ICDCS 2019

Road Gradient Estimation Using Smartphones: Towards Accurate Estimation on Fuel Consumption and Air Pollution Emission on Roads

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Background

Road gradients exist in different types of roads

Rural roads

Urban roads

Highway roads

http://theclimbingcyclist.com/gradients-and-cycling-how-much-harder-are-steeper-climbs/
http://www.ipernity.com/doc/jonathan.cohen/35071855
https://www.civilnoteppt.com/2017/09/classification-of-gradient-civil.html

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Driving on a road with road gradients causes a series of problems:

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Road gradient

Fuel efficiency

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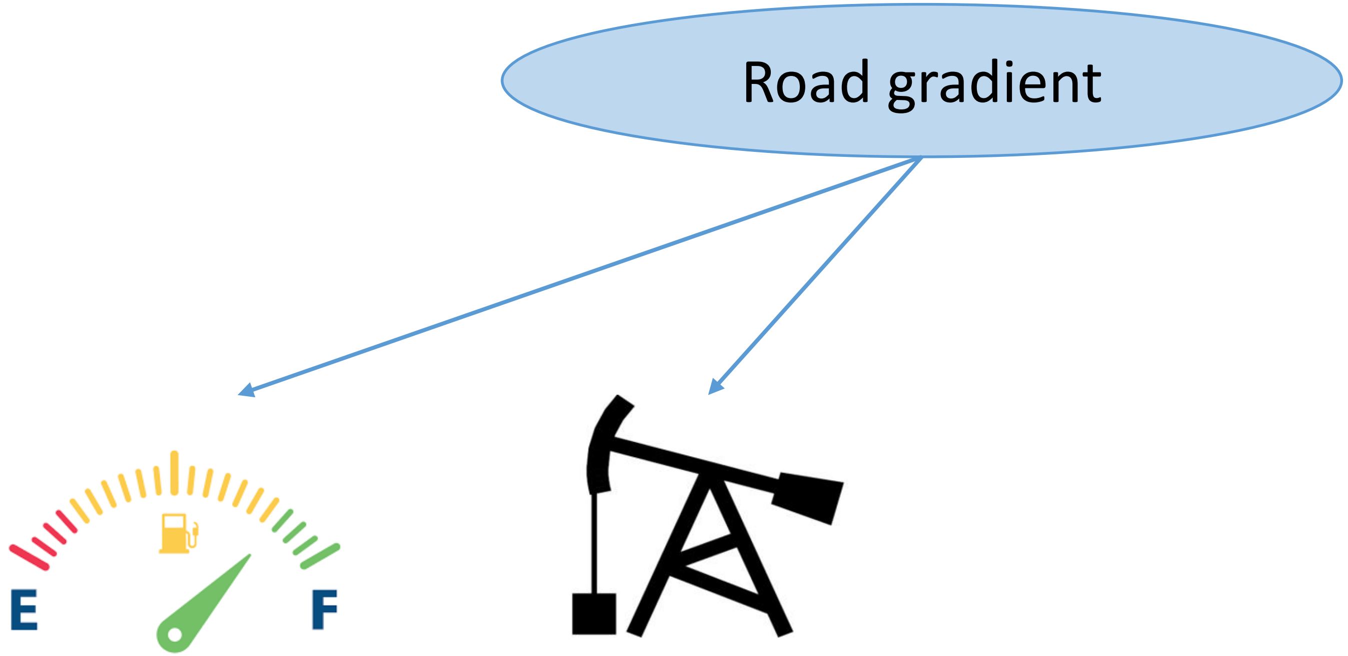

Fuel efficiency   Fuel depletion

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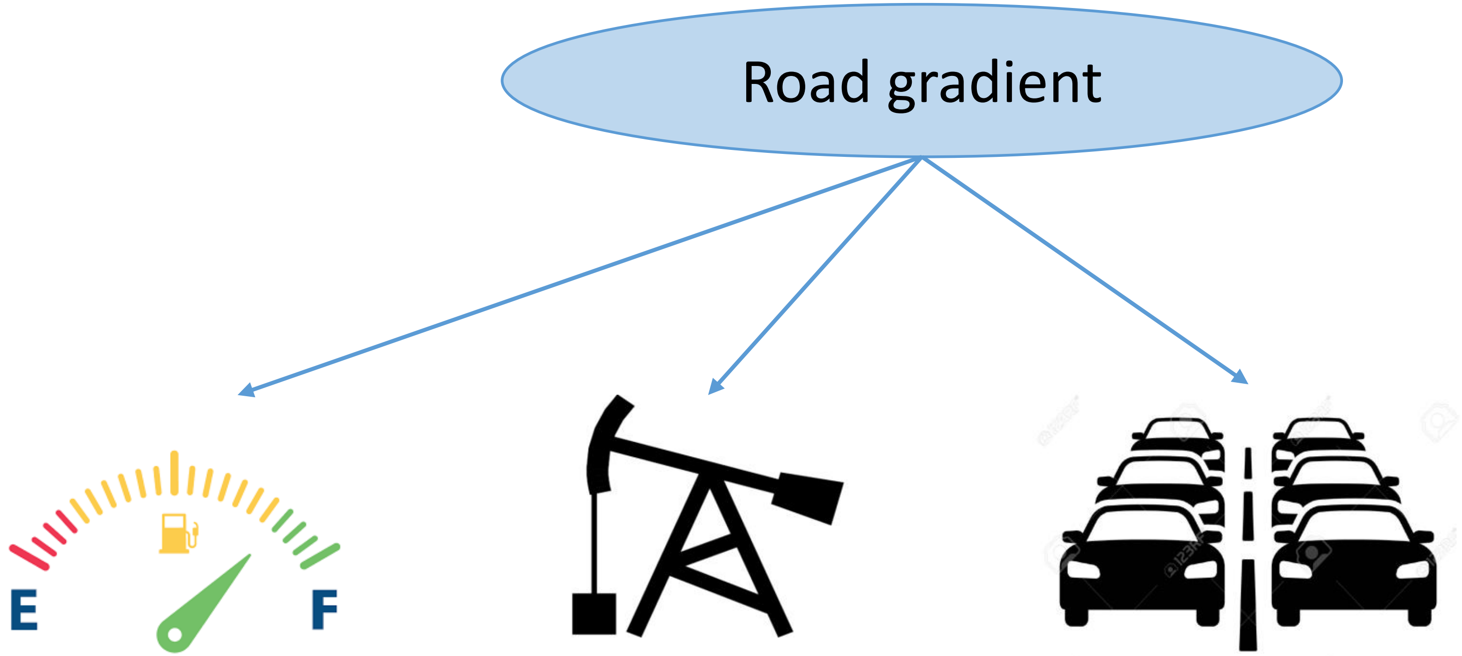

