evs 27

# Real-Time Road Slope Estimation and 3D Map Generation Algorithm for Energy Management Systems


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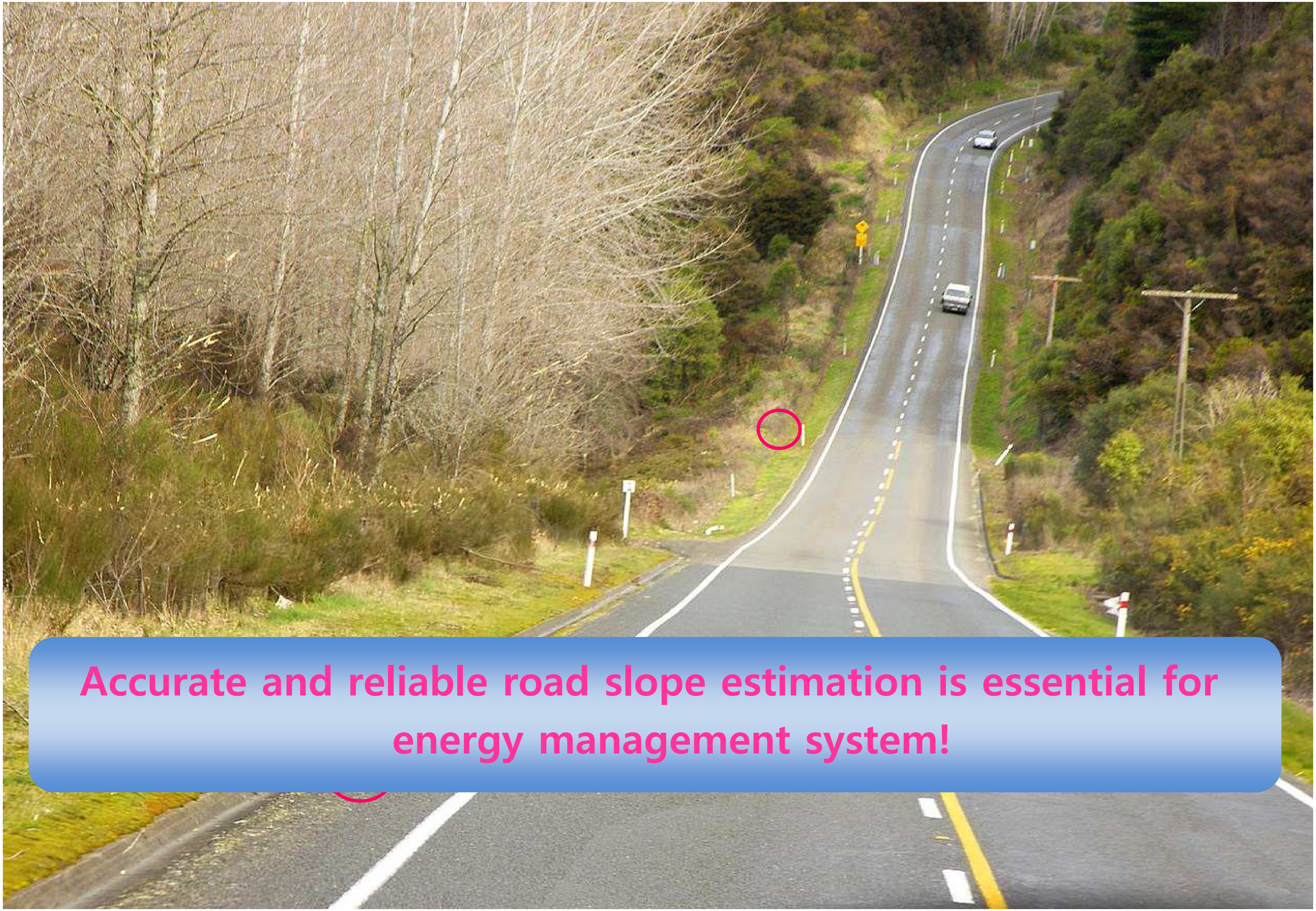
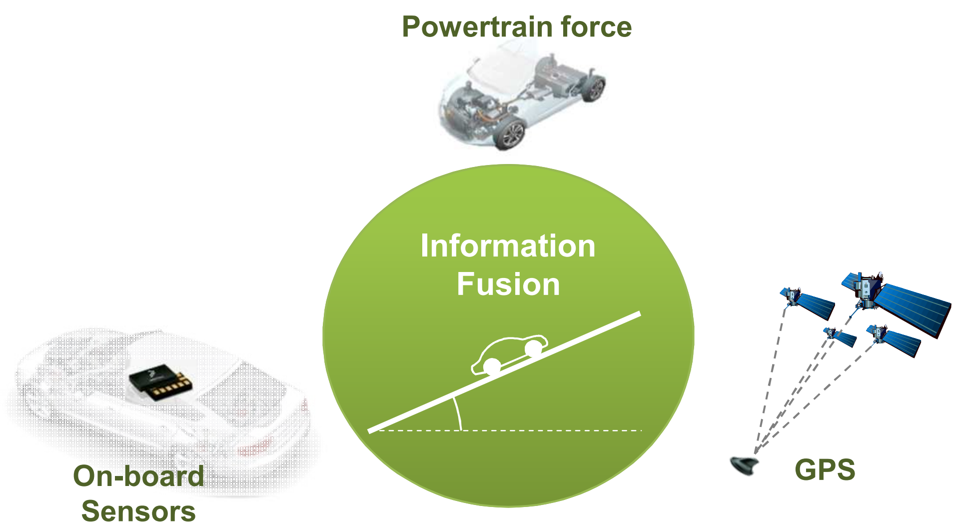
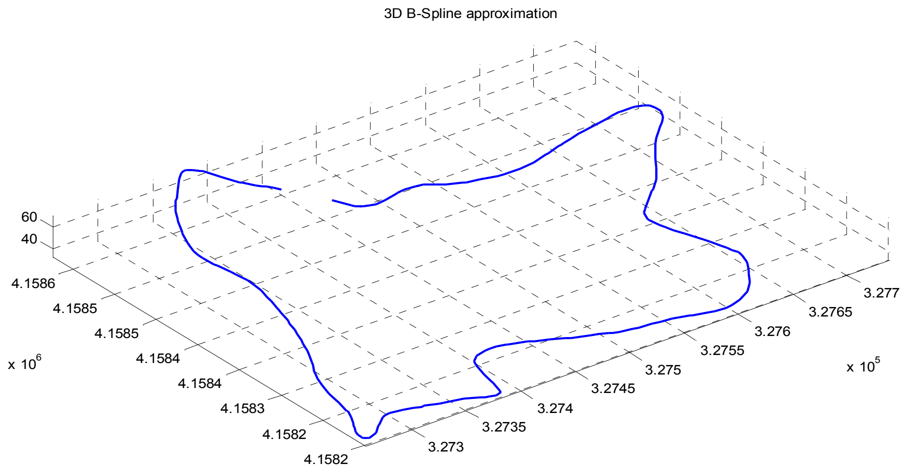

Accurate and reliable road slope estimation is essential for energy management system!

# Research Objectives

- **Road slope estimation algorithm based on information fusion**
  - On-board sensors: accelerometer, wheel speed sensors
  - GPS information
  - Powertrain force information
- **3D map generation algorithm based on the road slope estimate**




Information fusion based road slope estimation




3D roadway map generation algorithm

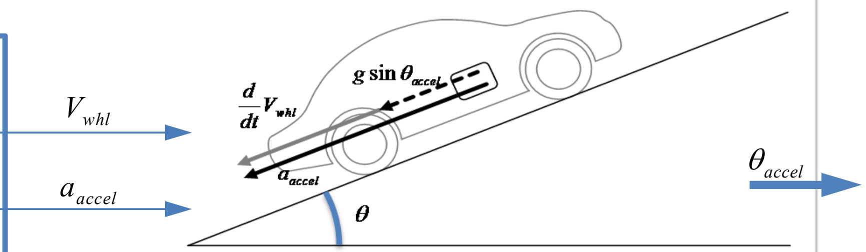
# Road slope estimation based on information fusion

