RUTGERS

# Cyber-Physical Systems for Smart Cities: A Mobility Perspective


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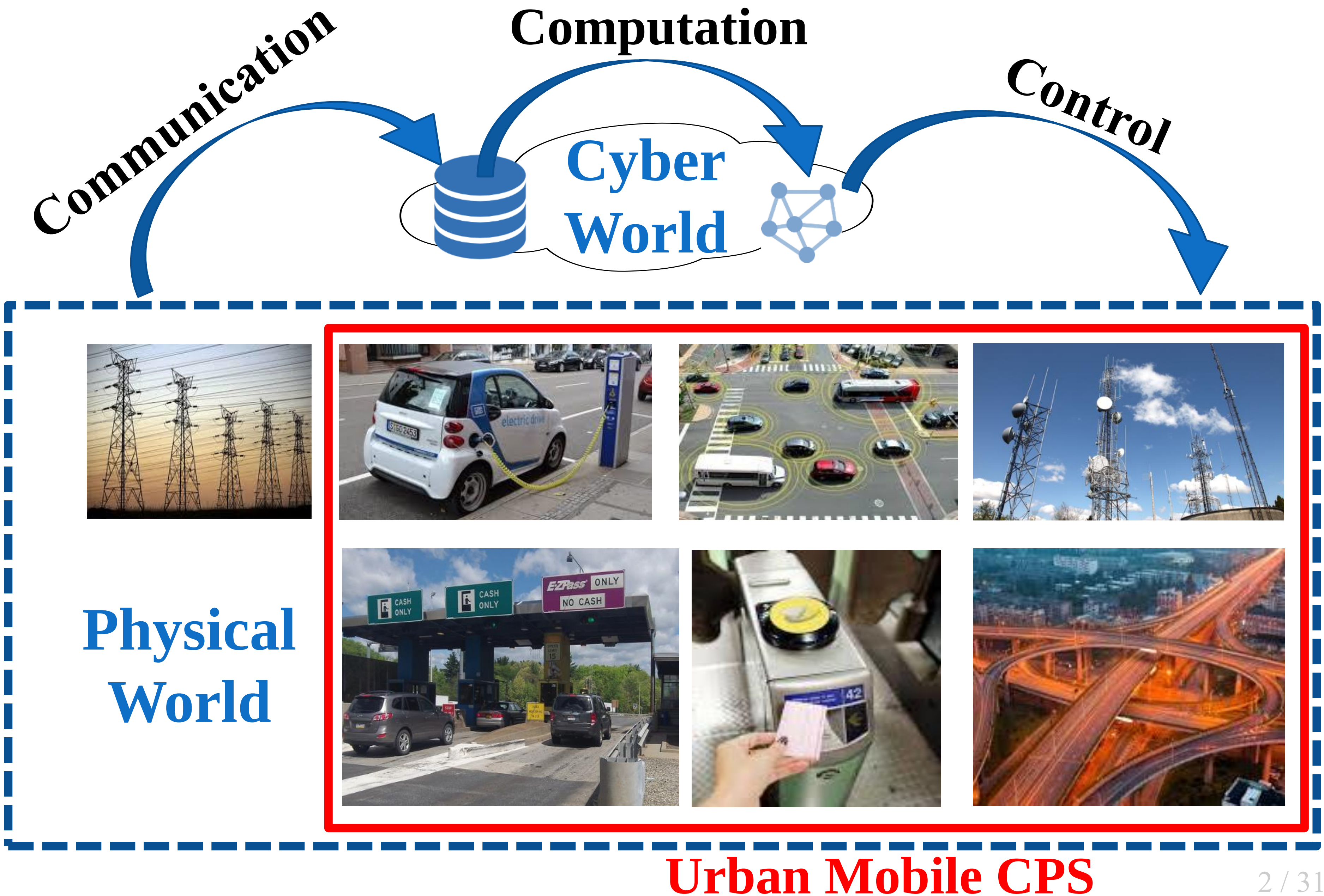
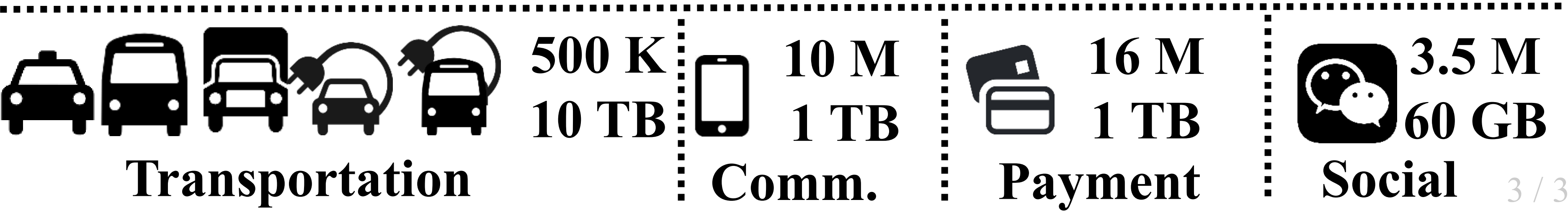
Computer Science

