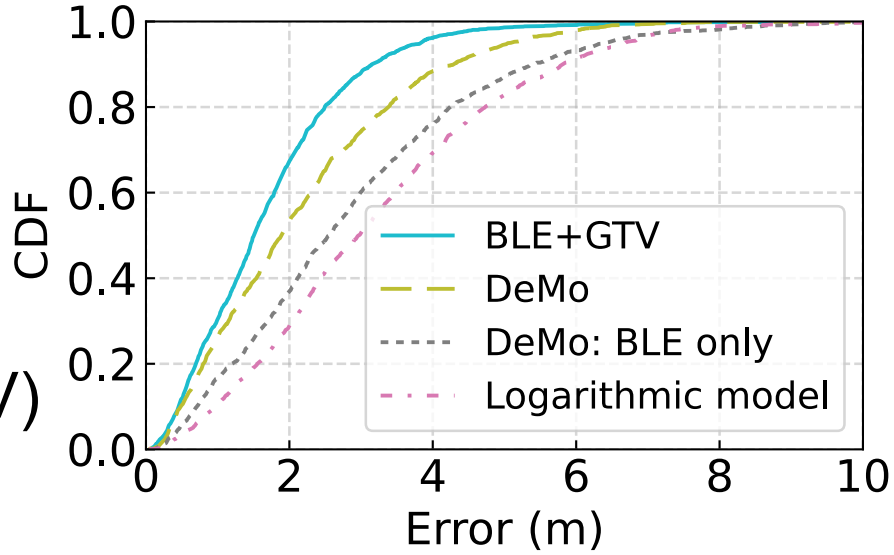
- **Speed detection accuracy (mean error)**
  - 0.52 m/s for the position-based approach
  - 0.43 m/s for direct integral method
  - 0.31 m/s for DeMo



- **Lesson**
  - Detect special road surfaces can improve the accuracy of speed estimation

Small-Scale Evaluation

- Positioning accuracy (mean error)
  - 3.22 m for logarithmic model
  - 2.86 m for DeMo: BLE only
  - 2.17 m for DeMo (BLE + IMU)
  - 1.70 m for BLE + Ground-Truth Velocity (GTV)



- **Lesson**
  - Without labor-intensive fingerprinting, a customized RSSI-distance model also can achieve accurate localization

Summary

- **DeMo: Indoor Delivery Monitoring System**
  - Fusion of BLE and IMU to achieve violation detection
  - RSSI-distance model for positioning
  - Deployed in 12 subway stations in Hong Kong since 2020
  - Covered 200+ shops with 40k+ deliveries
  - Diverse application scenarios like malls and warehouse
- **Data & Code Release**
  - Available at: *https://github.com/Starry102/DeMo*