Fuel efficiency   Fuel depletion   Traffic congestion

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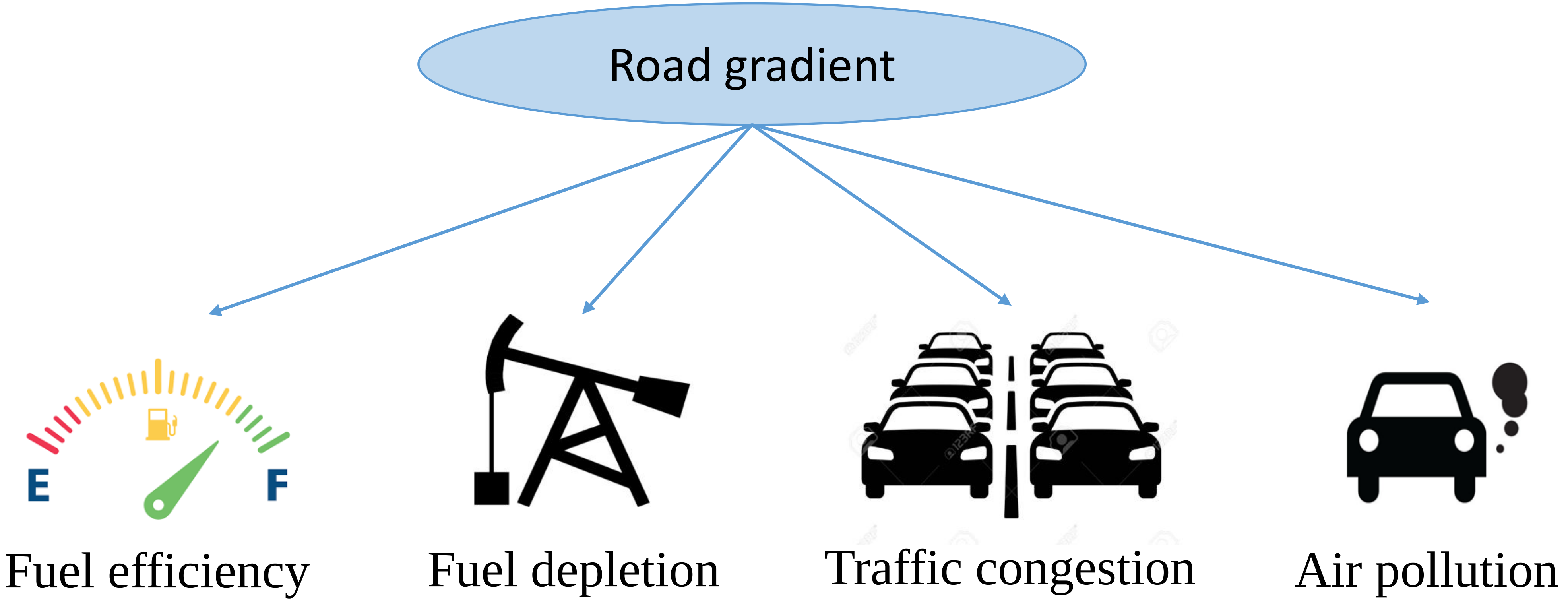

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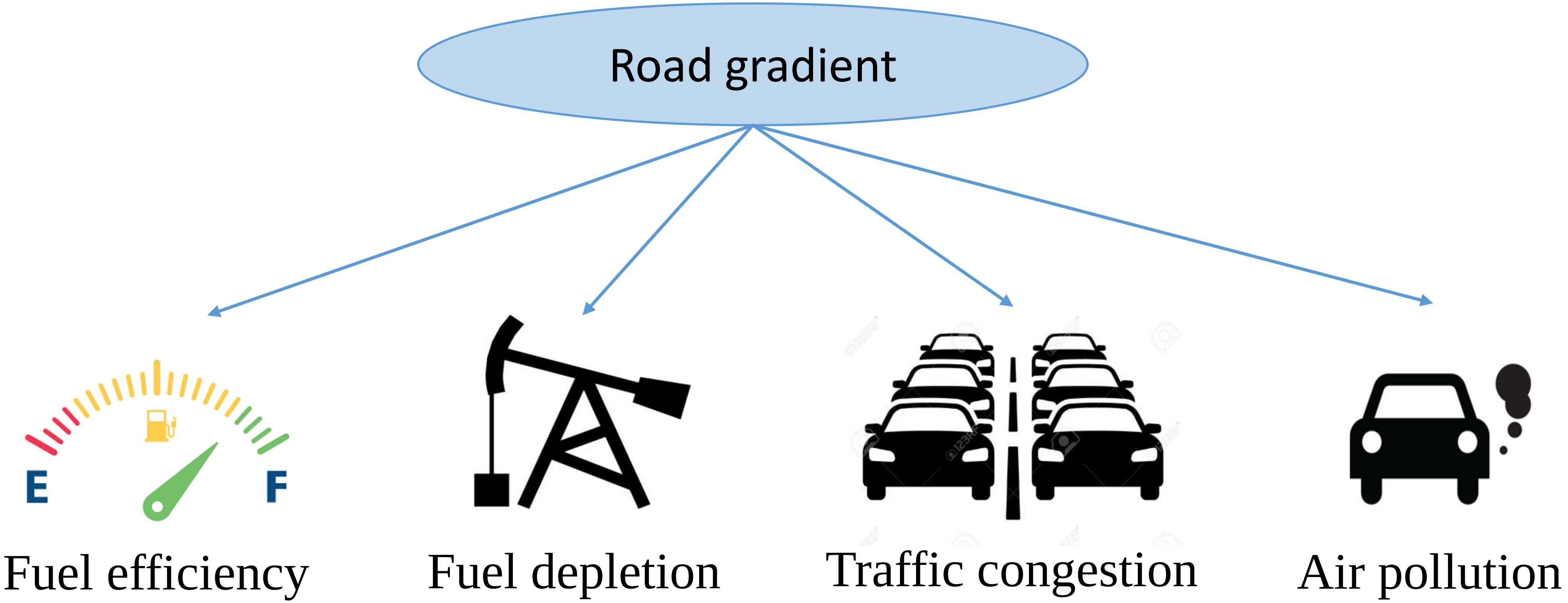