Rutgers University

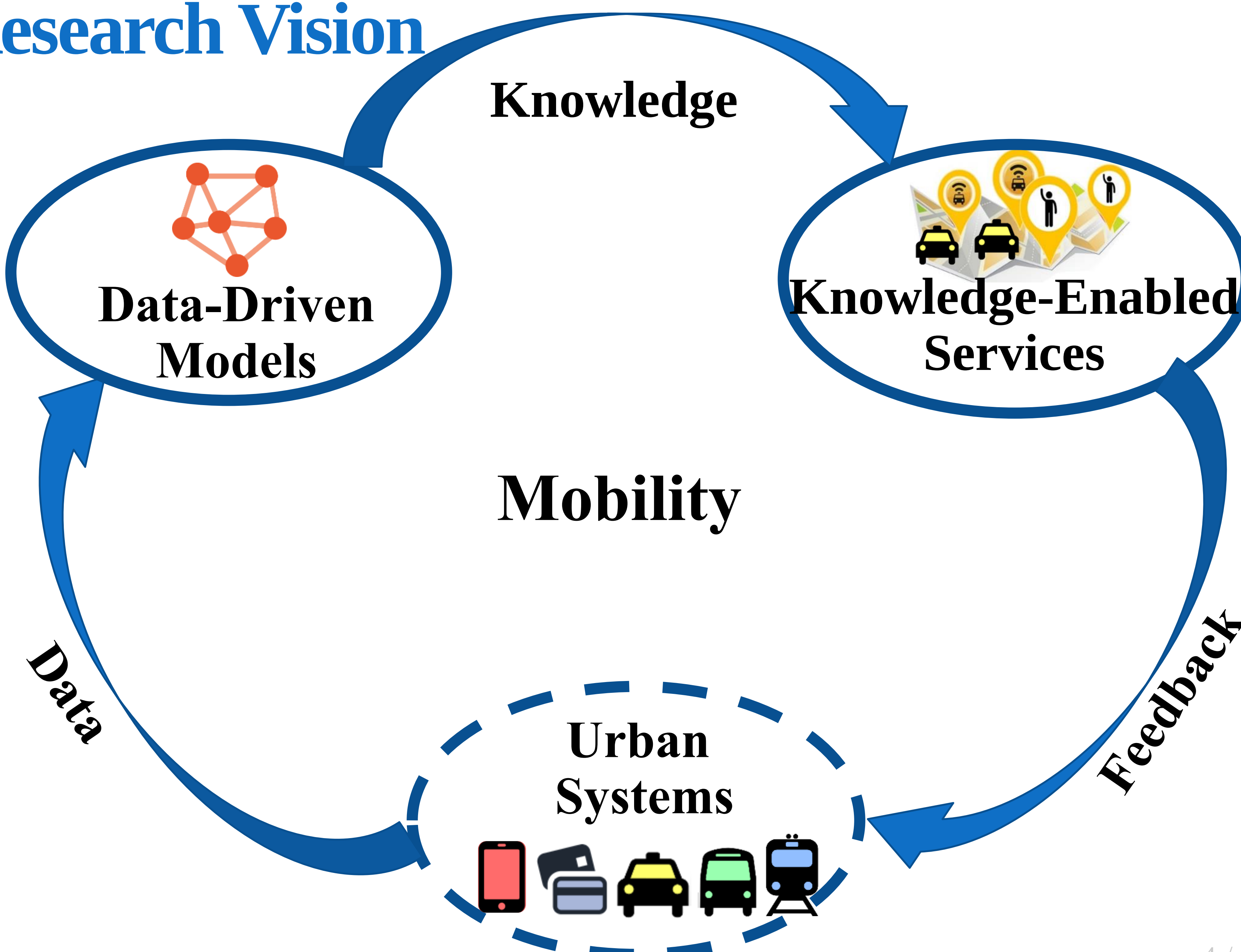

# Cyber-Physical Systems



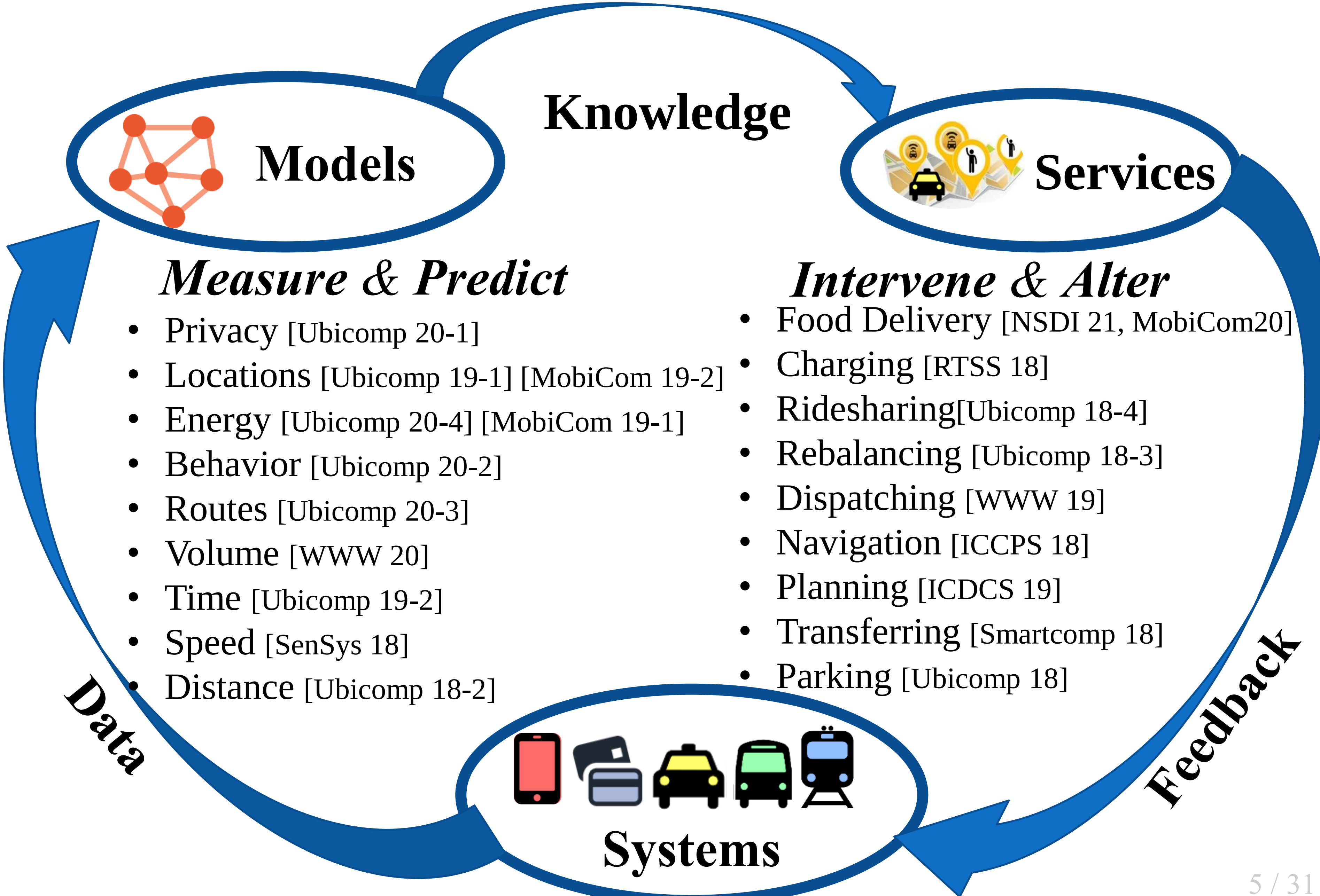
# Urban Mobile CPS

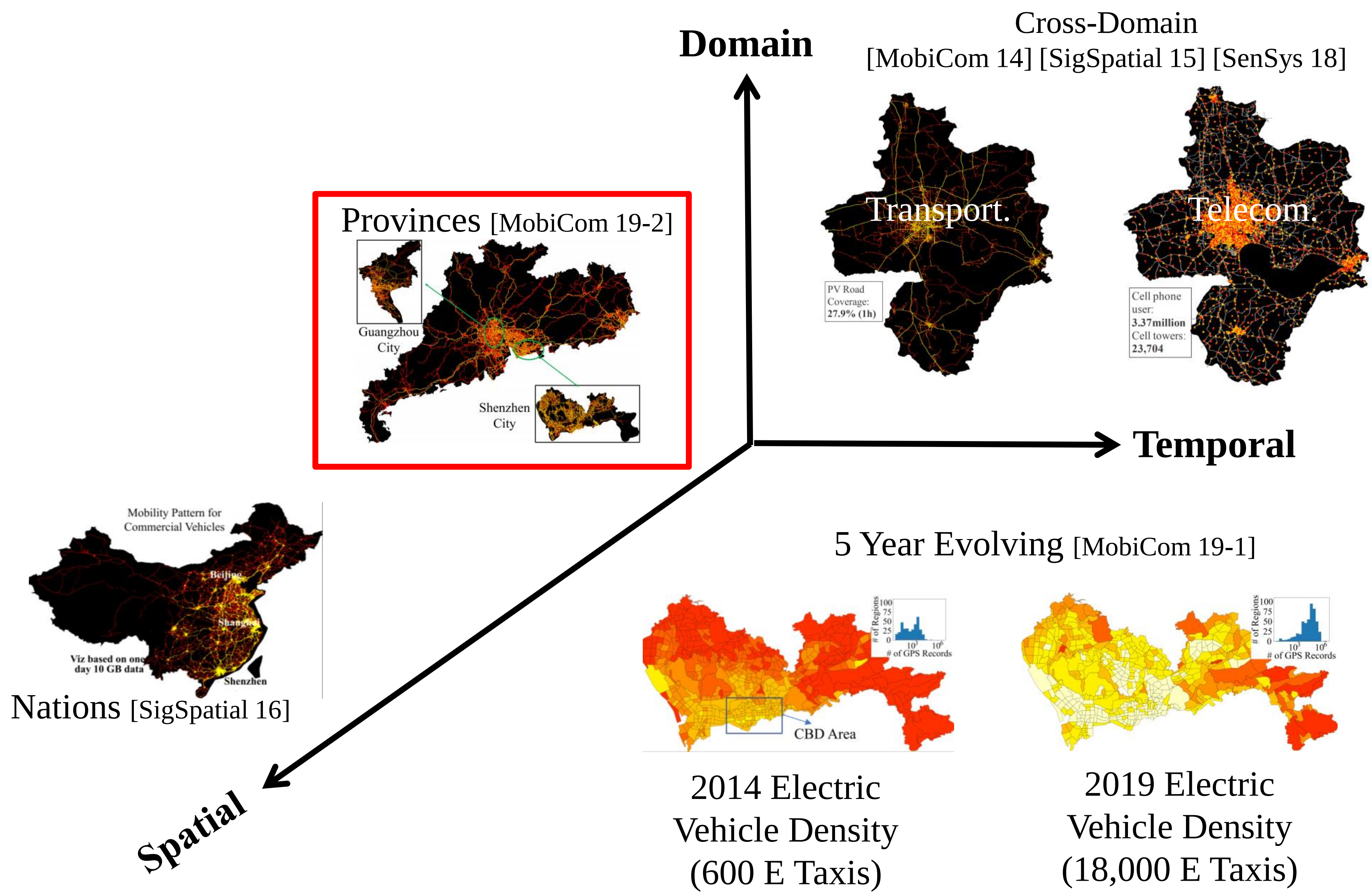
# Research Vision



# Contributions 2018-2020



# Advancing State-of-the-Arts



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MobiCom 2019
The 25th Annual International Conference on Mobile Computing and Networking

# VeMo
# Enabling Transparent Vehicular Mobility Modeling at an Individual Level with Full Penetration

Yu Yang, X. Xie, Z. Fang, F. Zhang, Desheng Zhang

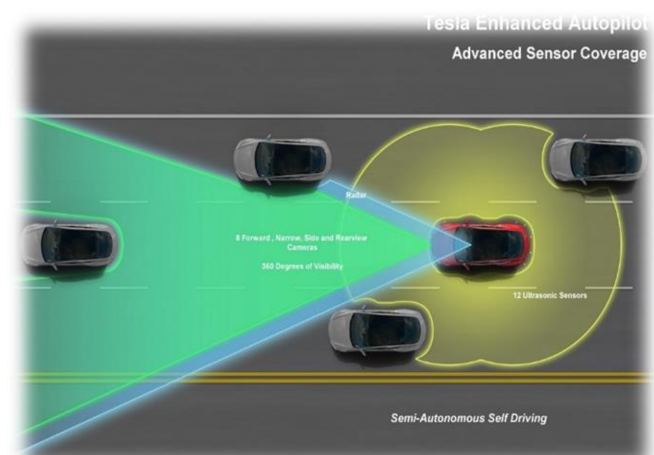
# Background: Vehicle Localization

What if we know

**All Vehicles' Locations in Real Time?**

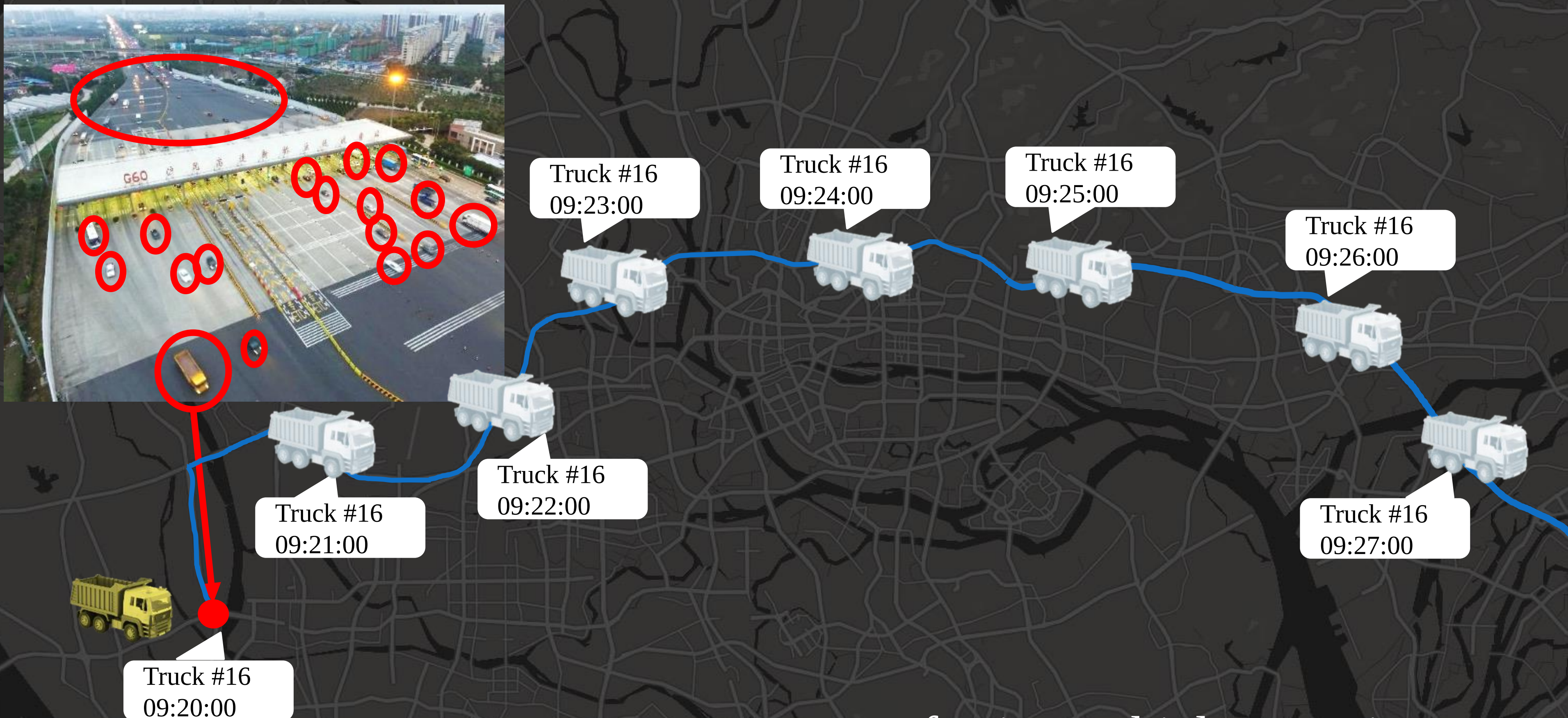

Location-based Services

Anomaly Detections




Sensing for Autonomous Driving

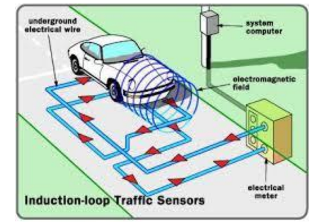
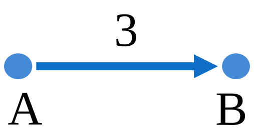
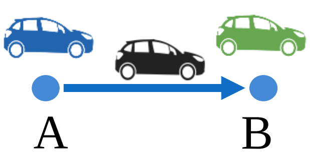
# Goal: Real-time Locations for all Vehicles