# System Overview

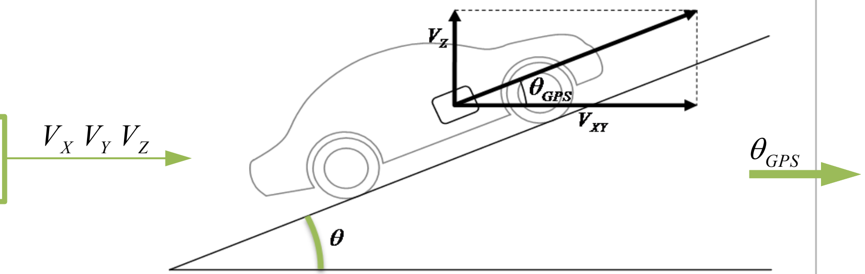
## Information sources for road slope

**On-board Sensors**

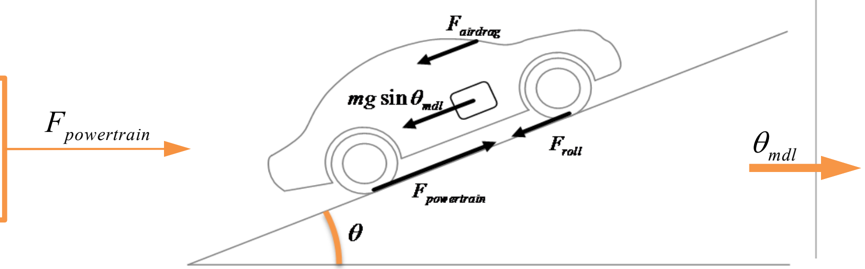
- Wheel Speed Sensors
- Accelerometer




**GPS Receivers**

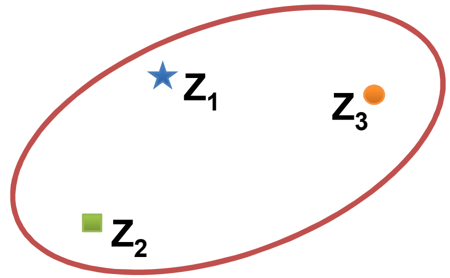



**Powertrain Force**

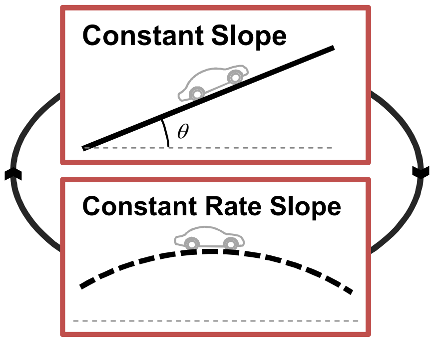



## Information fusion : IMMPDAF

**Probabilistic Data Association**




**Multiple Road Slope Model**



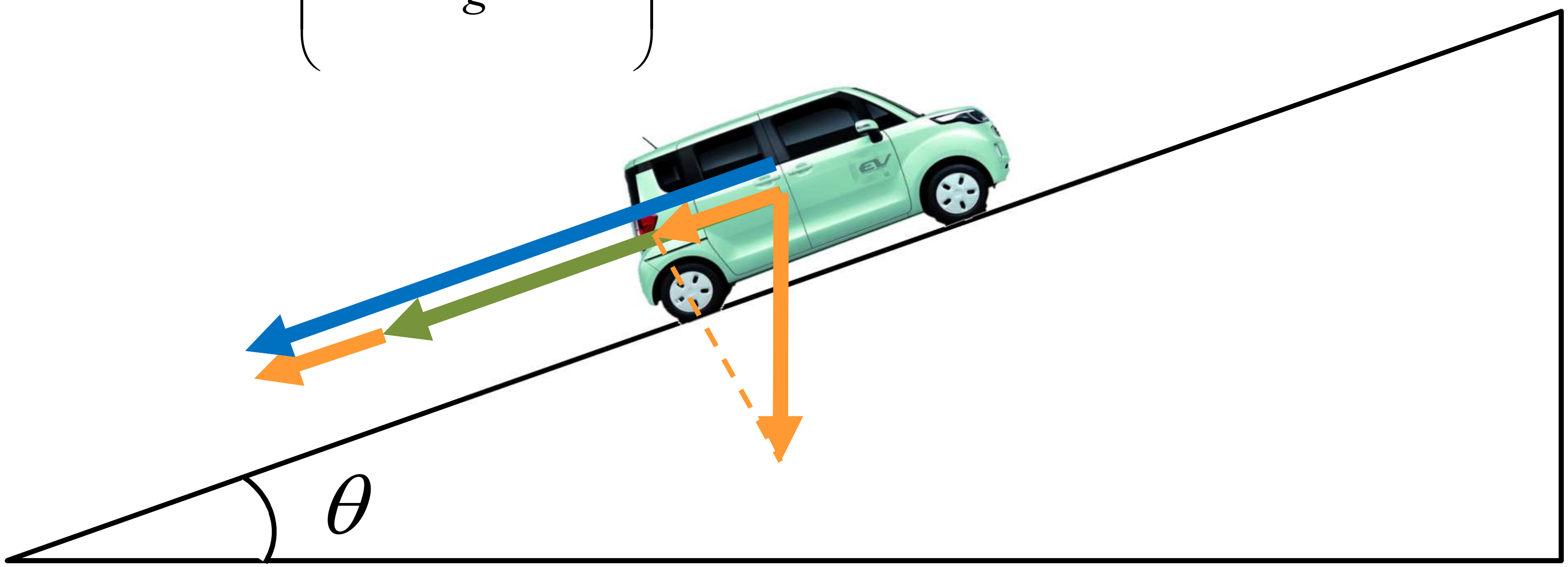
# On-board Sensors based Estimation (I)

## On-board sensors based road slope estimation

- Wheel speed sensors $V_{wheel}$
- Longitudinal accelerometer = Vehicle acceleration + Gravity

$a_{acc}$ $\qquad \frac{d}{dt}V_{wheel}$ $\qquad g\sin\theta$

$$\theta = \sin^{-1}\left(\frac{a_{acc} - \frac{d}{dt}V_{wheel}}{g}\right)$$



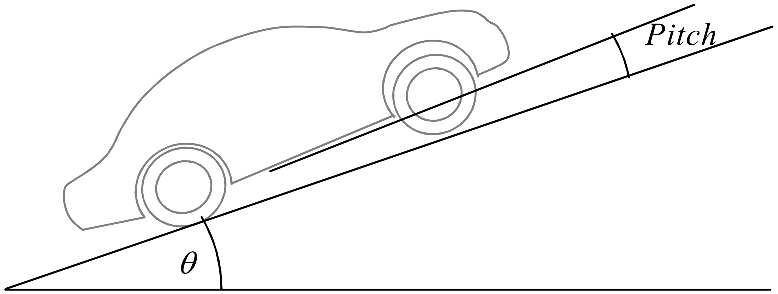
# On-board Sensors based Estimation (II)

## Advantages

- Does not required the prior knowledge of the vehicle model and parameters
- Independent to the external environment condition

## Disadvantages

- Acceleration sensor noise
- **Differential error** of wheel speed sensors
- **High-frequency noise** from the vehicle pitch motion