Accurate road gradient estimation becomes necessary

Related Work

- Current web maps (e.g., Google Maps) only provide traffic congestion information for driving vehicles [ENGADGET’16]

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  - ➢High operation cost because of machine installation and maintenance

Challenges

Propose a road gradient estimation system to estimate road gradients based on measured vehicle states from a smartphone in a vehicle

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- Measurement noises
- Lane change actions

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Challenge 1: How to obtain accurate vehicle states with a smartphone?

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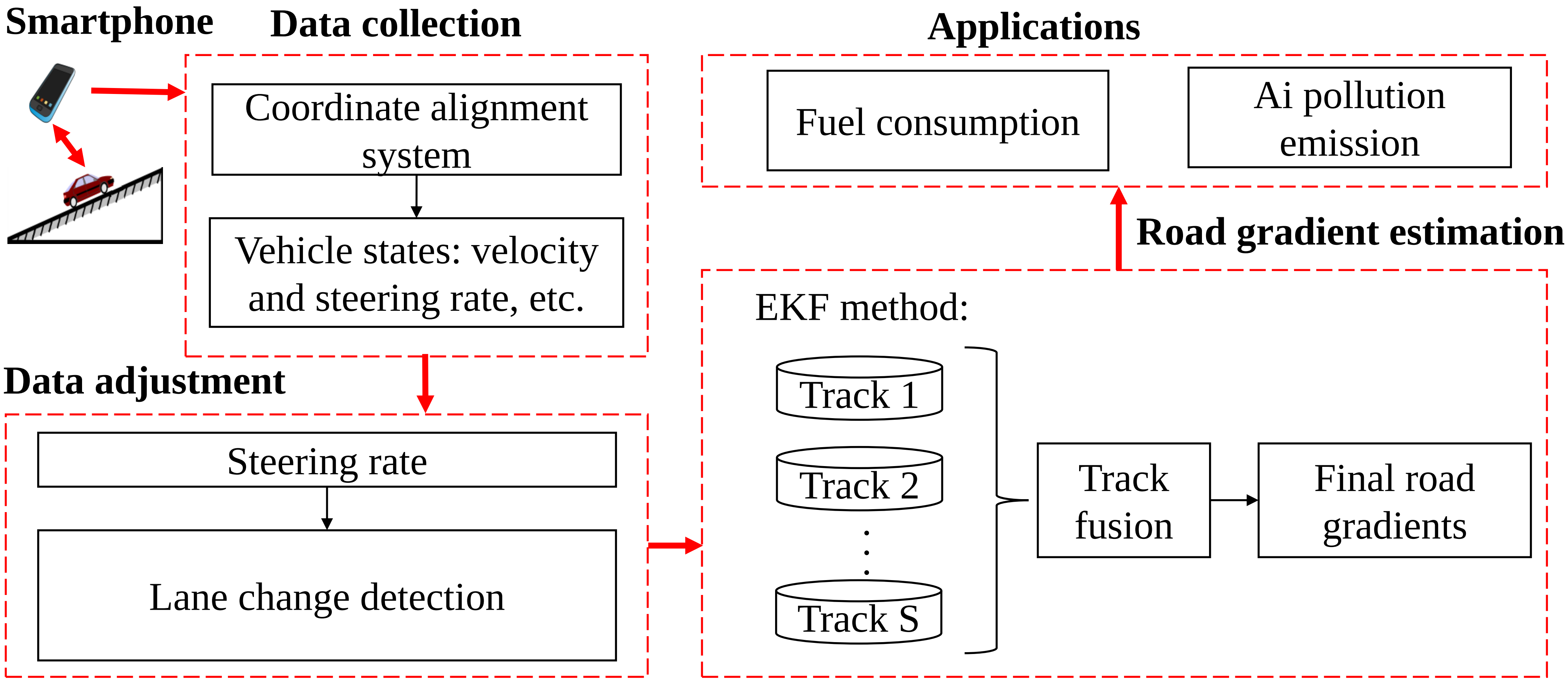
Challenge 2: How to ensure road gradient estimation accuracy based on measured vehicle states?

- Longitudinal velocities measured with different sensors cause different road gradient estimation results

Road Gradient Estimation System



Challenge 1

How to obtain accurate vehicle states with a smartphone?

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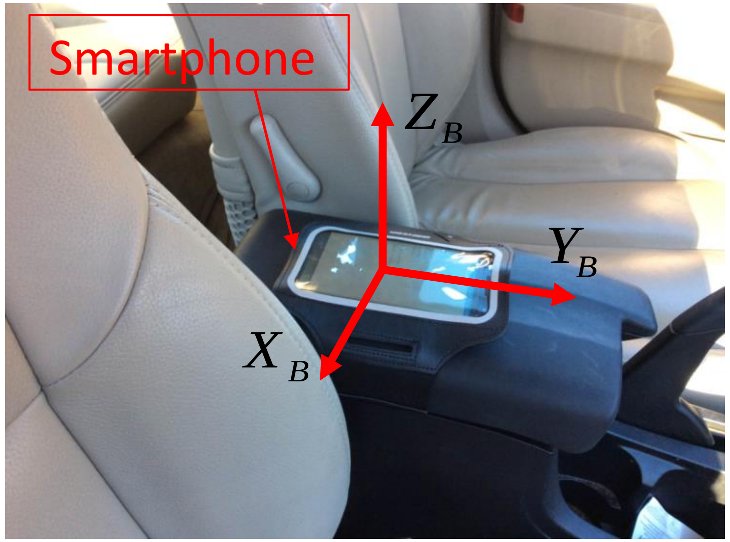
Data collection + Data adjustment