Inferring Vehicle Locations

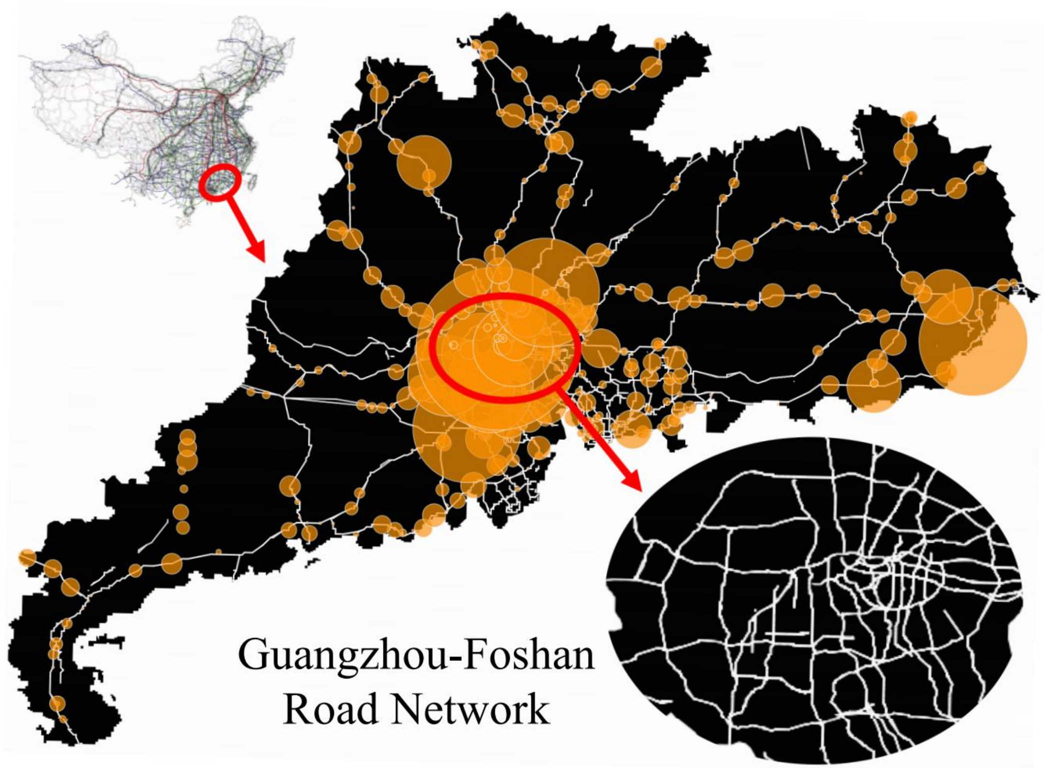
- Real-time (<10s)
- High-Accuracy (<100m)
- All Vehicles (**without GPS**)

# State of the Arts

<table>
<tr><th rowspan="2">Approach / Objective</th><th>Mobile Sensing</th><th colspan="2">Stationary Sensing</th></tr>
<tr><td><br>Smartphone (e.g. Google Map)</td><td><br>Traffic Cameras</td><td><br><br>Loop Sensors</td></tr>
<tr><td>Aggregate<br><br></td><td>R.Balan[MobiSys'11]<br>J.Aslam[SenSys'12]<br>D.Zhang[MobiCom'14]</td><td colspan="2">S.Zhang[ICCV'17]<br>Z.Qin[SenSys'18]<br>Y.Yang[UbiComp'18]</td></tr>
<tr><td rowspan="2">Individual<br><br></td><td rowspan="2">A.Thiagarajan[SenSys'09]<br>D.Zhang[SenSys'13]<br>X.Gao[UbiComp'14]</td><td>Partial Penetration</td><td>Full Penetration</td></tr>
<tr><td>A.T. [NSDI'11]<br>Z.Yang [MobiSys'16]</td><td>?</td></tr>
</table>

# Opportunities of ETC-based Sensing

- **Ubiquitous**
  - 45% Countries
- **Low Cost**
  - No additional infrastructure
- **Low Privacy Risk**
  - No GPS and No Camera
- **Full Penetration**
  - All Vehicles



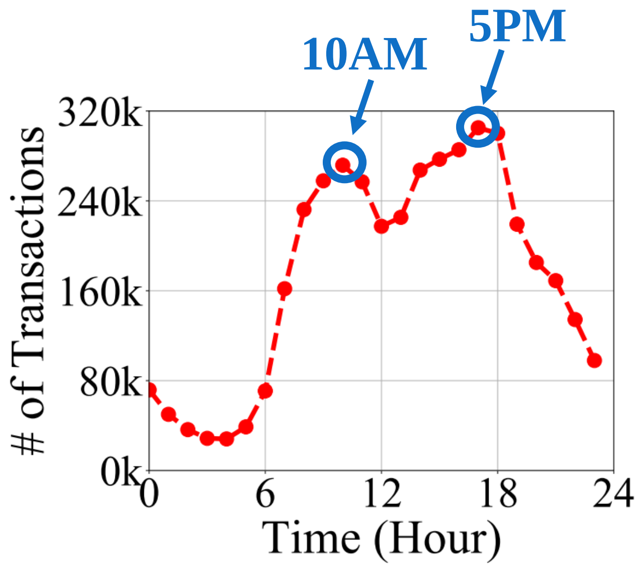

| Field | Value |
|---|---|
| Entering/Exit Toll Station | Humen Station |
| Entering/Exit Time | 2016-07-01 13:00:01 |
| Vehicle Id | F37SS1D4GU |
| Vehicle Type | Car/Bus/Truck |
| Axis Count | 2 |
| Weight | 1500kg |
| Number of Daily Transactions: 4 millions | |
| Number of Daily Vehicles: 2 millions | |

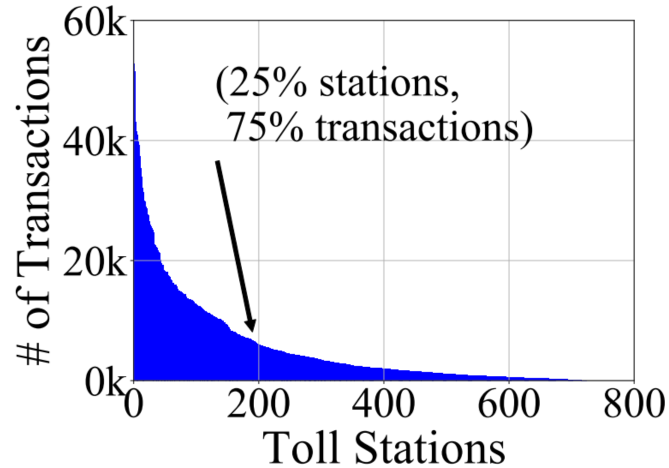
Guangdong Province ETC

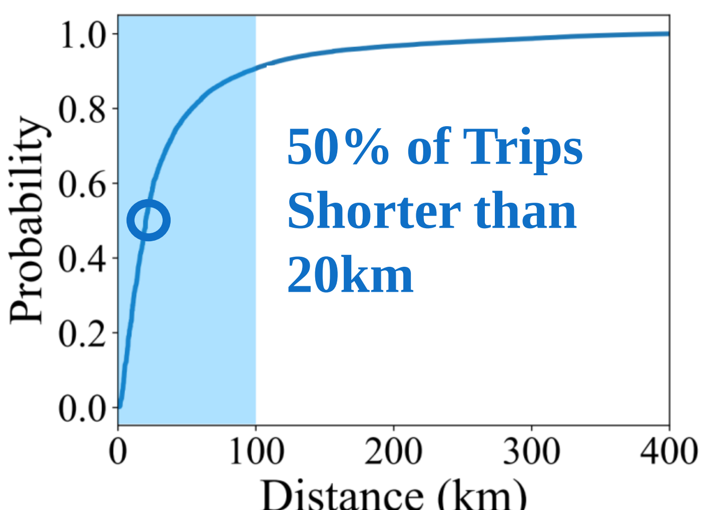
- Area: 170K $km^2$ ~ 7.5✕ New Jersey
- Population: 80 million~ 9✕ New Jersey
- Expressway: 8000 km ~ 17✕ New Jersey

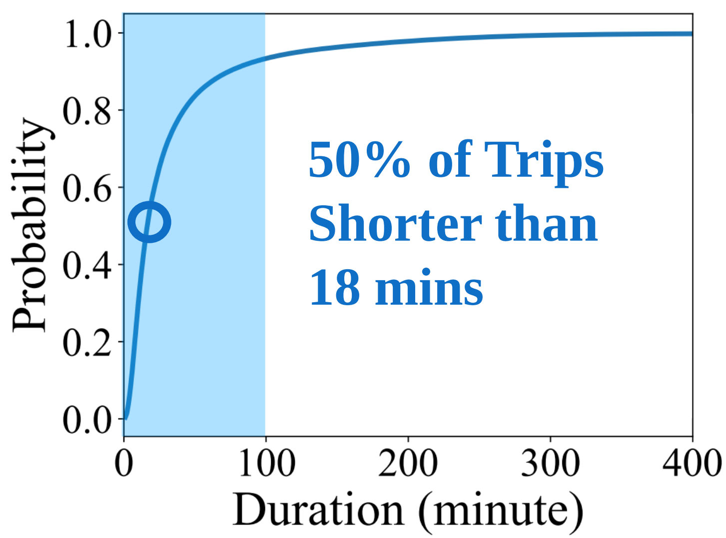
*http://www.nationmaster.com/country-info/stats/Transport/Road/Expressway-length*