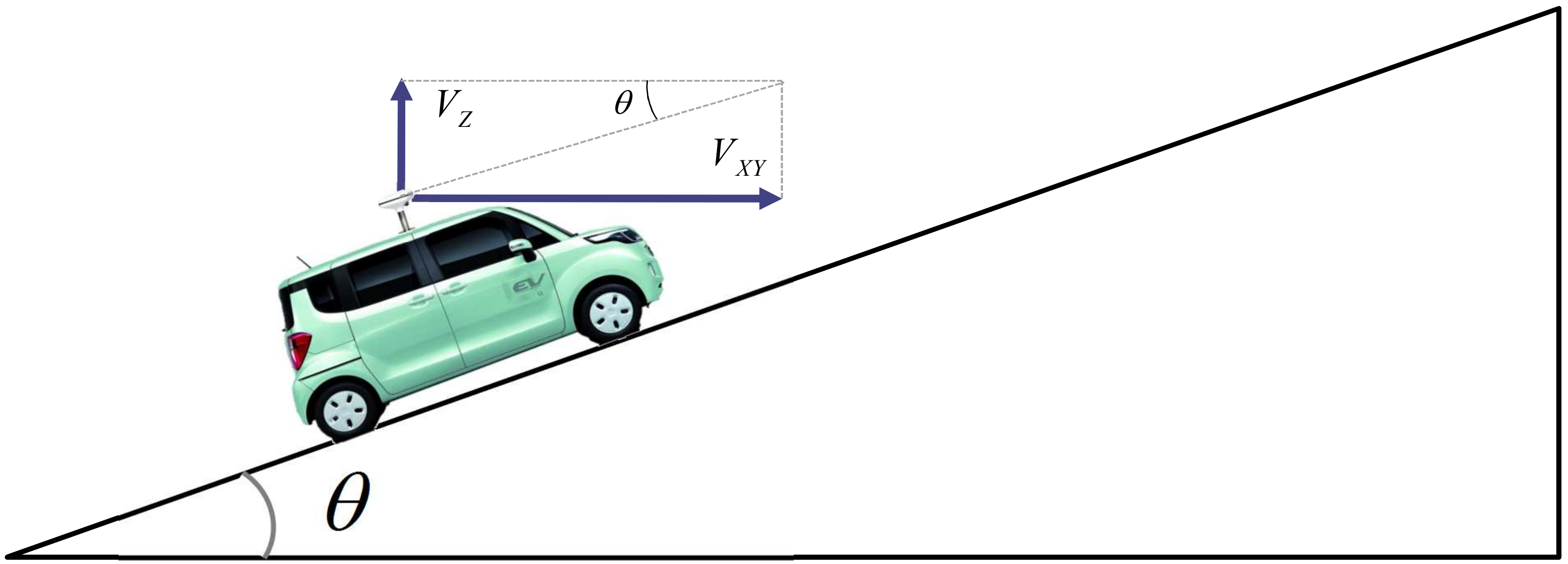


# GPS based Estimation (I)

## GPS based road slope estimation

- The ratio of vertical to horizontal velocity from **GPS receiver**

$$\theta = \tan^{-1}\left(\frac{V_Z}{V_{XY}}\right)$$

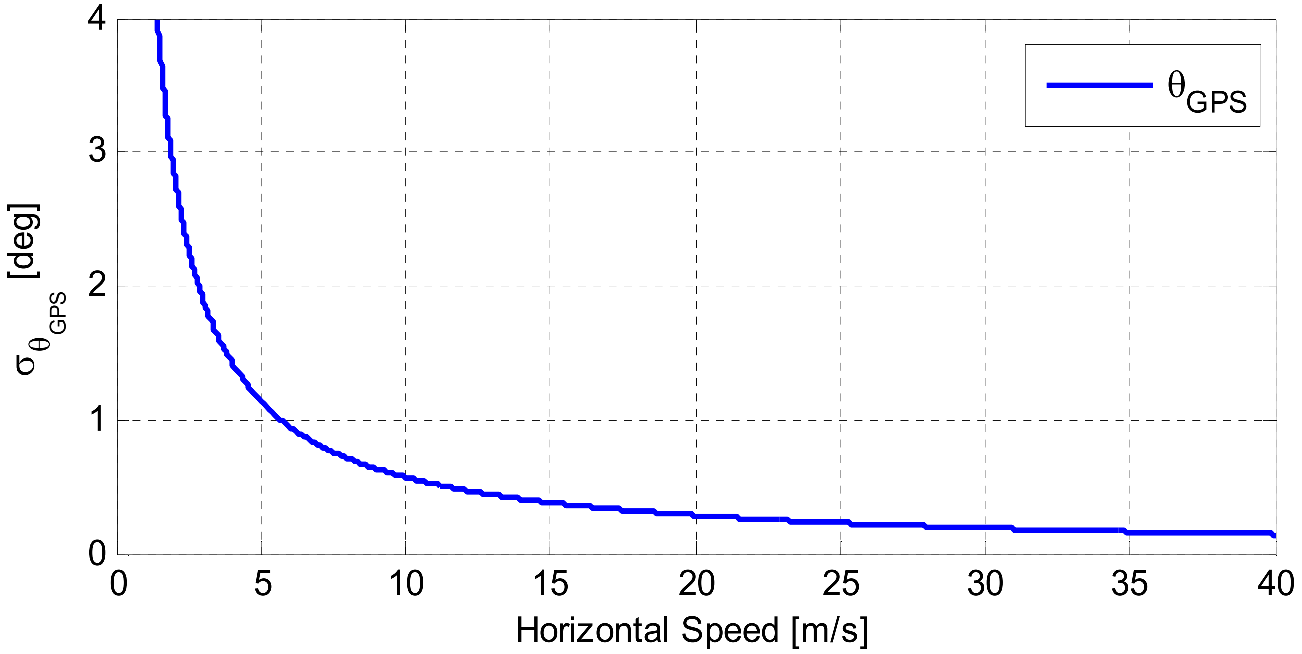


# GPS based Estimation (II)

- **Disadvantages**
  - Highly depend on the GPS signal condition
  - Cannot update the road slope during the **stop or low speed condition**

$$\theta = \tan^{-1}\left(\frac{V_Z}{V_{XY}}\right)$$

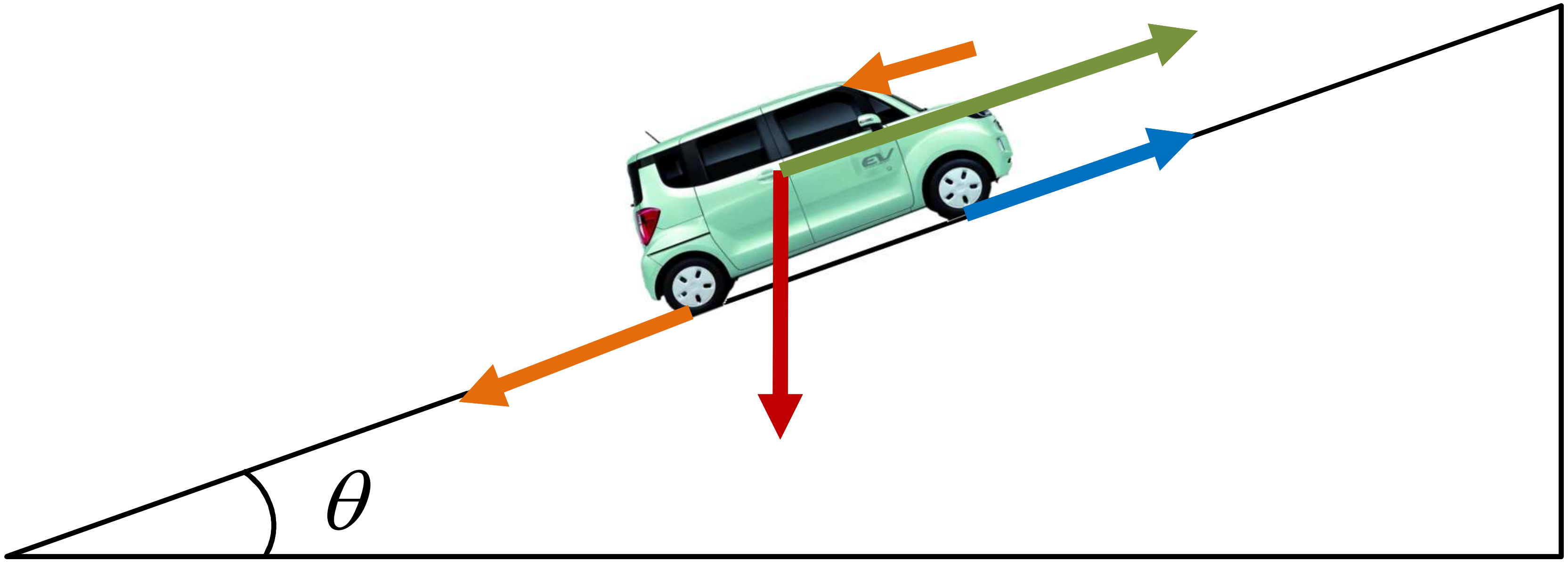
- 



# Powertrain Force based Estimation (I)

## Longitudinal dynamic Model

$$\theta = \sin^{-1}\left(\frac{1}{g}\left(\frac{\frac{T_{wheel}}{R_{eff}} - F_L}{M} - a\right)\right)$$



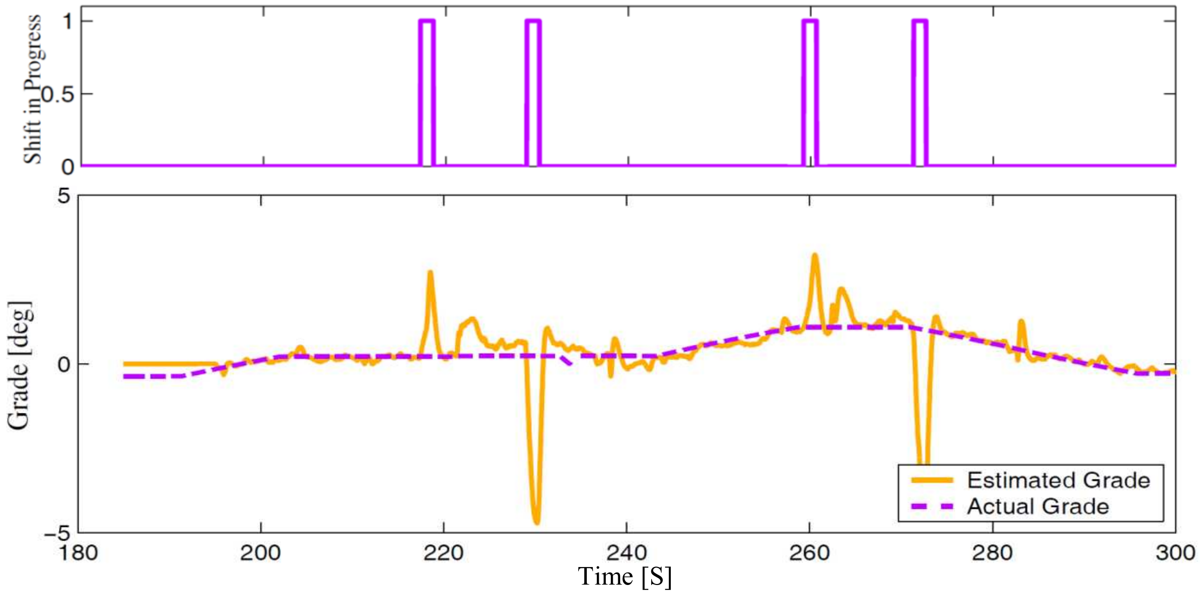
# Powertrain Force based Estimation (II)

## Advantages

- Independent to the external environment condition
- Additional sensors do not require for road slope estimation

## Disadvantages

- Sensitive to the changes of model parameters
- Cannot update the road slope during braking and stop