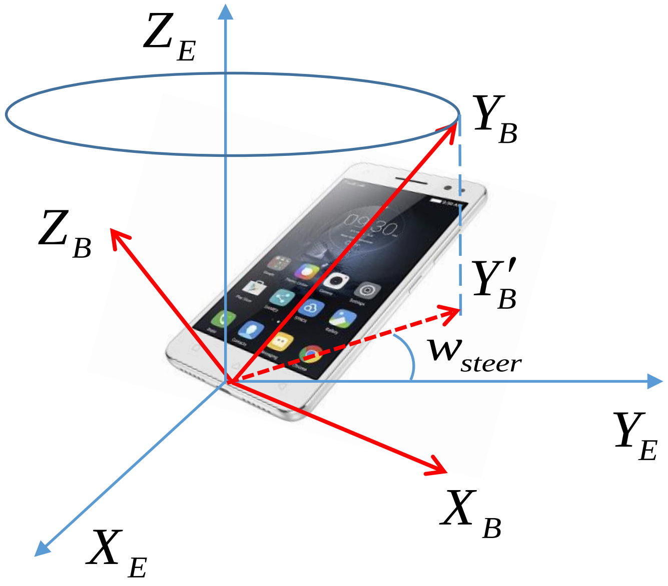
Data Collection

Build a smartphone coordinate alignment system to measure vehicle states

- Vehicle states include longitudinal velocity, vehicle acceleration, vehicle steering rate and vehicle position (latitude and longitude)
- Includes smartphone coordinate system and road coordinate system



Smartphone in the vehicle



Smartphone coordinate alignment system

Data Adjustment

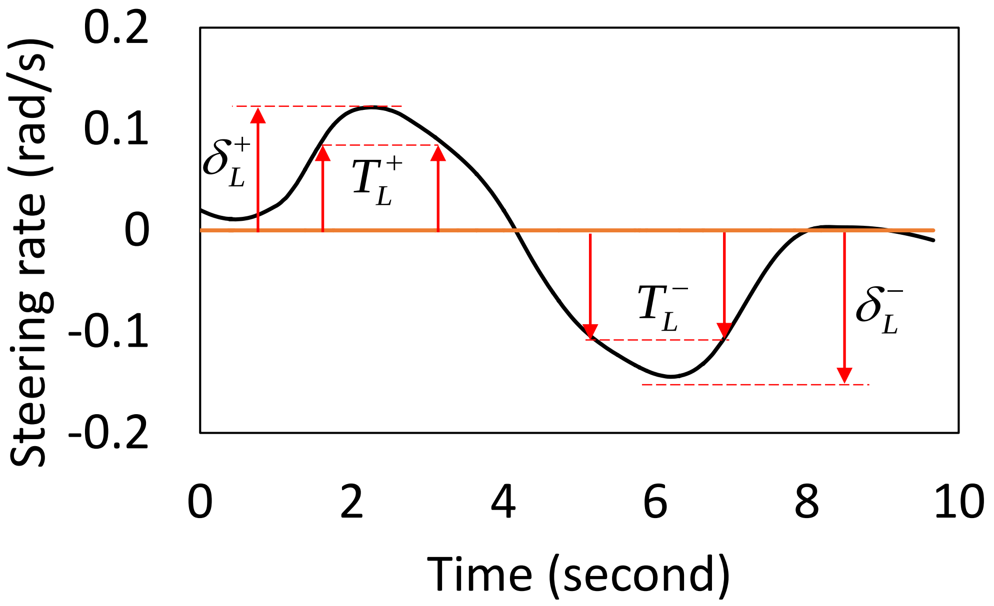
Detect lane change actions based on steering rates for vehicle state adjustment

- Lane change feature extraction
- Lane change detection
- Longitudinal velocity adjustment

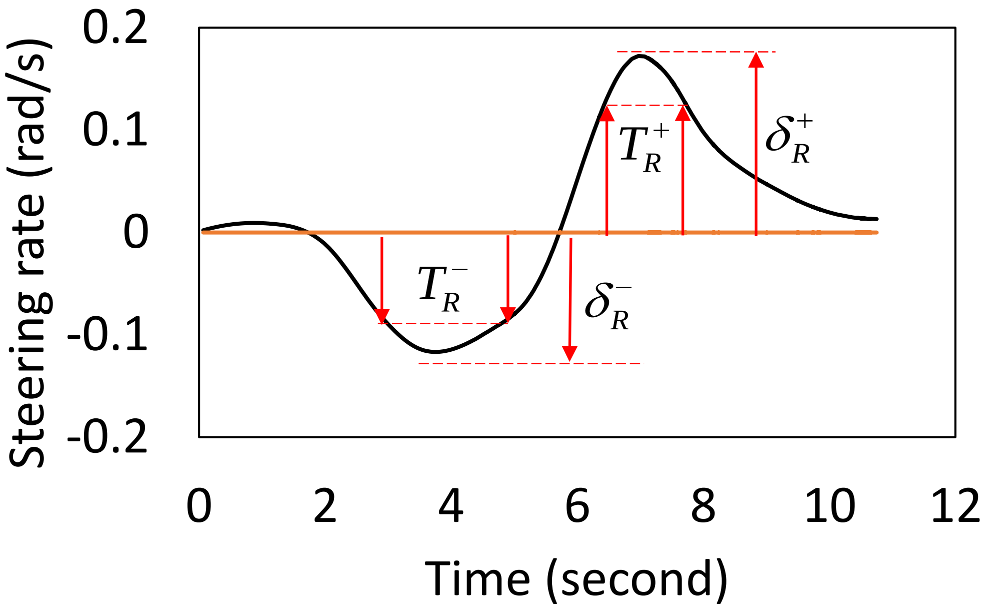
Data Adjustment

Lane change feature extraction

- Maximum absolute bump magnitude δ (larger than 0.1 rad/s)
- Time duration T of the bump (more than 1.3 seconds)



Steering rates for left lane change



Steering rates for right lane change

Data Adjustment

Lane change detection

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- Detect a lane change by comparing two neighboring bumps