# Opportunities of ETC-based Sensing



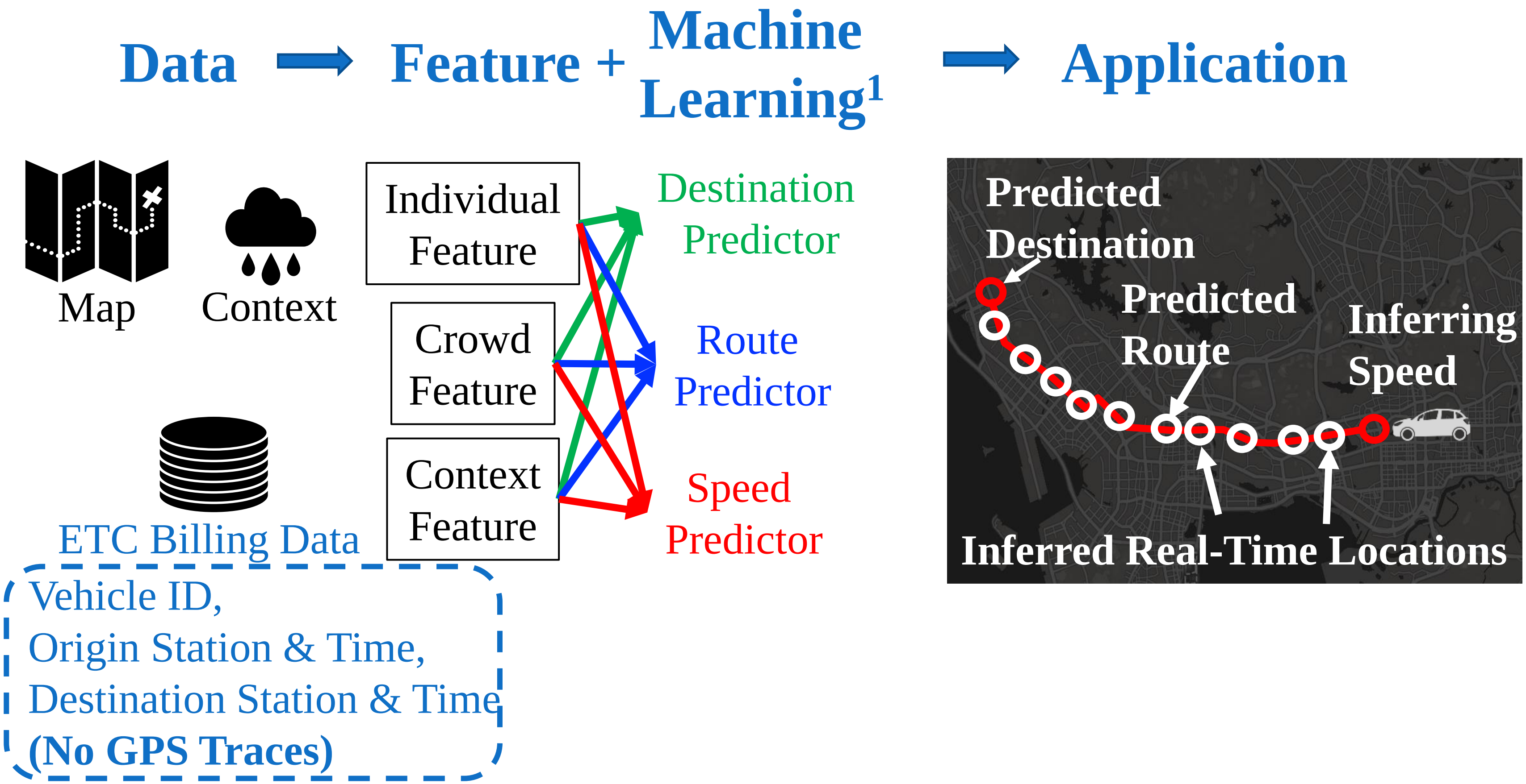




**Trip Length Distribution in terms of Distance and Duration**

# Challenges of ETC-based Sensing

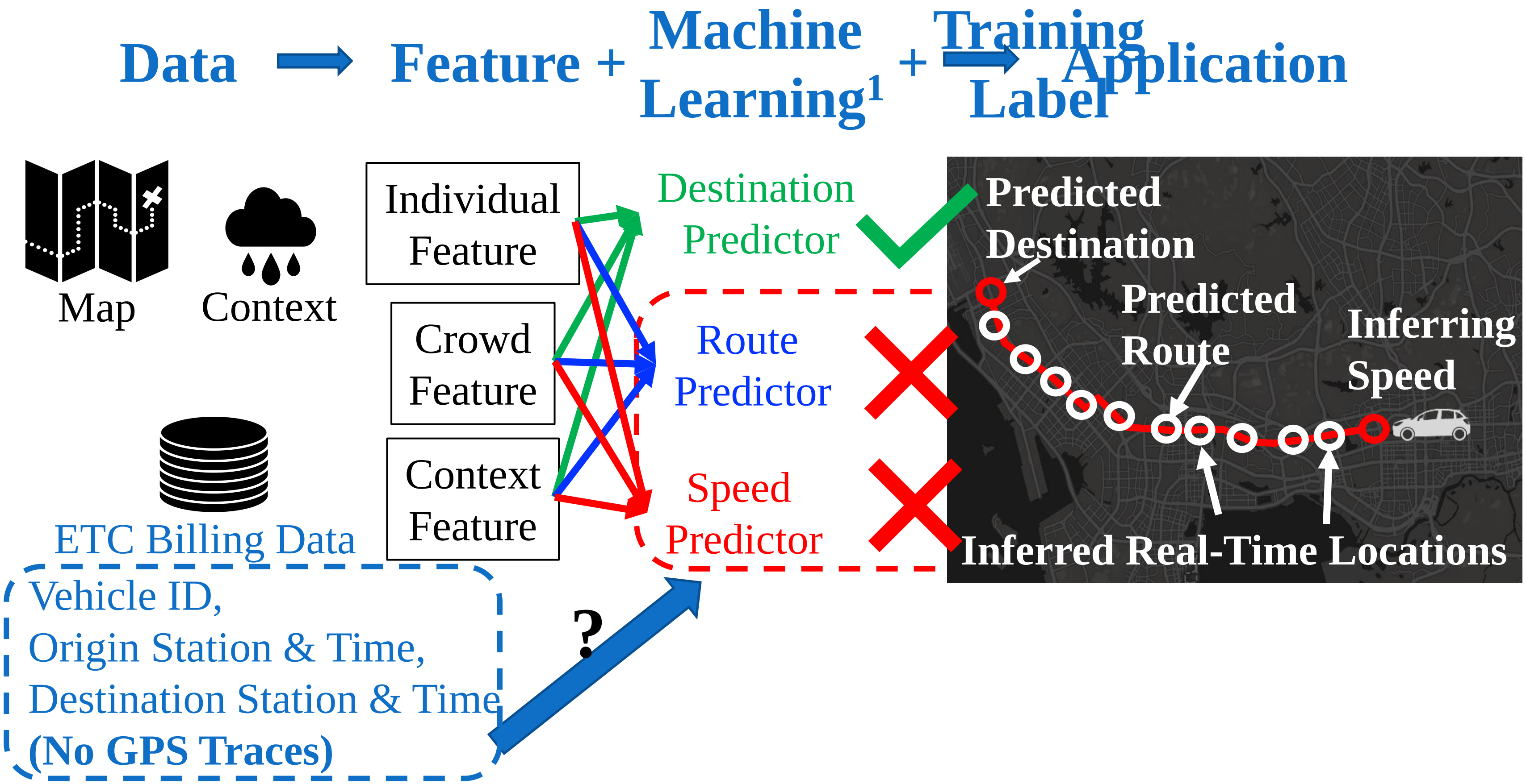

| Elements | Uncertainty |
|---|---|
| Destination | > 4 / each origin (Entropy=2.3) |
| Route | > 3 / each origin & destination |
| Speed | Standard Deviation: 35 km/h |

# System Overview



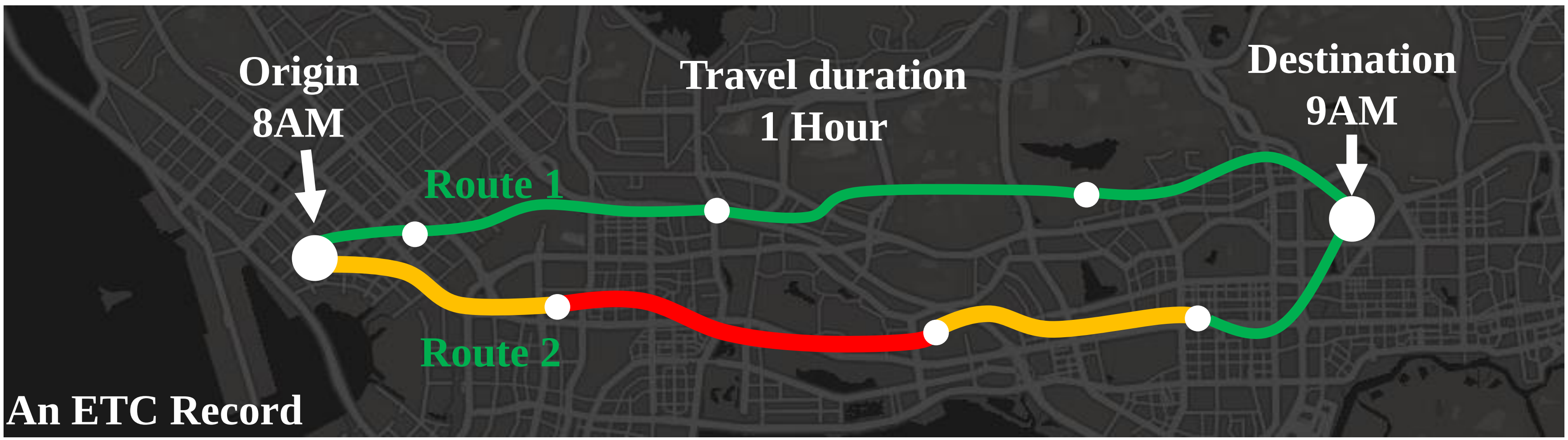

*[1] Lakshminarayanan, Balaji, et al. "Mondrian forests: Efficient online random forests." NIPS. 2014.*

# System Overview




[1] Lakshminarayanan, Balaji, et al. "Mondrian forests: Efficient online random forests." NIPS. 2014.