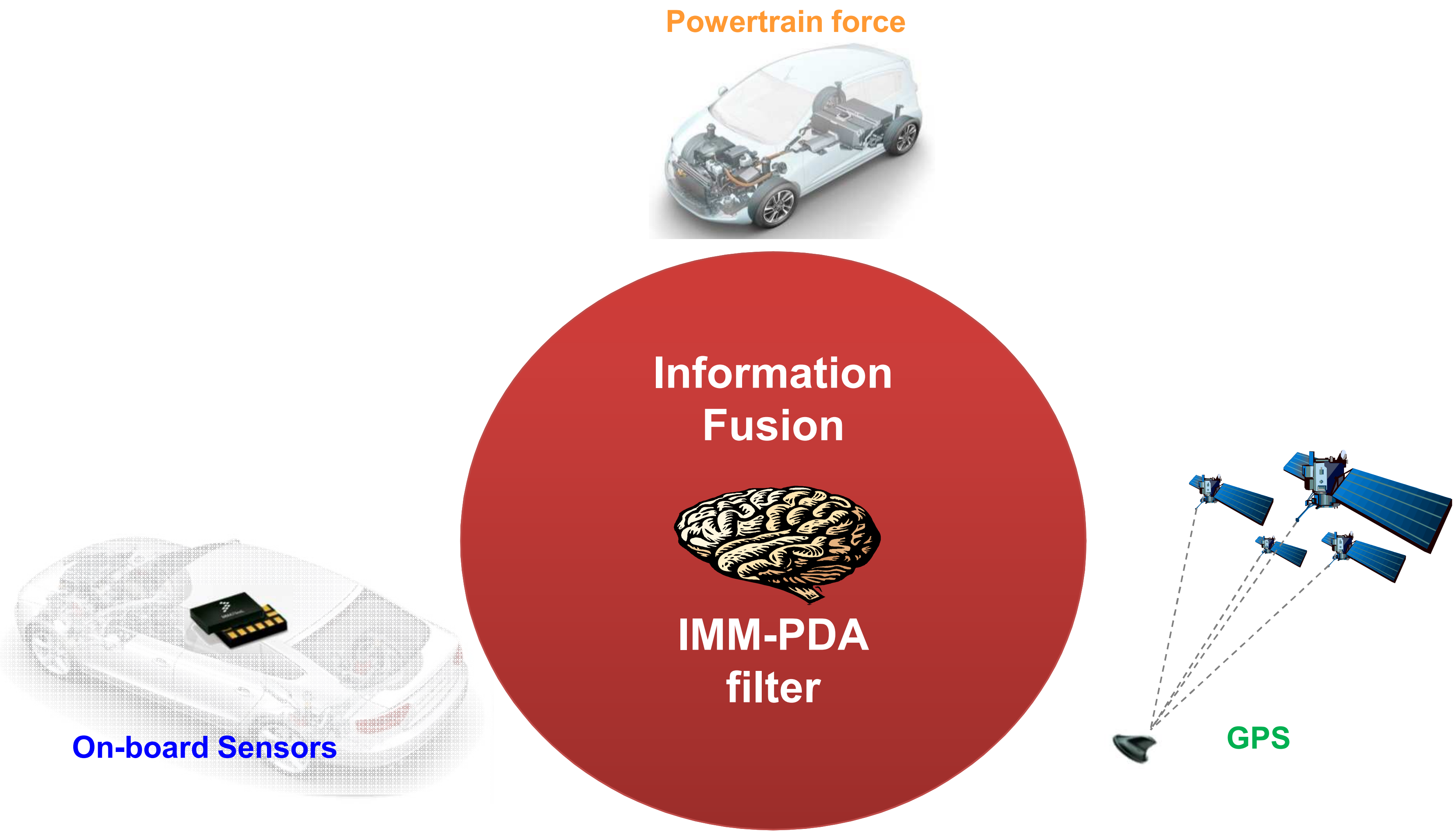


# Characteristics of Road Slope Measurement Sources

## Summary

| | On-board sensor based Estimation | GPS based estimation | Powertrain force based estimation |
|---|---|---|---|
| Independent to pitch motion | X | O | X |
| Independent to external environment | O | X | O |
| Can work in stop condition | O | X | X |
| Independent to braking | O | O | X |
| No additional cost | X | X | O |

## Information fusion with IMMPDA filter



# IMM-PDAF

Probabilistic Data Association
- Sensor fusion

IMMPDAF

Interacting Multiple Model
- Adapting road slope conditions

Filter
- Bayesian Theory

# Multiple Road Slope Model

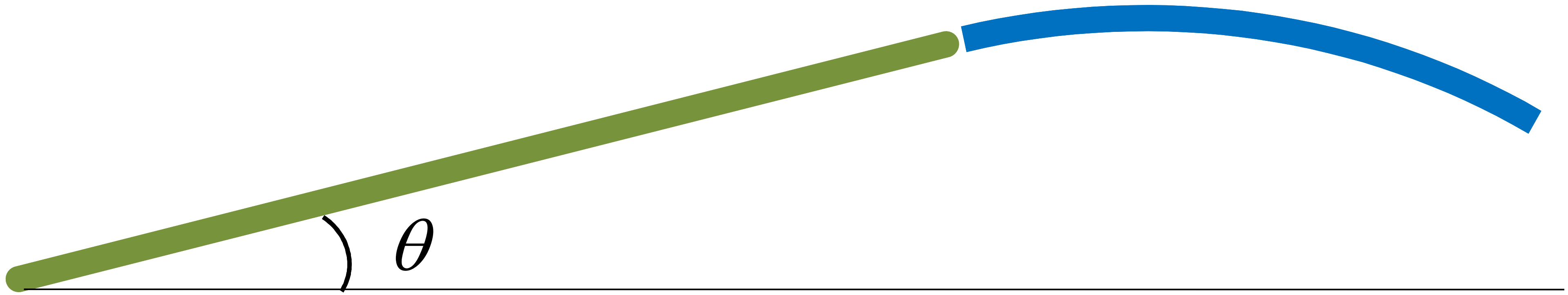
## Constant Slope Road (CSR) Model

$$\theta = \text{constant} \;\Rightarrow\; \dot{\theta} = 0 \;\Rightarrow\; \theta_{k+1} = \theta_k$$

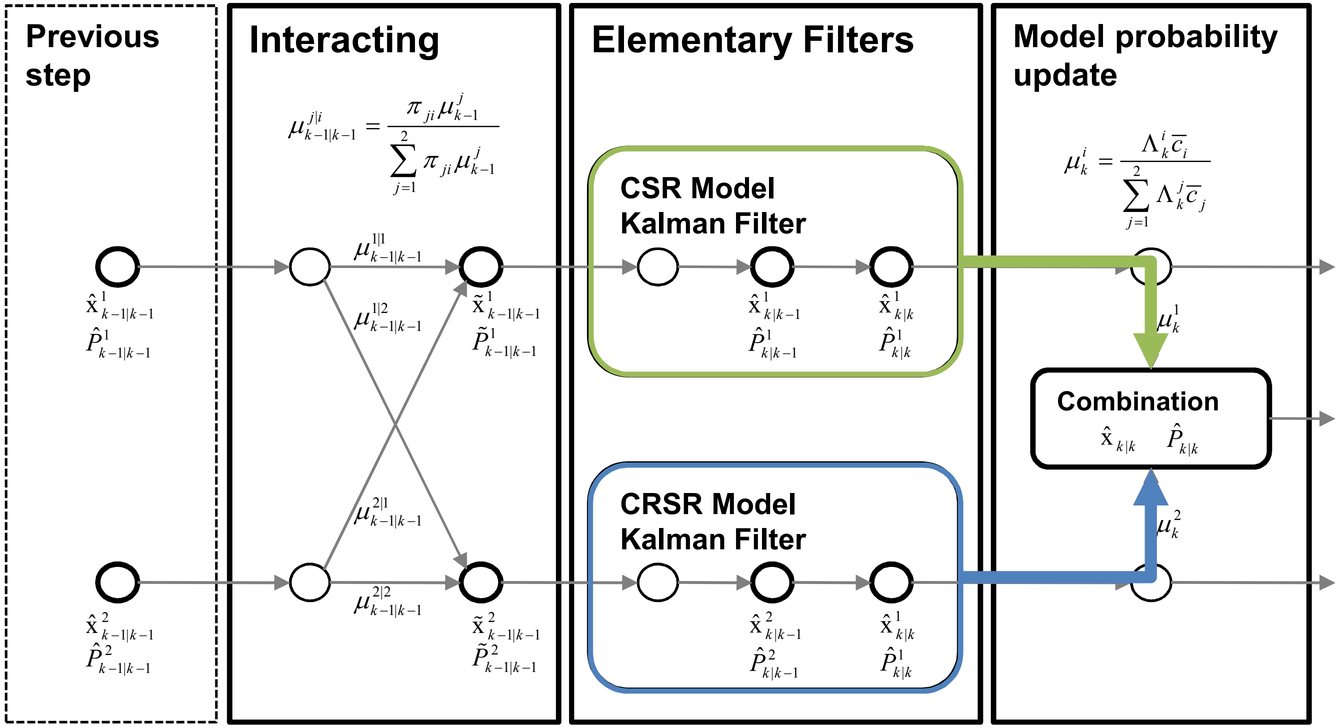
## Constant Rate Slope Road (CRSR) Model