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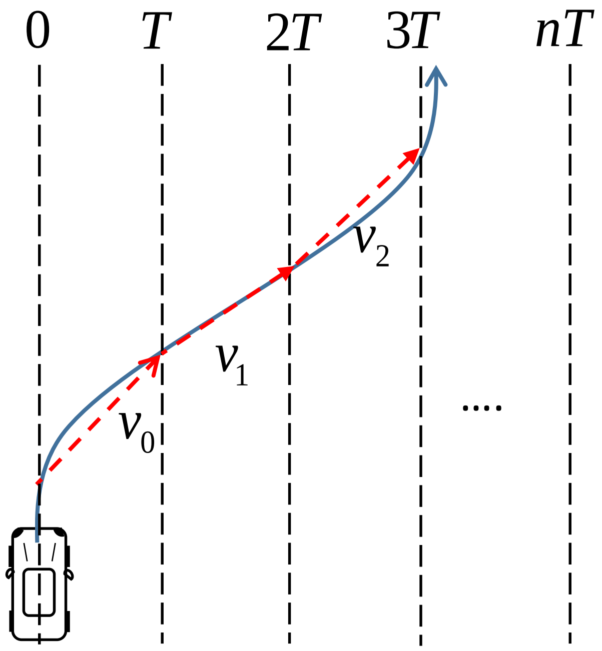
Longitudinal velocity adjustment

- Adjust longitudinal velocity to eliminate effects of lane change actions

$$v_i^L = v_i \cos\left(\sum_{j=0}^{i} w_{steer}^{j} T\right)$$



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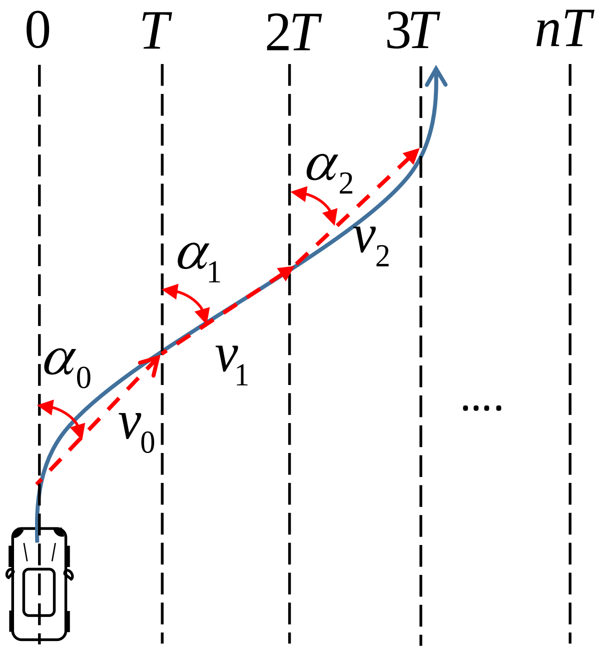

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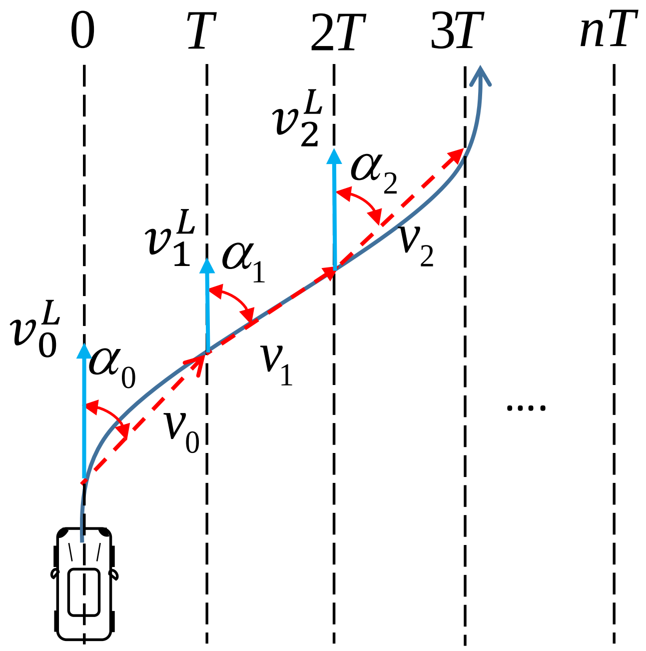

Challenge 2

How to ensure road gradient estimation accuracy based on measured vehicle states?

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Vehicle state space equation + Track fusion

Road Gradient Estimation

Vehicle state space equation

- Derive the dynamics equation of road gradient θ based on driving equation [TITS'14]:

$$\dot{\theta} = \frac{\rho A_f C_d v a}{m g cos\theta}$$

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- Convert the equation in a discrete form

$$\begin{bmatrix} v(t+1) \\ \theta(t+1) \end{bmatrix} = \begin{bmatrix} v(t) + \hat{a}(t) \\ \theta(t) + \dfrac{\rho A_f C_d v(t) \hat{a}(t)}{m g cos\theta(t)} \end{bmatrix}$$

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- Apply Extended Kalman Filter (EKF) to update v and θ

$$\begin{bmatrix} v(t+1) \\ \theta(t+1) \end{bmatrix} = \begin{bmatrix} v(t+1|t) \\ \theta(t+1|t) \end{bmatrix} + K(\hat{v}(t+1) - v(t+1|t))$$