# Historical Route and Speed Learning **without GPS**




$$\max \sum_{ETC\ Records} \log P(\mathit{Travel\ Duration} \mid \mathit{Route}, \mathit{Speed})$$

Joint Optimization with
Expectation Maximization & Block Coordinate Descent

# Evaluation: Methodology

Guangdong Province, China

ETC

Training | Test

Models

Predicted locations

?
=

Actual locations

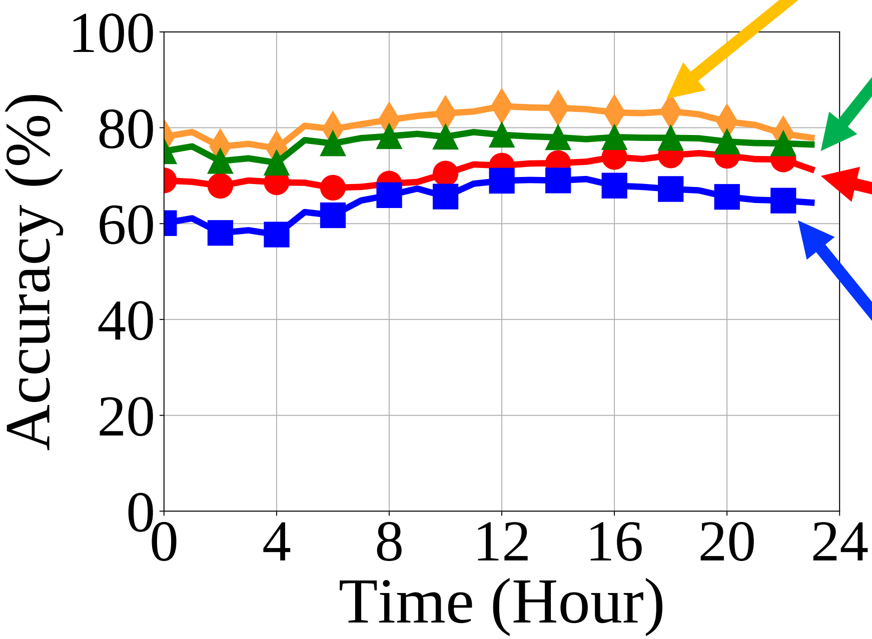
Ground Truth Given By Vehicle OBD Devices

| Types: | Commercial | Personal |
|---|---|---|
| Time: | January 2016 | |
| #Vehicles: | 14,000 | 100,000 |
| #Records: | 410 million | 430 million |

Record Format

ID, Time, GPS location, Speed. Uploaded every 10-15 seconds


# Evaluation Results




[ VeMo | Correctly Predicted Route ] (81%)

>

Cellular Network (CTrack) [1][2] (77%)

- 3000 Cell Towers in A City

>

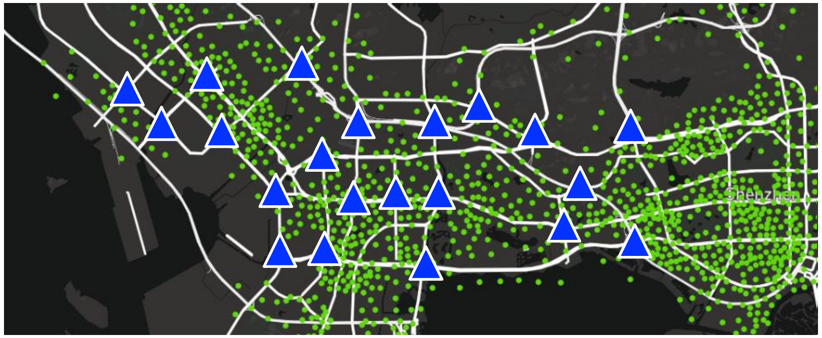
VeMo (71%)

- Our work (79 Toll Stations in A City)

>

Surveillance Camera Network (STrack) (64%)

- Cameras in 500 Road Segments

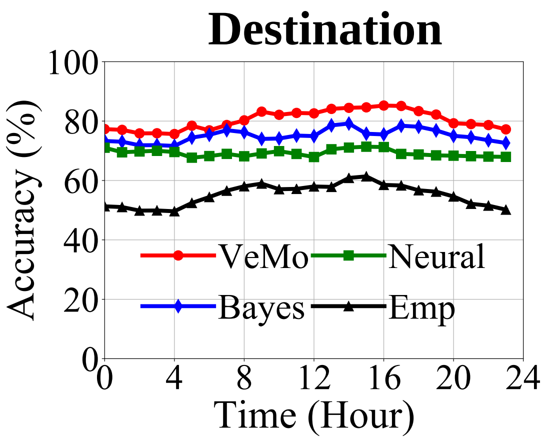


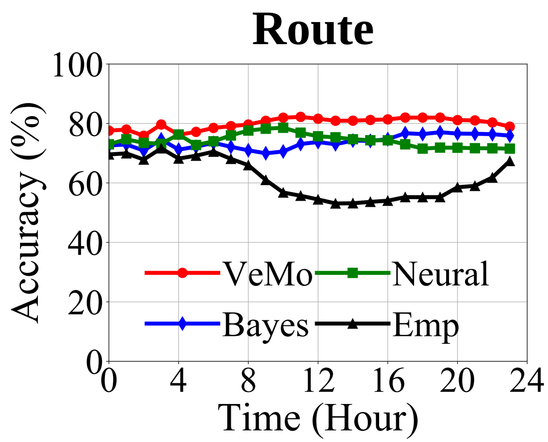

*[1] Arvind Thiagarajan, et al. Accurate, low-energy trajectory mapping for mobile devices. NSDI. 2011*

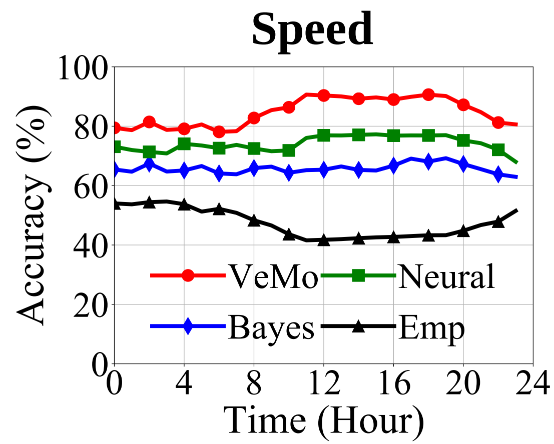
*[2] Xiaoyang Xie, et al. coSense: Collaborative Urban-Scale Vehicle Sensing based on Heterogeneous Fleets, UbiComp 2019*

# Evaluation Results

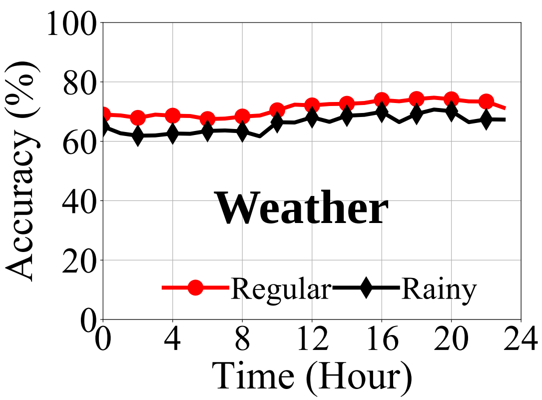
**Intermediate Result**

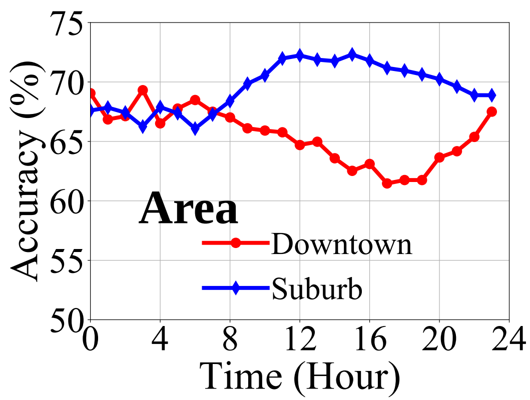


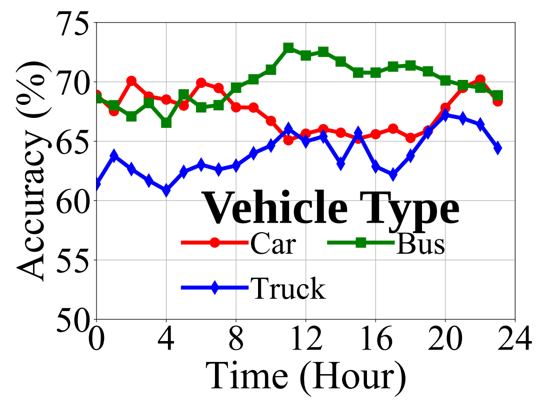




**Factor**



## Lessons Learned

Question:
Is it possible to sense **Individual Vehicles**
with **Full Penetration** in **Real Time** without GPS?

Case Study:
Electric Toll Collection Network
as a Stationary Sensing System

Generalization?

# Generalization: From ETC to Urban Infrastructure

Utilizing Interactions between **Urban Infrastructure** and **Residents** to infer their Real-Time Locations?