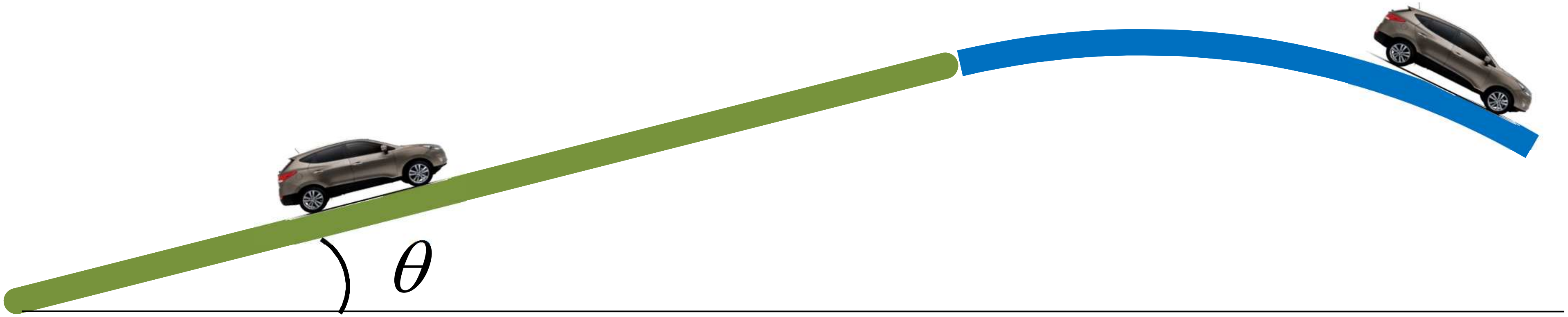
$$\dot{\theta} = \text{constant} \;\Rightarrow\; \begin{aligned} x_1 &= \theta \\ x_2 &= \dot{\theta} \end{aligned} \;\Rightarrow\; \frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\Rightarrow\; \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}_{k+1} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}_k$$



# Interacting Multiple Model (IMM) Filter



## PDA Algorithm

$$\beta_{k,j} = \Pr(\theta_j \mid z_k, m_k, Z_{k-1}) = \frac{f(z_k \mid \theta_j, m_k, Z_{k-1}) \Pr(\theta_j \mid m_k, Z_{k-1})}{\sum_{j=0}^{m} (z_k \mid \theta_j, m_k, Z_{k-1}) \Pr(\theta_j \mid m_k, Z_{k-1})}$$

$$\Pr(\theta_j \mid m_k, Z_{k-1}) = \frac{\frac{1}{m} P_D P_G \mu_F (m-1)}{(1 - P_D P_G)\mu_F(m) + P_D P_G \mu_F (m-1)}$$

$$\Pr(\theta_0 \mid m_k, Z_{k-1}) = \frac{(1 - P_D P_G)\mu_F(m)}{(1 - P_D P_G)\mu_F(m) + P_D P_G \mu_F (m-1)}$$

$$f(z_k \mid \theta_j, m_k, Z_{k-1}) = \frac{1}{P_G} N(z_k; H\bar{x}_k, S_k) V_G^{-(m-1)}$$

$$f(z_k \mid \theta_j, m_k, Z_{k-1}) = V_G^{-m}$$

$$\beta_{k\,j} = \frac{\exp(-\frac{1}{2} v_{k,j}^T S_k^{-1} v_{k,j})}{b + \sum_{j=1}^{m_k} \exp(-\frac{1}{2} v_{k,j}^T S_k^{-1} v_{k,j})}$$

$$\beta_{k\,0} = \frac{b}{b + \sum_{j=1}^{m_k} \exp(-\frac{1}{2} v_{k,j}^T S_k^{-1} v_{k,j})}$$

$$b = \lambda (2\pi)^{\frac{n}{2}} \left| S_k \right|^{\frac{1}{2}} (1 - P_D P_G) / P_D$$

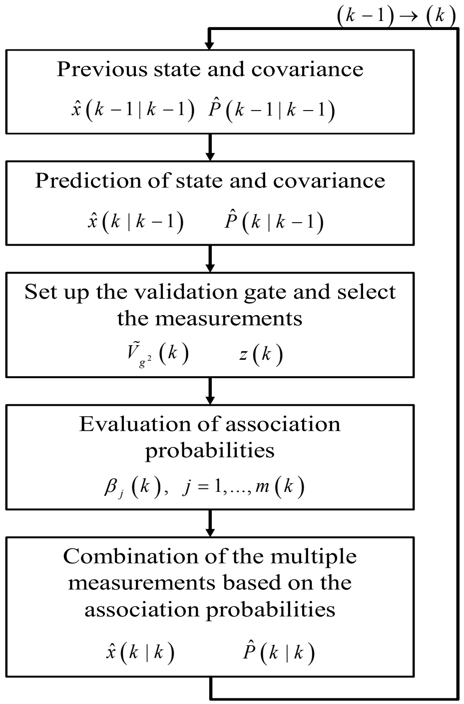
$$v_{k,j} = z_{k,j} - H\,\bar{x}_k$$

## PDA Filter

$$\hat{x}_k = \bar{x}_k + K_k \sum_{j=1}^{m_k} \beta_{k,j} v_{k,j}$$

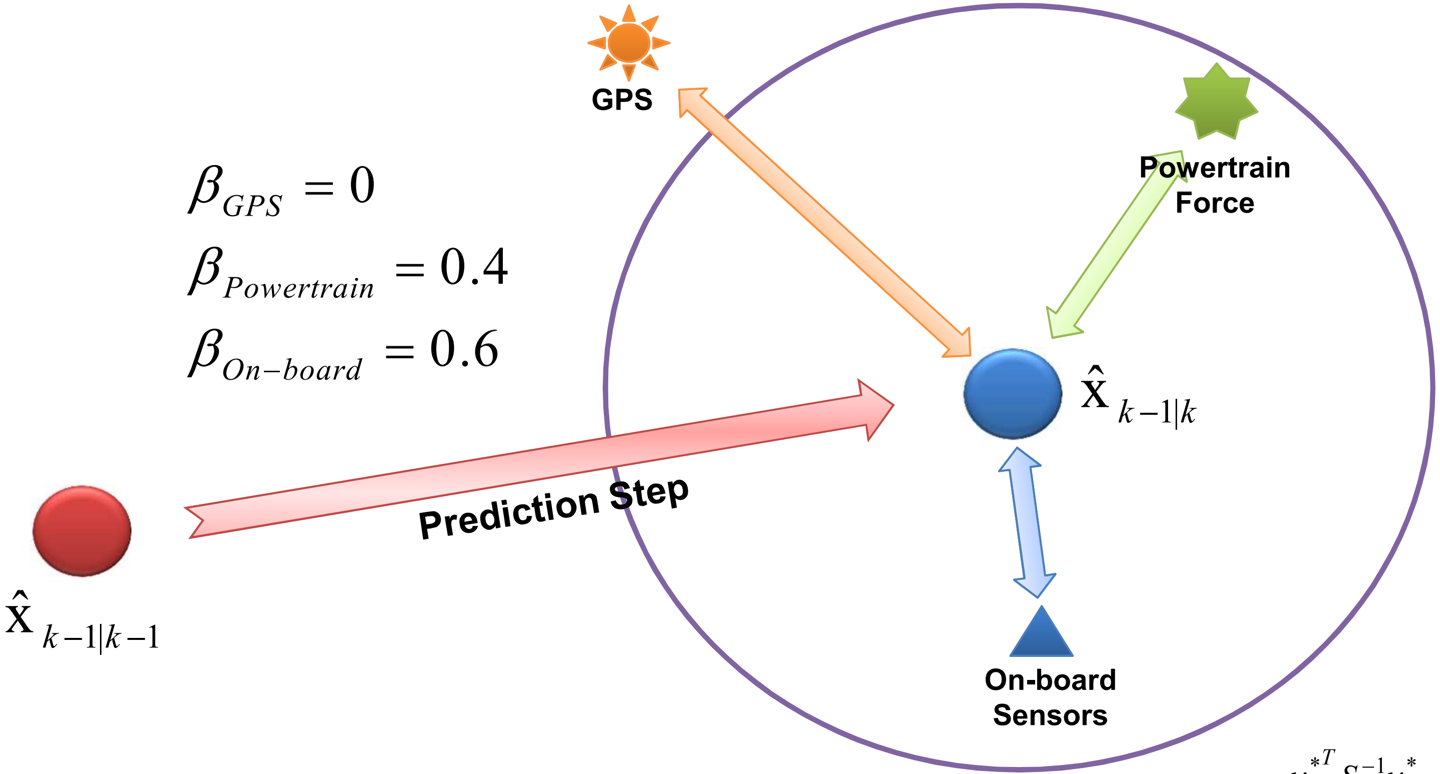
$$\hat{P}_k = \beta_{k,0} \bar{P}_k + (1 - \beta_{k,0}) \hat{P}_k^j + K_k \left[ \sum_{j=1}^{m_k} \beta_{k,j} v_{k,j} v_{k,j}^T - v_k v_k^T \right] K_k^T$$