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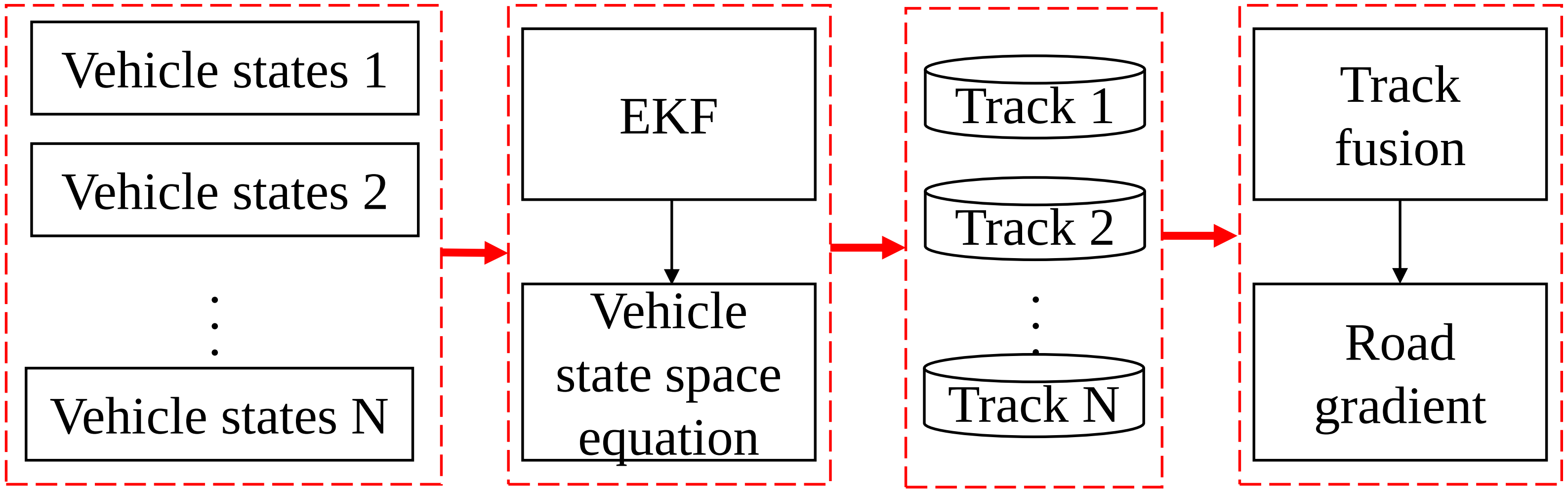
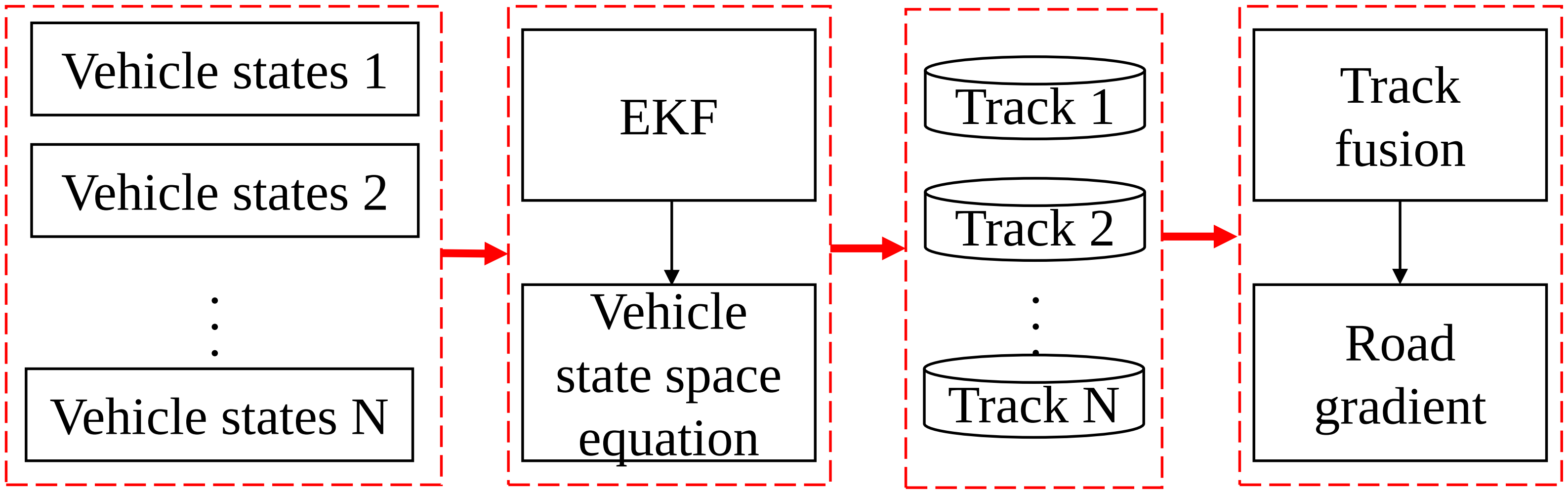
Road Gradient Estimation

Track fusion based road gradient estimation



Road Gradient Estimation

Track fusion based road gradient estimation



Fuse different road gradient estimation tracks to obtain final θ

$$\bar{\theta} = U \sum_{k=1}^{N} (P_k^{-1} \theta_k)$$

where P_k represents estimation error covariance matrix in EKF for the k^{th} track;
U represents system covariance matrix of N tracks and equals to $(\sum_{k=1}^{N} P_k^{-1})^{-1}$

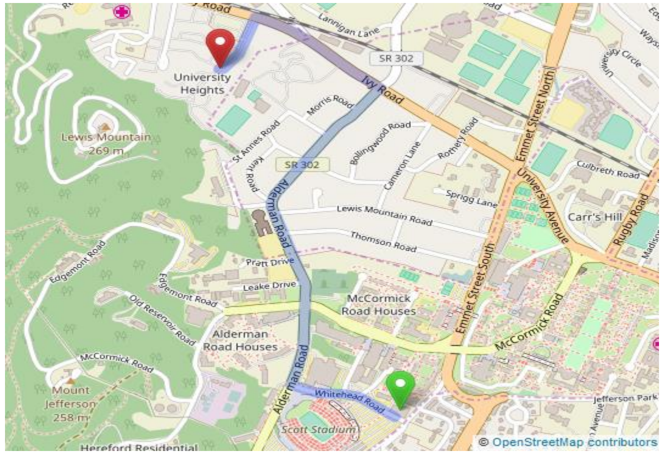
Performance Evaluation

Experiment settings

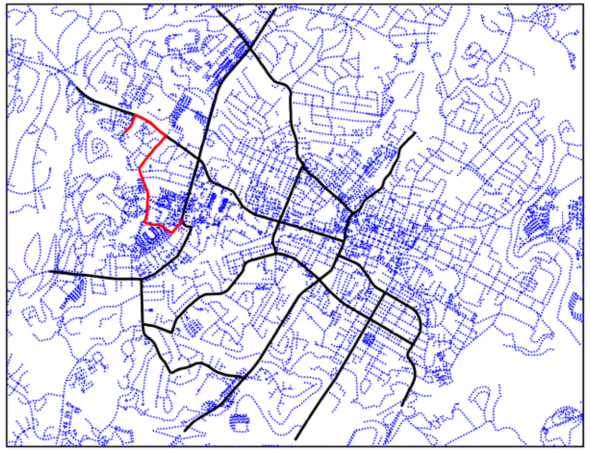
- Implement our proposed system (OPS) by installing a Samsung Galaxy smartphone into Nissan Altima 2006 to collect experimental data