Opportunities

- Low Cost
- Transparent
- High Penetration

Challenges

- Uncertainty
- Implicit
- Biased

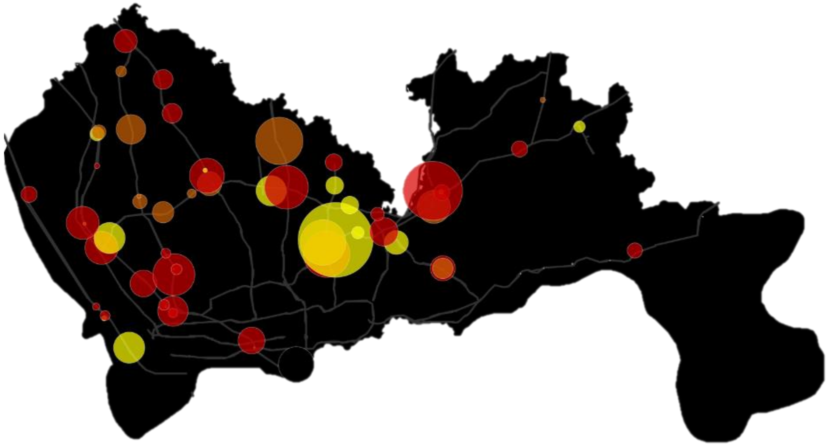
Examples

- Cellular Network
- Payment Network
- Social Network
- Vehicular Network
- ……

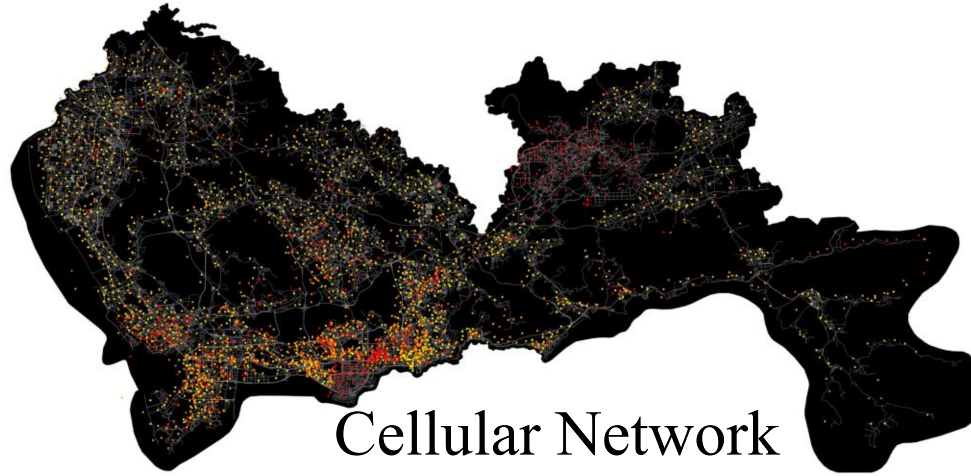
Unifying by Fundamental Properties governing Mobility Sensing

***Spatial Granularity & Temporal Continuity***

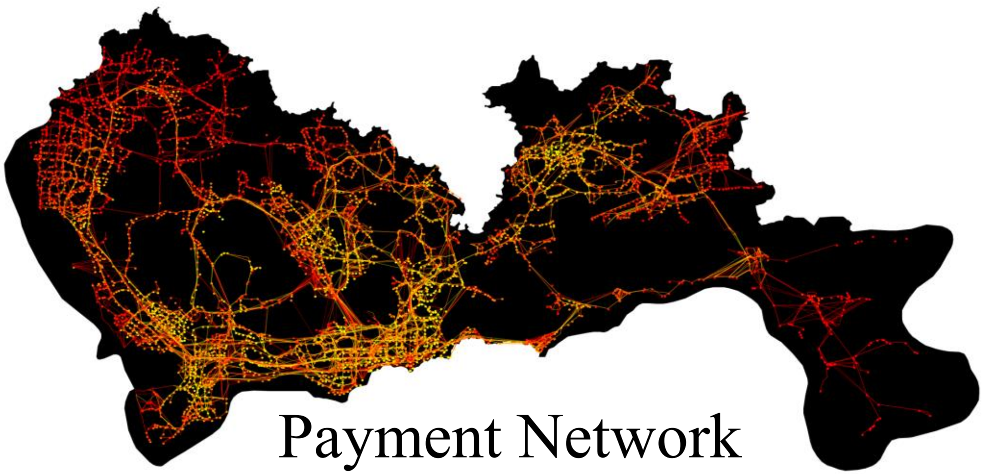
# Generalization: From ETC to Urban Infrastructures for Mobility Sensing



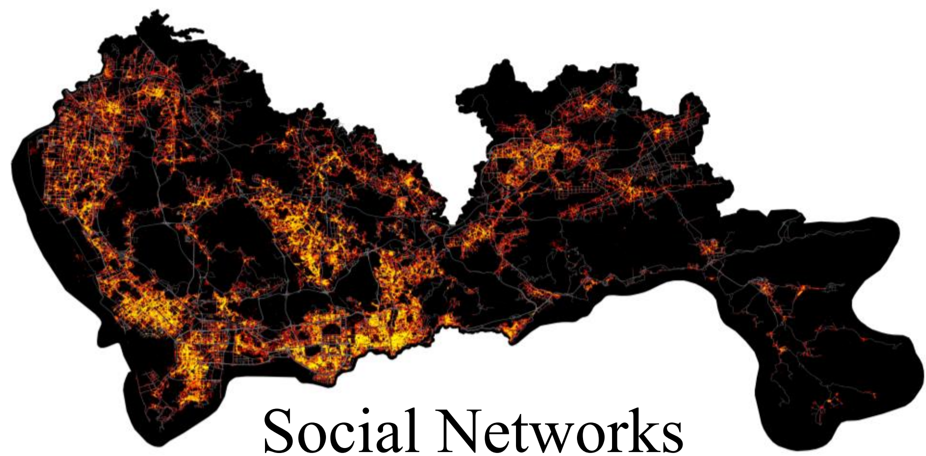
Toll Collection System
(1,470 Stations (79 in Shenzhen))



Cellular Network
(3,595 Towers)

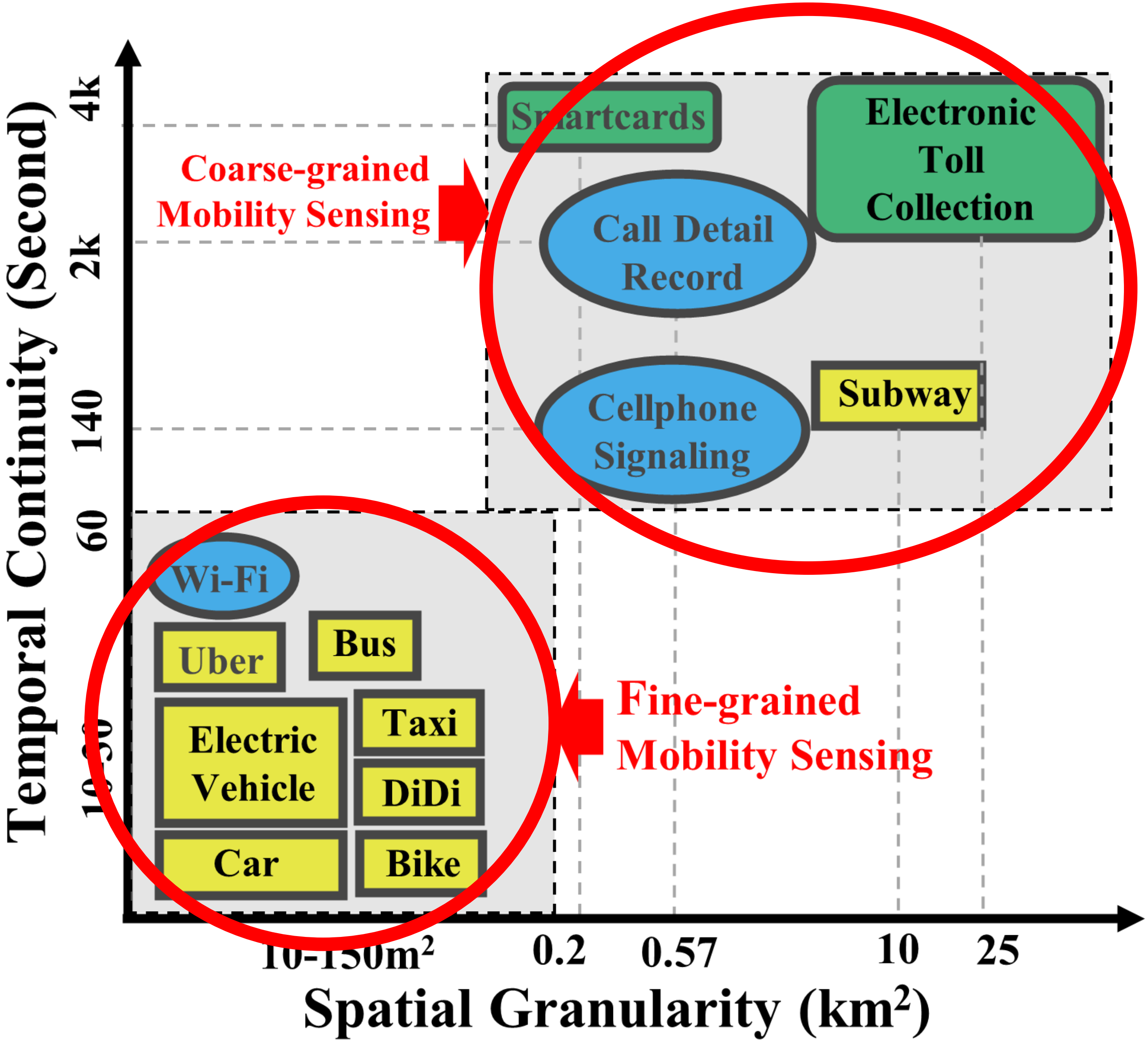


Payment Network
(10,082 Stations)