$$v_k = \sum_{j=1}^{m_k} \beta_{k,j} v_{k,j}$$



- **Weighting each measurement using Bayesian filtering theory**

$$\beta_{GPS} = 0$$
$$\beta_{Powertrain} = 0.4$$
$$\beta_{On-board} = 0.6$$



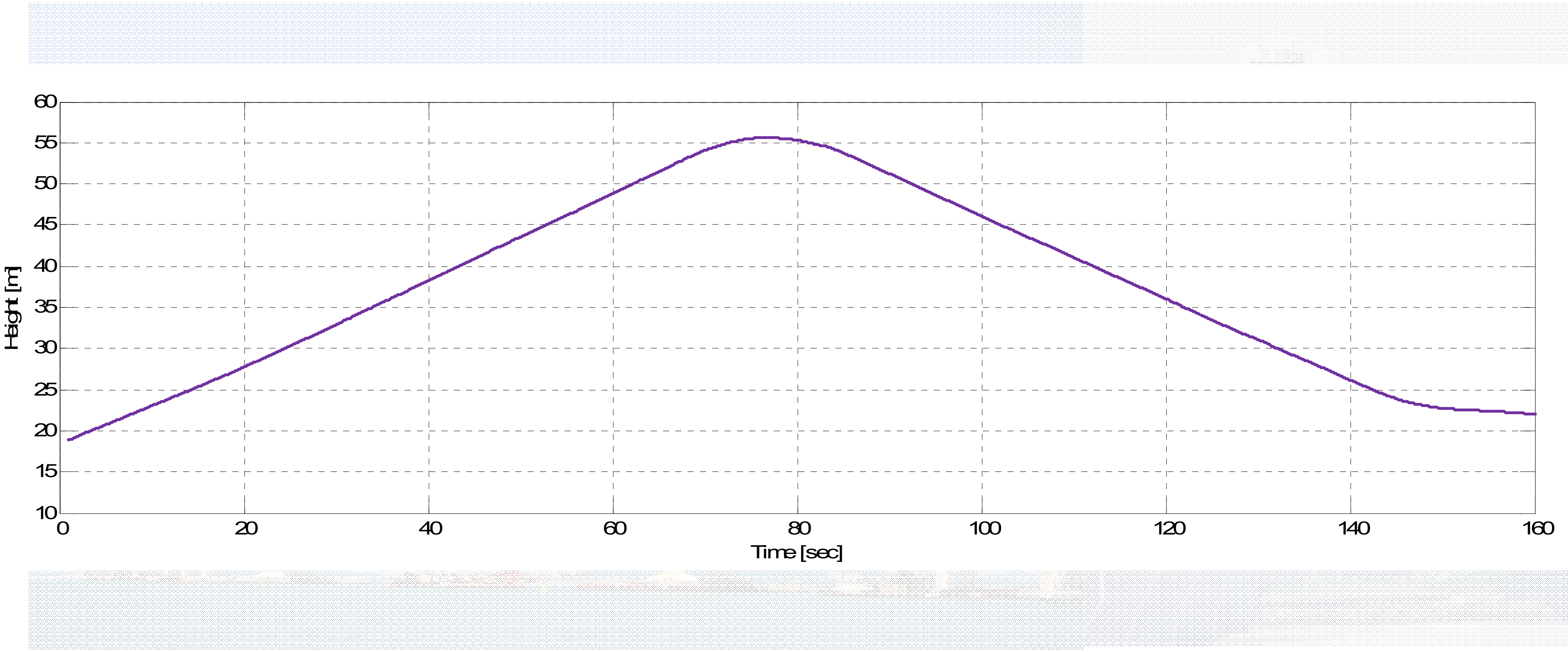

**Validation Gate**

$$\nu^{*T} S^{-1} \nu^{*} = R \ , \ \nu^{*} = z^{*} - H\bar{x}$$
$$V_R = c_n |S|^{1/2} R^{n/2}$$

# Experiments

# Experiments – Constant Slope Condition (I)

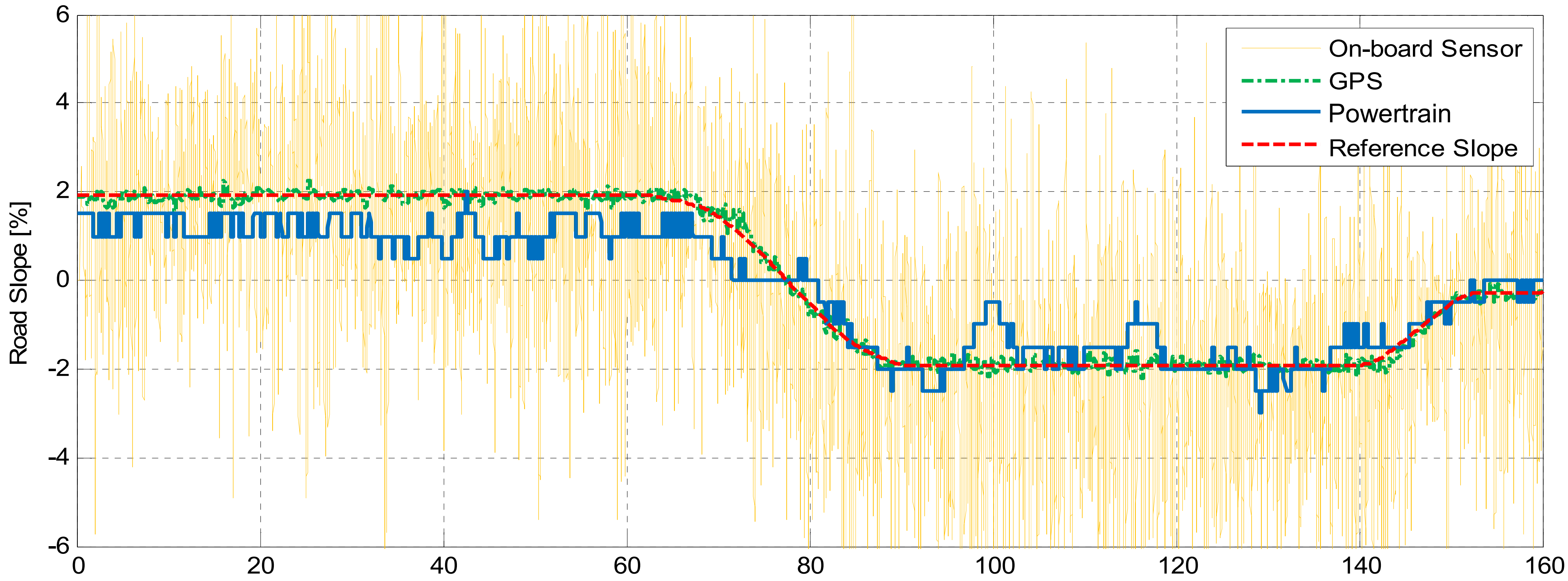
- **Test site – Yeongjong Grand Bridge**
  - ▶ Reference slope angle: 1.95 %




**Test Site**

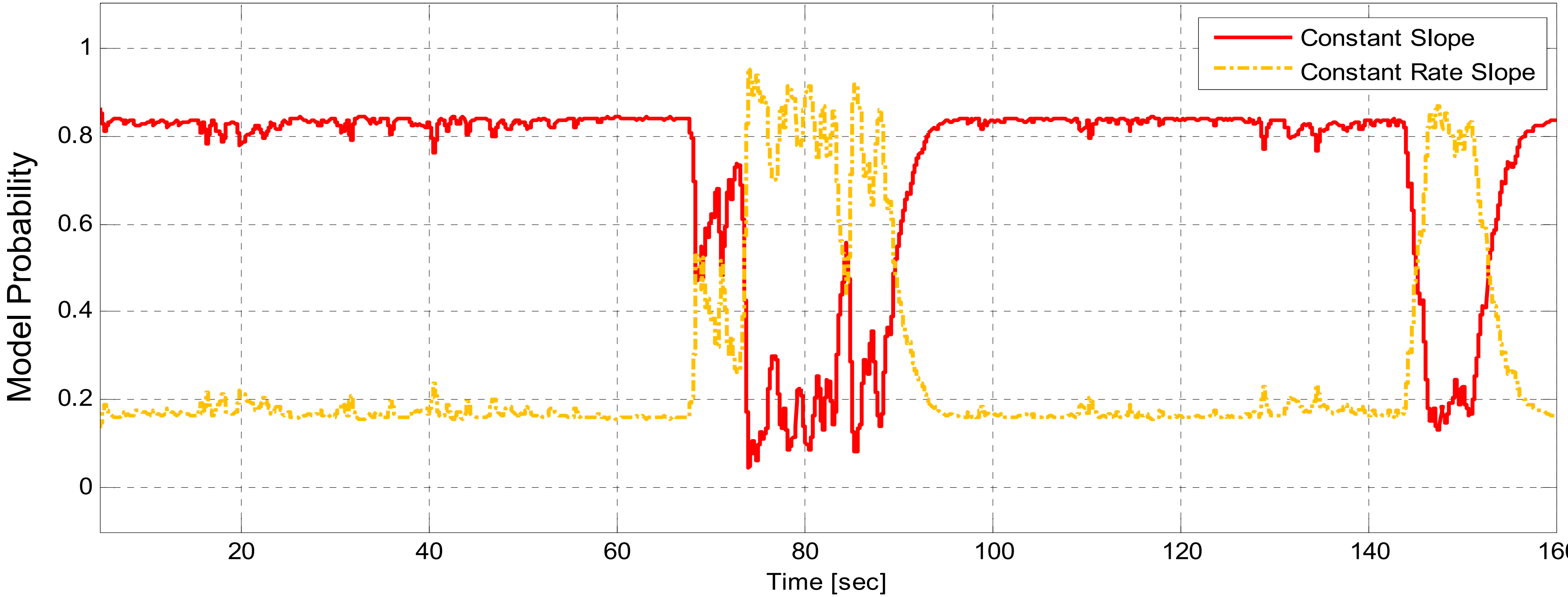
# Experiments – Constant Slope Condition (II)