Comparison methods

- EKF based method (EKF) [JPCMS’14] uses EKF to estimate road gradients
- Artificial Neural Network based method (ANN) [JMST’17] estimates road gradients with vehicle states as inputs and road gradient as output



Small-scale road

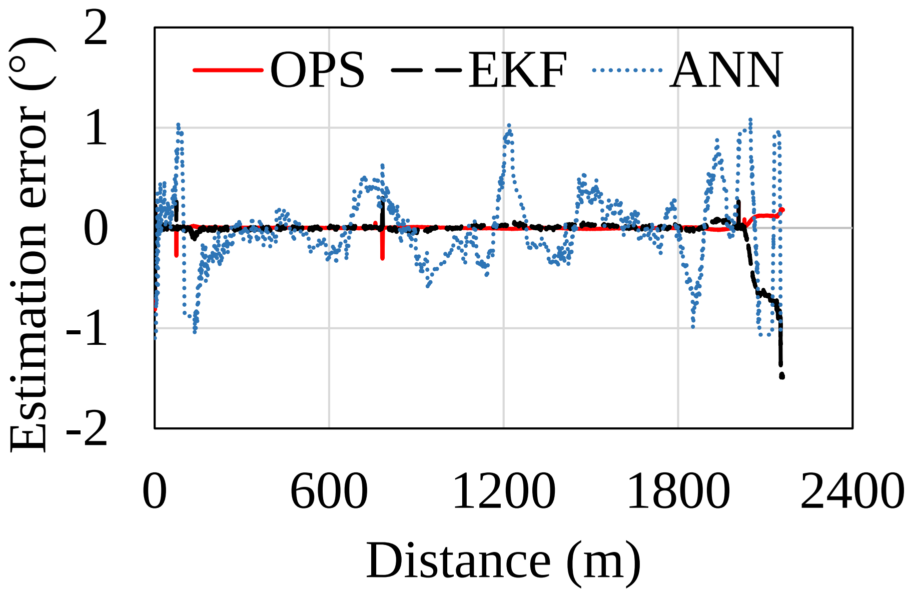


Large-scale road network

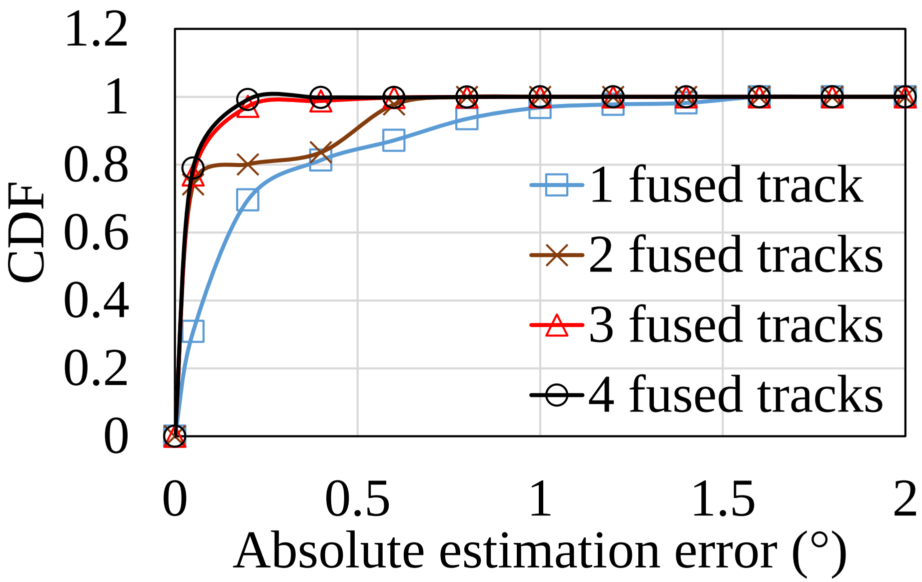
Performance Evaluation

Road gradient estimation results in a small-scale road (2.16 km)

- MREs of OPS, EKF and ANN are 11.9%, 20.3% and 31.6%
- Road gradient estimation accuracy of OPS increases as more tracks are used



Absolute road gradient estimation errors



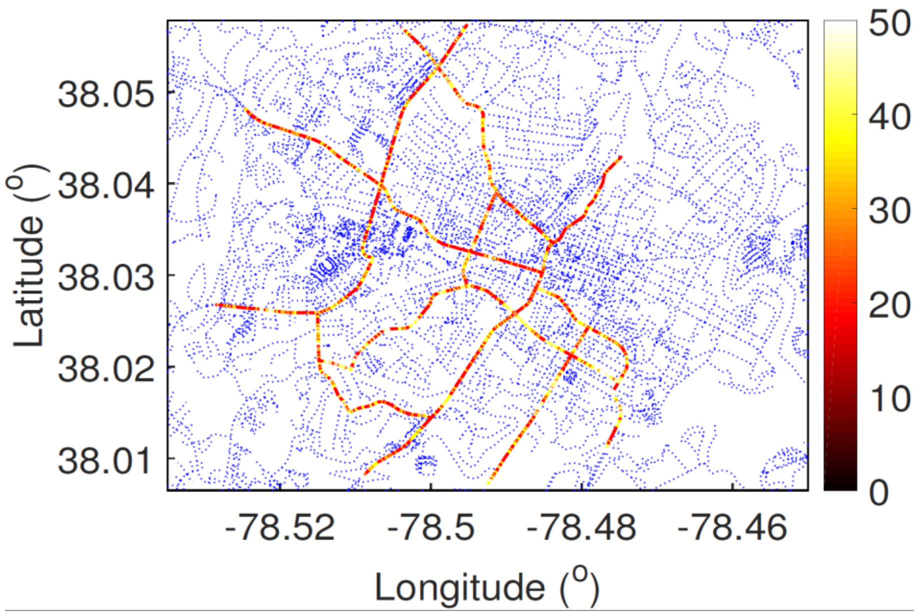
CDFs of OPS with different track fusions