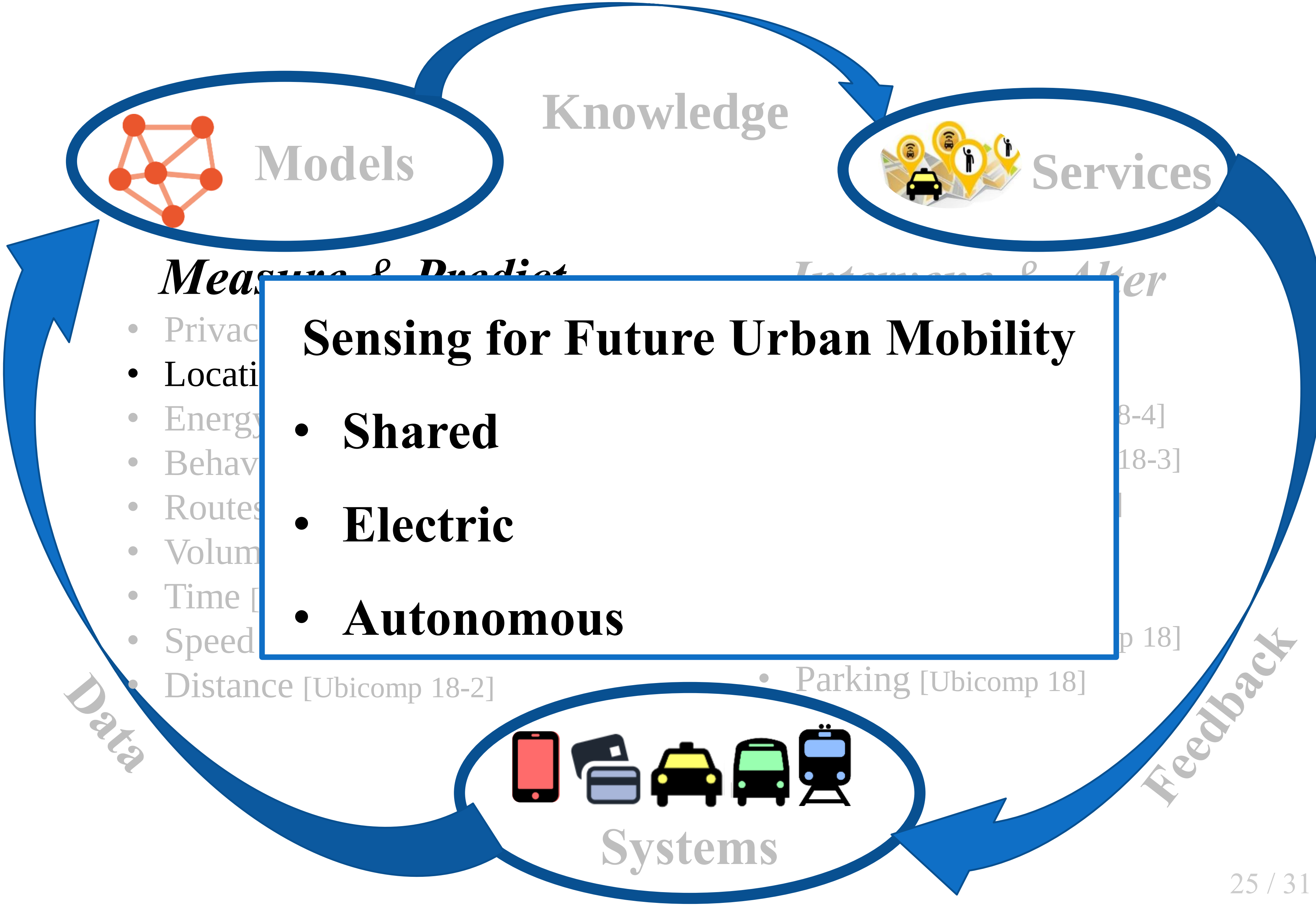


Social Networks
(480,555 Point of Interests)

# Generalization: From ETC to Urban Infrastructures for Mobility Sensing



# Future Urban CPS

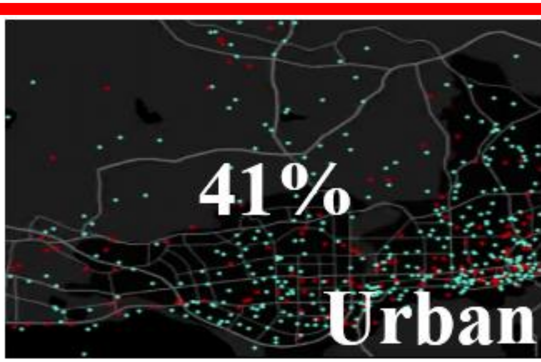


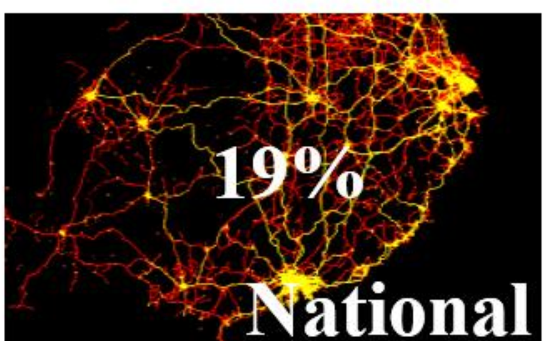

**Sensing for Future Urban Mobility**

- **Shared**
- **Electric**
- **Autonomous**

# Sharing: Resource Management (Sharing Economy)

## Scales


## Mobility Modality

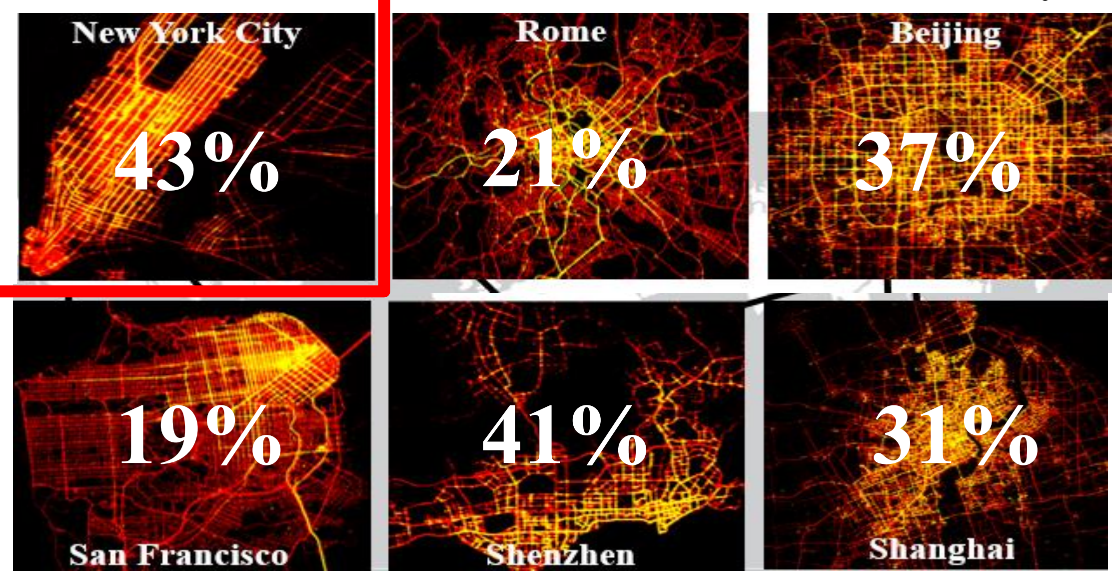
37%

31%

24%

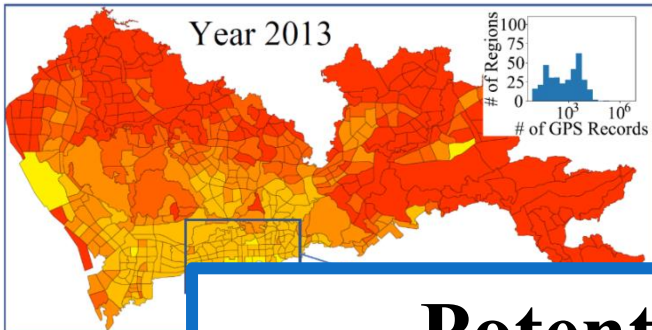
[UbiComp 2018]
[IPSN 2015]
[SenSys 2013]

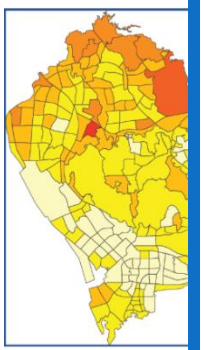
## Locations



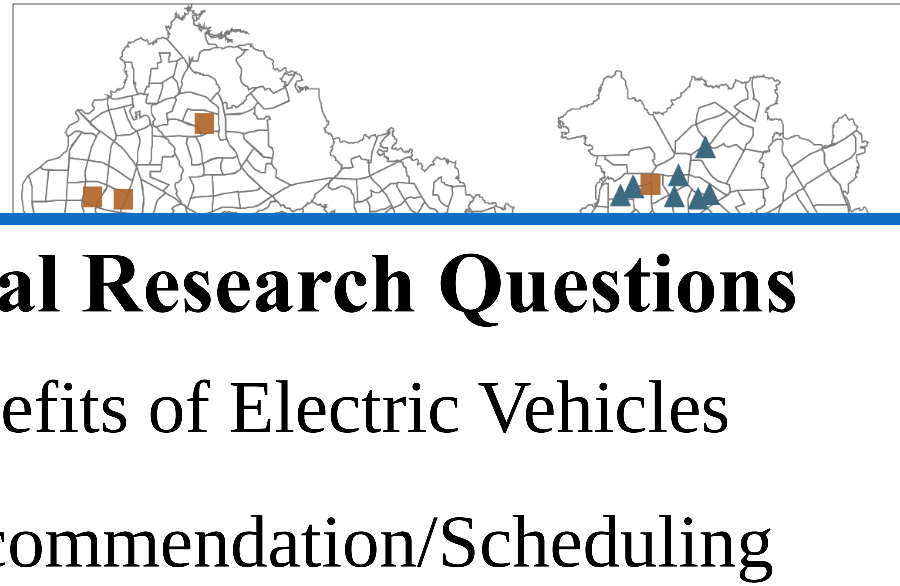

Terrain Population Vehicle #

# **Electric**: Mobility and Charging Pattern Evolving of Electric Vehicles



**Charging Station Evolving**



| Year | Number |
|---|---|
| 2013 | 31 |
| 2014 | 33 |
| 2015 | 36 |
| 2016 | 56 |
| | 97 |
| | 117 |

## Potential Research Questions

- Quantify Benefits of Electric Vehicles
- Charging Recommendation/Scheduling
- Charging Station Deployment
- Plug-in vs. Swapping vs. Wireless
- Co-Charging with Private Electric Vehicles