- Raw data from each measurement method



# Experiments – Constant Slope Condition (IV)

## ■ Slope estimation with IMMPDA filter

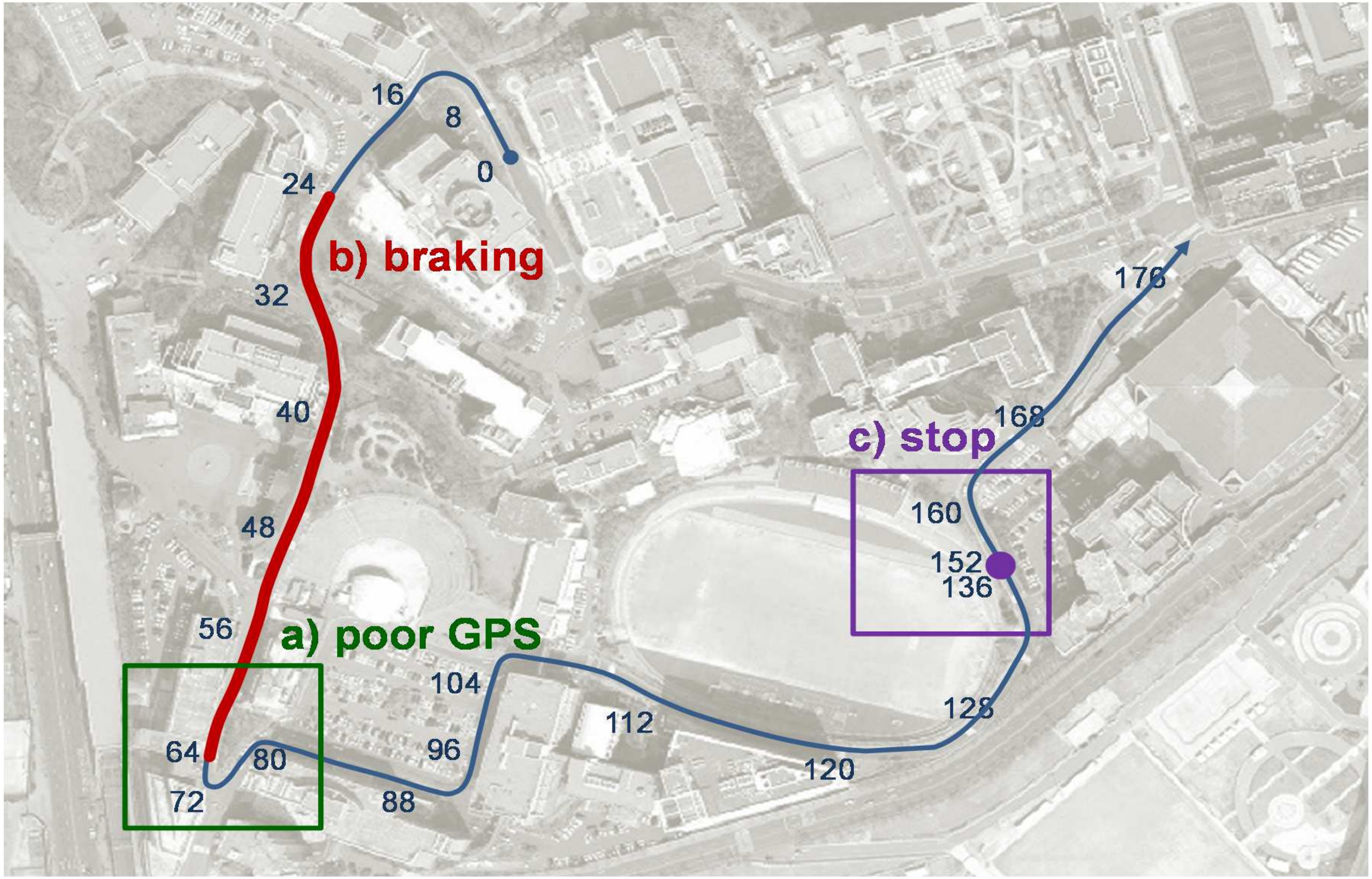



**RMS Error of the IMMPDA filter**

| On-board | GPS | PT | CSRM-PDAF | CRSRM-PDAF | IMM-PDAF |
|---|---|---|---|---|---|
| 1.83 | 0.10 | 0.53 | 0.08 | 0.08 | 0.06 |

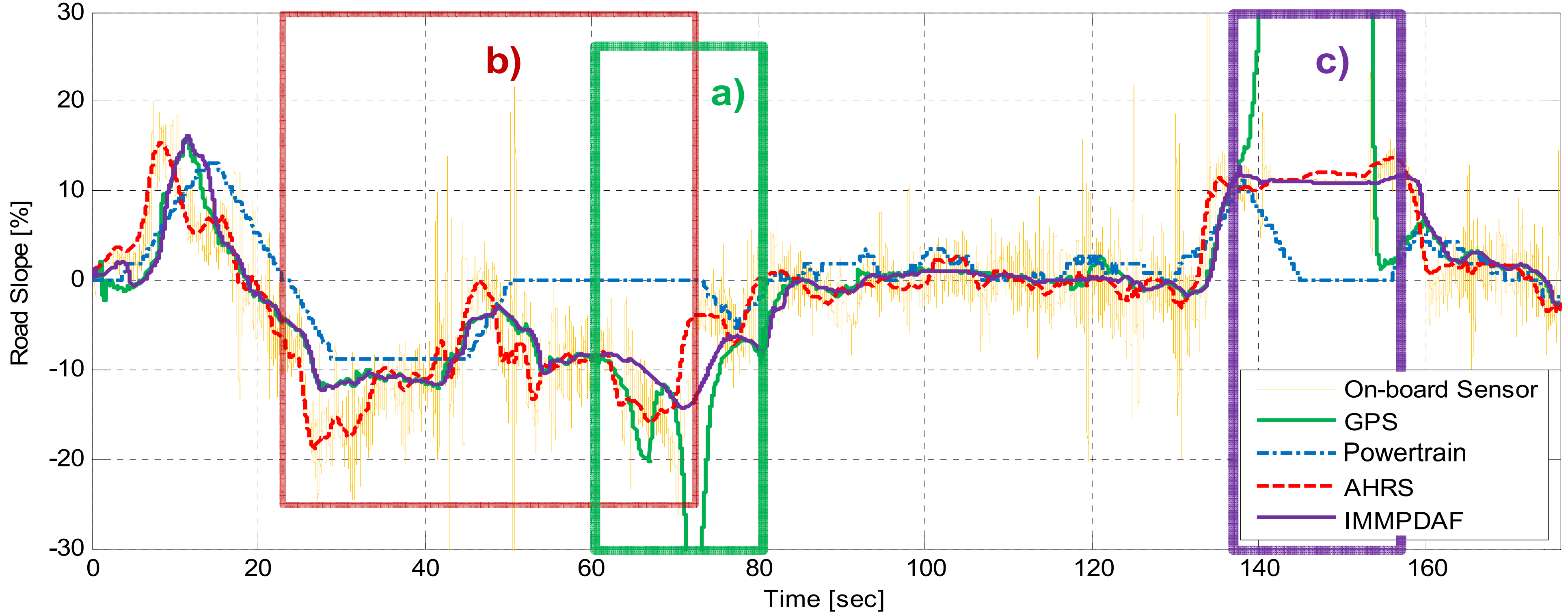
# Experiments – Poor Measuring Condition (I)