CDF: Cumulative Distribution Function
MRE: Mean Relative Error

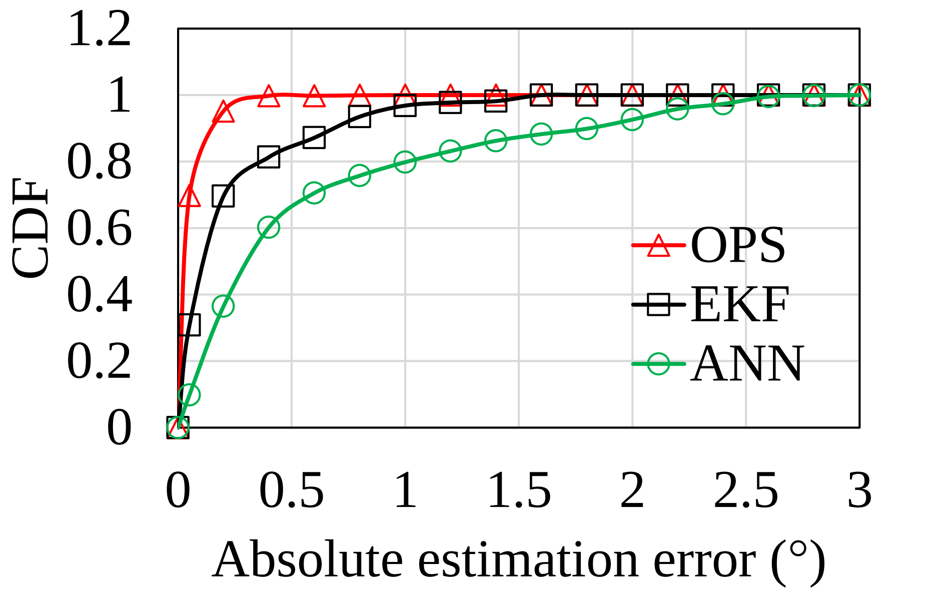
Performance Evaluation

Road gradient estimation results in a large-scale road network (164.8 km)

- MRE of OPS keeps around 12% and works well on different road types
- OPS has higher road gradient estimation accuracy than EKF and ANN



Road gradient estimation result in the road network

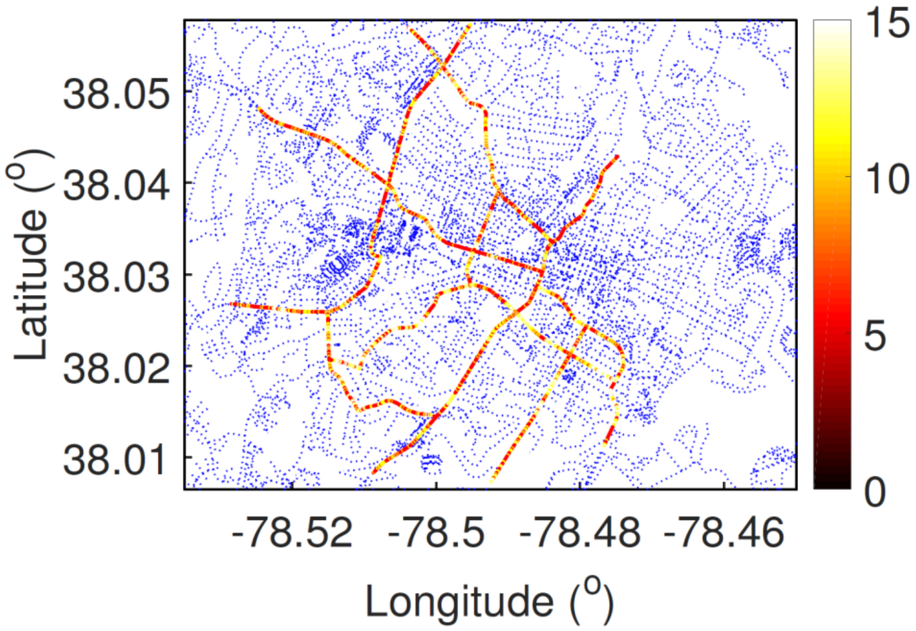


CDFs comparisons among different methods

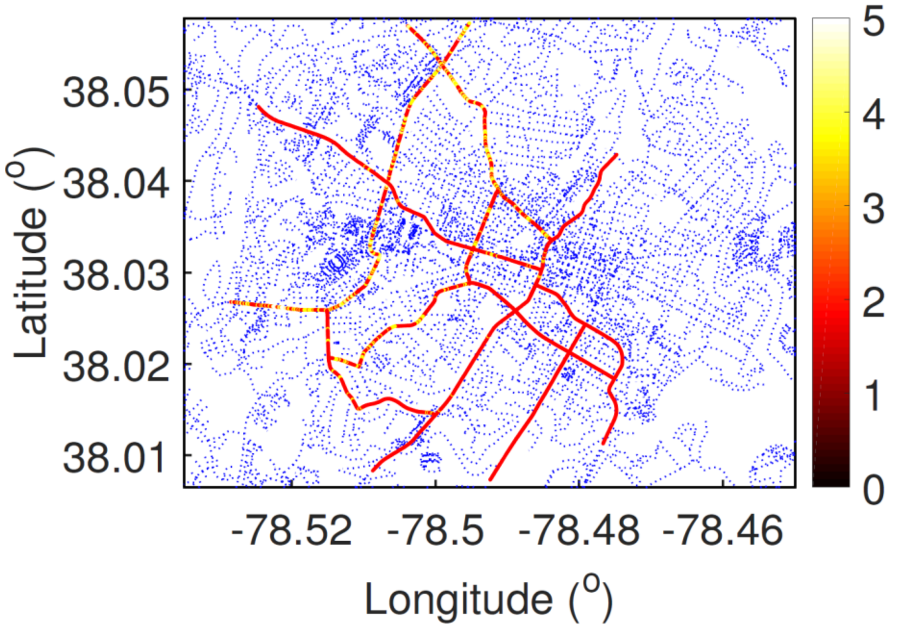
Performance Evaluation

Fuel consumption and air pollution emission estimations

- High fuel consumptions and vehicle air pollution emissions are always located at roads with large road gradients



Fuel consumption estimation result



Carbon dioxide emission estimation result

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Future work

- Explore more accurate vehicle driving equations
- Consider other driving behaviors

Thank you!