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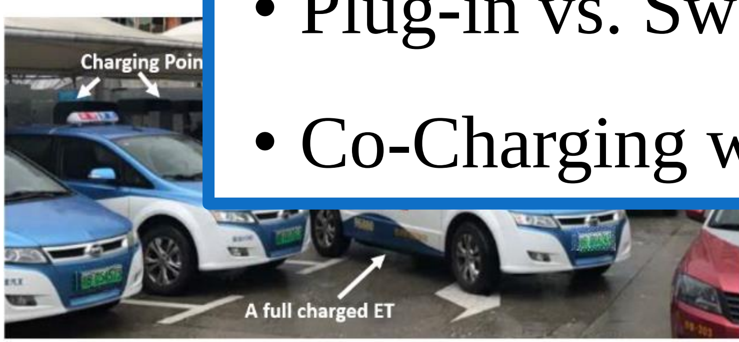
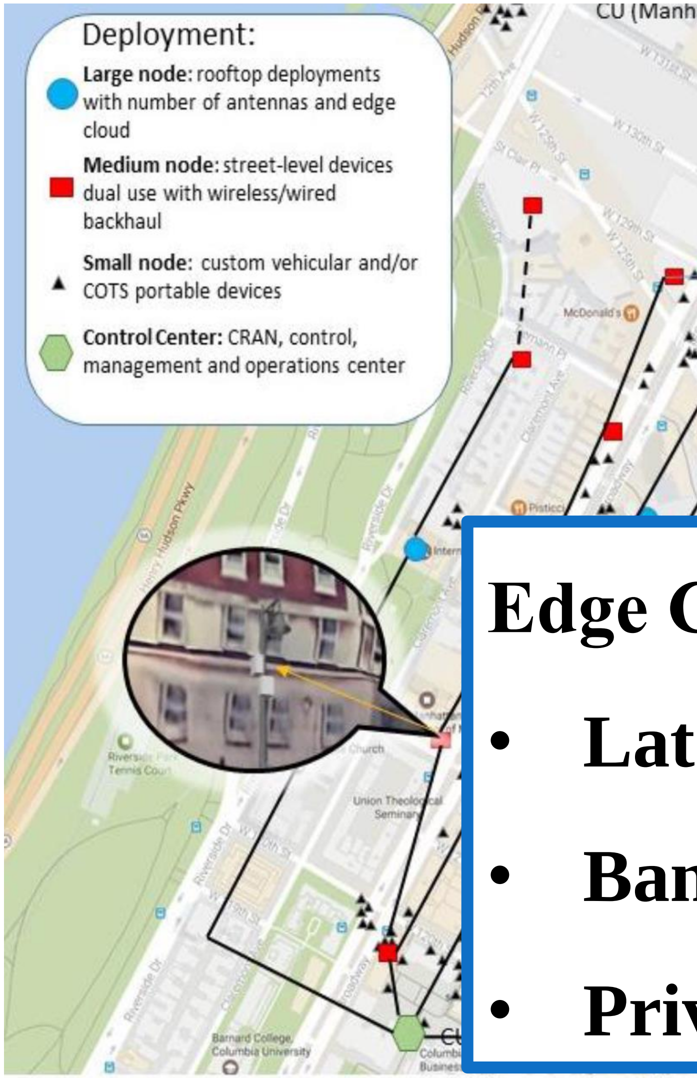
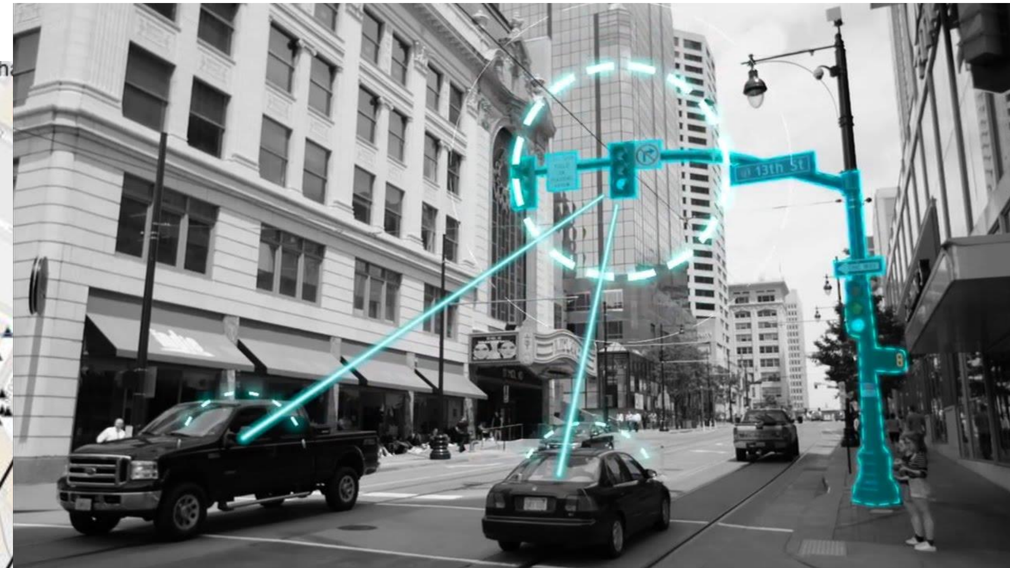



# **Autonomous**: Interaction between Vehicles and Edge Devices



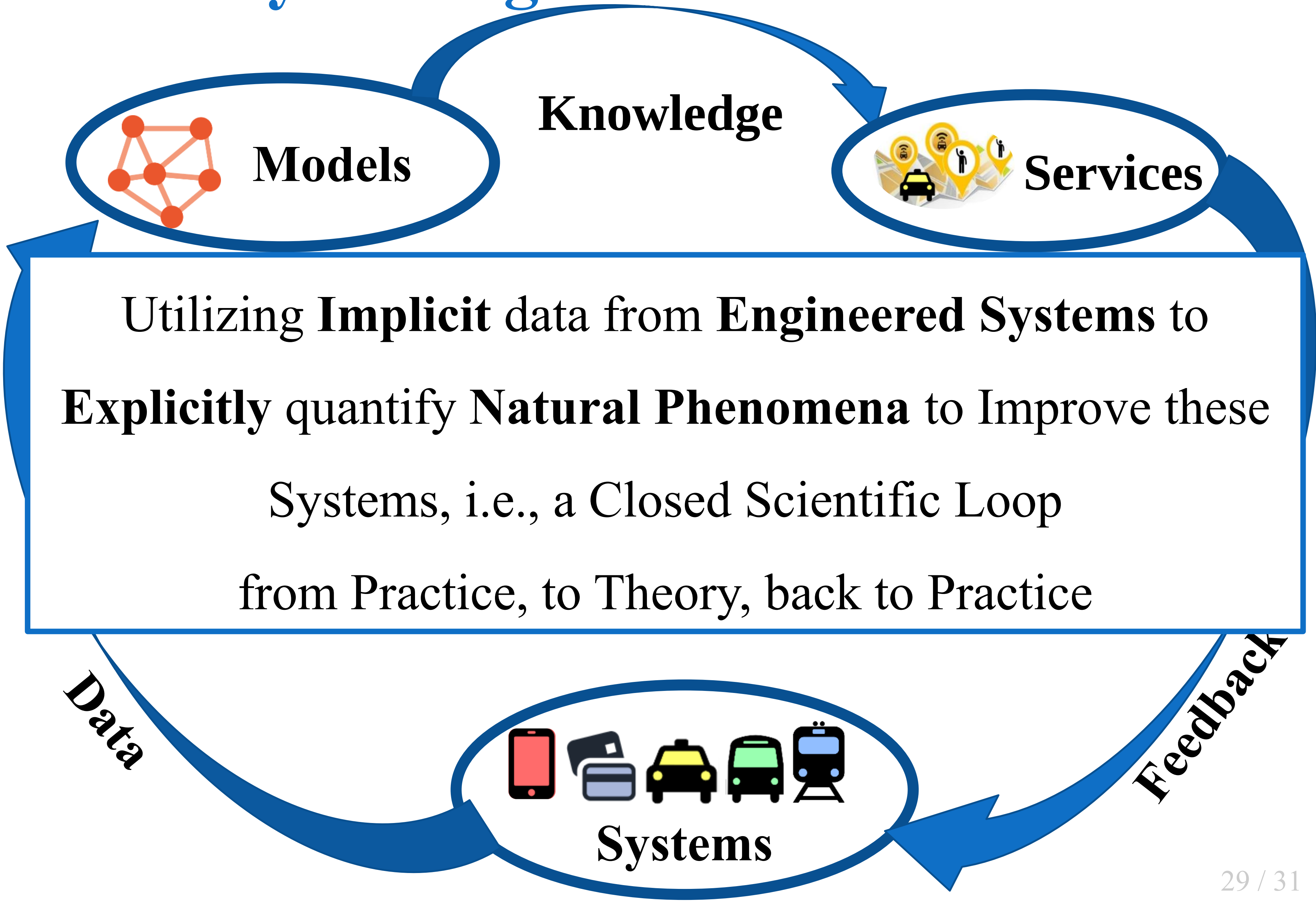



**Edge Computing**

- **Latency:** Highly Responsive Services
- **Bandwidth:** Edge Analytics
- **Privacy:** Local Data Processing

**NSF PAWR: COSMOS: Cloud-Enhanced Open Software-Defined Mobile-Wireless Testbed (Rutgers Winlab & Columbia & NYU)**

# Takeaway Message




Utilizing **Implicit** data from **Engineered Systems** to **Explicitly** quantify **Natural Phenomena** to Improve these Systems, i.e., a Closed Scientific Loop from Practice, to Theory, back to Practice

# Ac

Prof. T
U

Zhao

Prof.

ang

**Rutgers CS PhD Students**

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CNS:1951890
CNS:1952096
OAC:2003874
CMMI:1932223

# Thanks

**Data and More Work**
**https://www.cs.rutgers.edu/~dz220/**

Knowledge

Models

Services

***Measure & Predict***

- Privacy [Ubicomp 20-1]
- Locations [Ubicomp 19-1] [MobiCom 19-2]
- Energy [Ubicomp 20-4] [MobiCom 19-1]
- Behavior [Ubicomp 20-2]
- Routes [Ubicomp 20-3]
- Volume [WWW 20]
- Time [Ubicomp 19-2]
- Speed [SenSys 18]
- Distance [Ubicomp 18-2]

***Intervene & Alter***

- Delivery [MobiCom 20]
- Charging [RTSS 18]
- Ridesharing[Ubicomp 18-4]
- Rebalancing [Ubicomp 18-3]
- Dispatching [WWW 19]
- Navigation [ICCPS 18]
- Planning [ICDCS 19]
- Transferring [Smartcomp 18]
- Parking [Ubicomp 18]

Data

Feedback

Systems

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