- **Test site – Hanyang University**



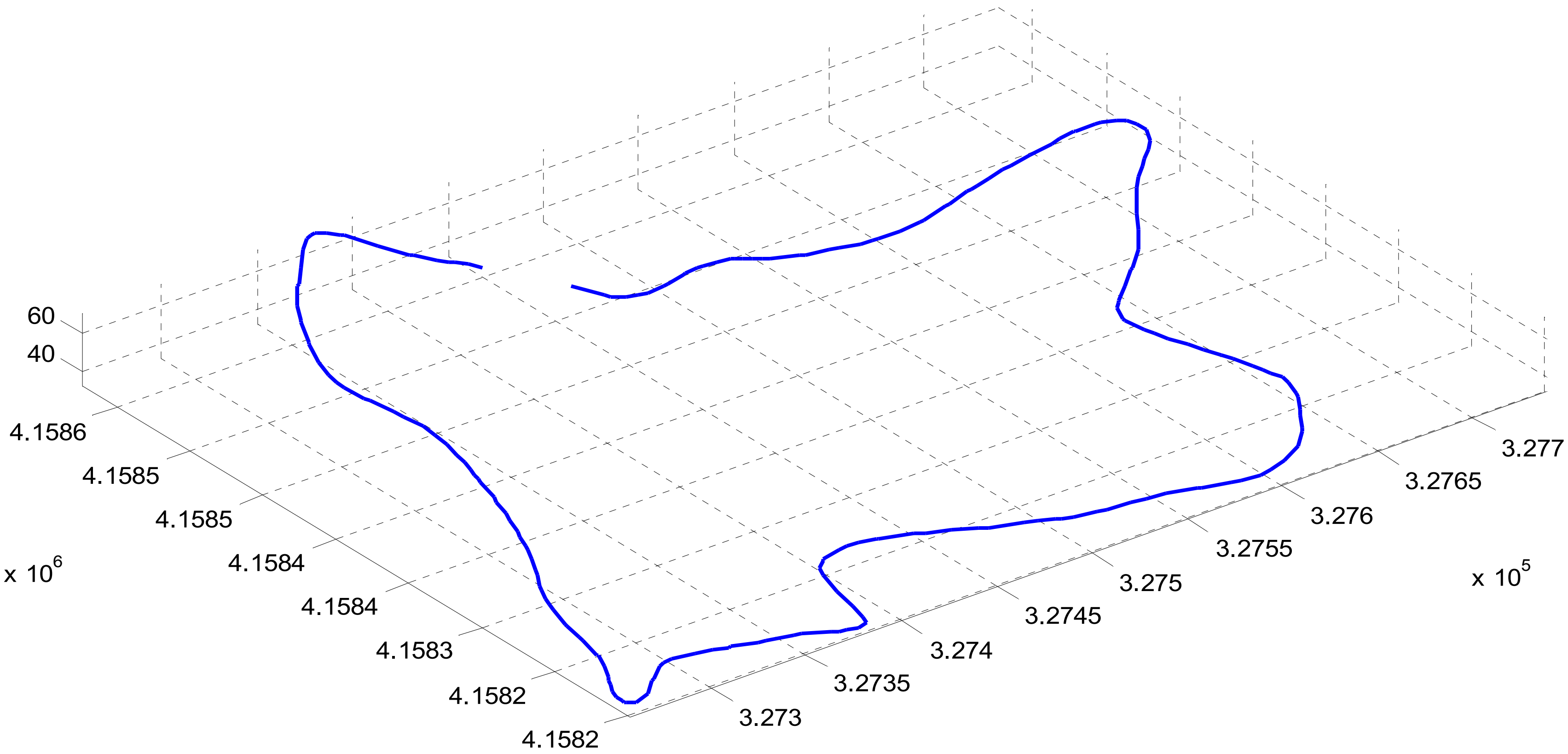
# Experiments – Poor Measuring Condition (II)

## ■ Estimation results



# 3D Road Map Generation

- **3D road map can provides future condition of road slope to the energy management system in order to generate optimal driving strategy**



# Conclusion

- A real-time road slope estimation algorithm based on information fusion of GPS, on-board sensors, and powertrain force is proposed to apply for the energy management system of electric vehicles

- The proposed information fusion algorithm can improve accuracy and reliability of the road slope estimate based on the IMMPDA filter

- Road slope estimated from the suggested estimation algorithm is used for 3D map generation

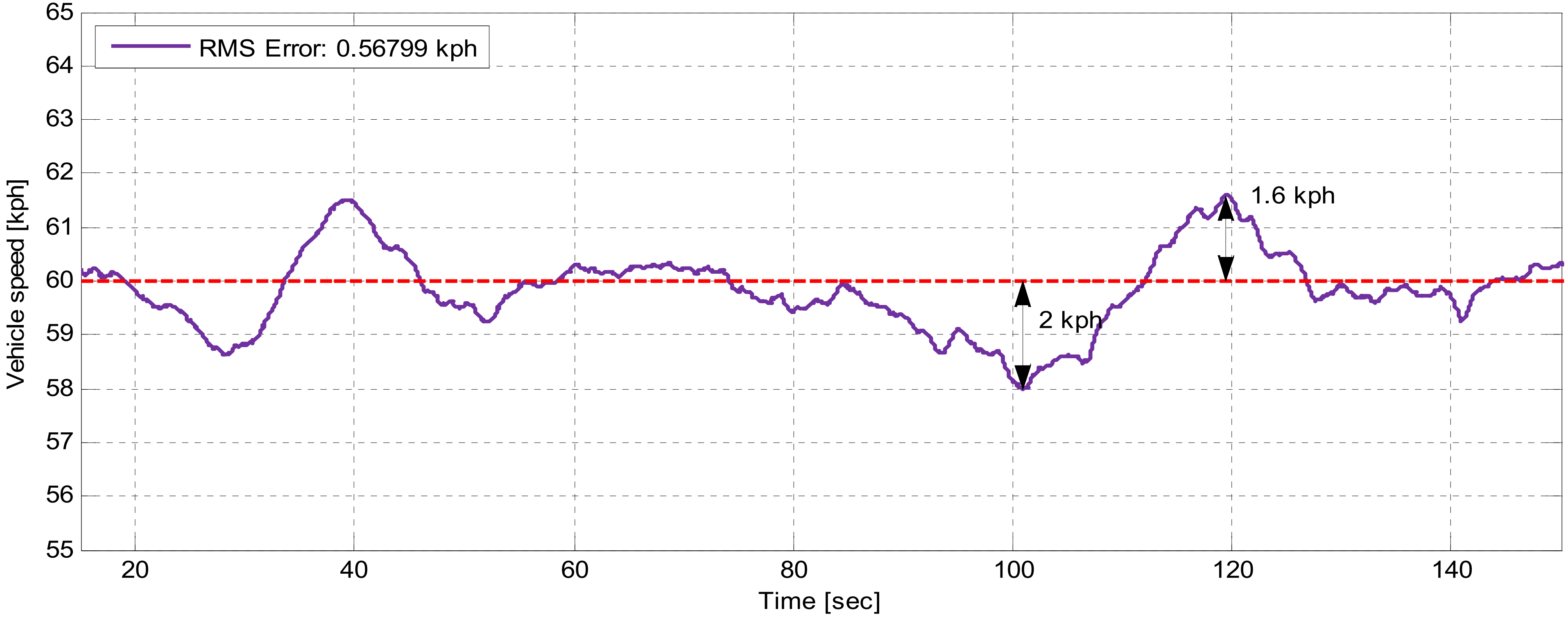
- The generated 3D map can provide predicted information of road slope to energy management system in order to generate optimal driving strategy

# Thank you for your attention.

# Case Studies

# Speed Control of Autonomous Car *A1*

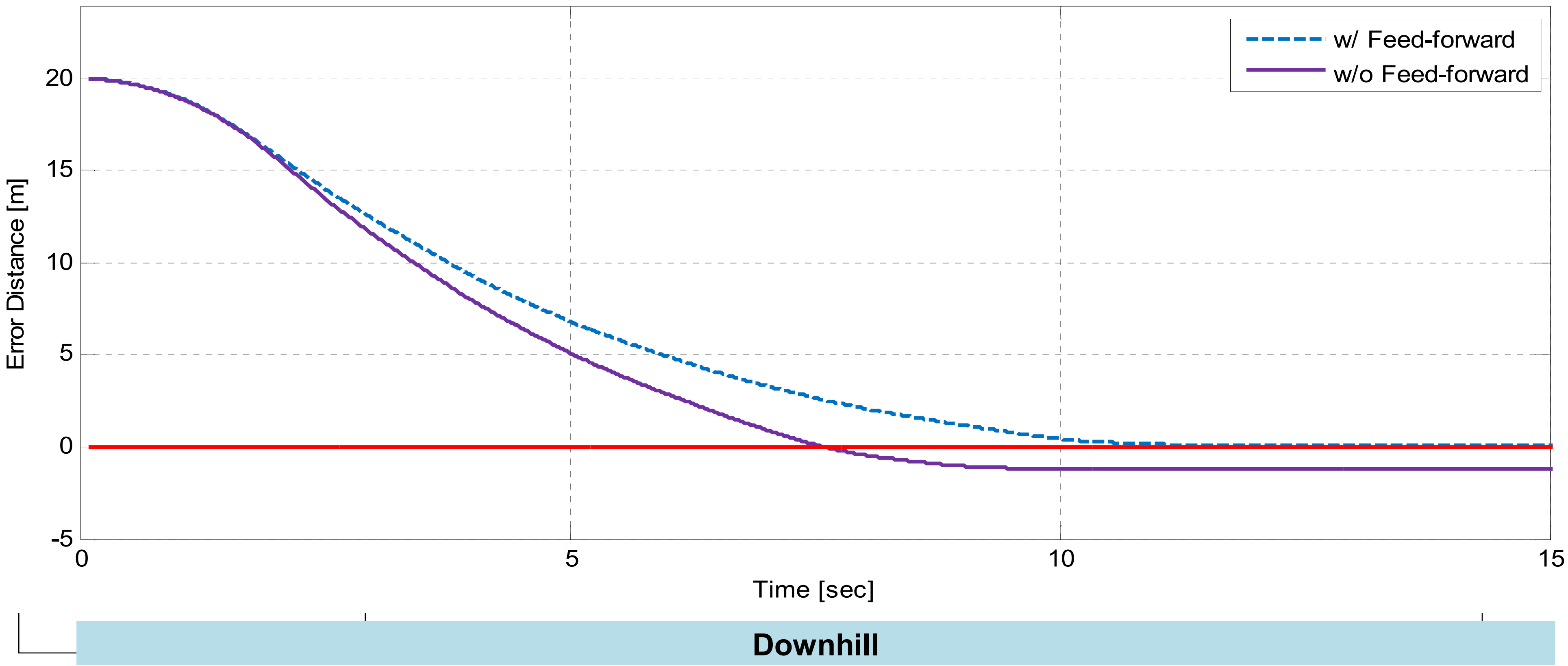
## ■ In the Variable Slope Condition




**With Road Slope Compensator**

# Distance Control of Autonomous Car *A1*

## In the Variable Slope Condition



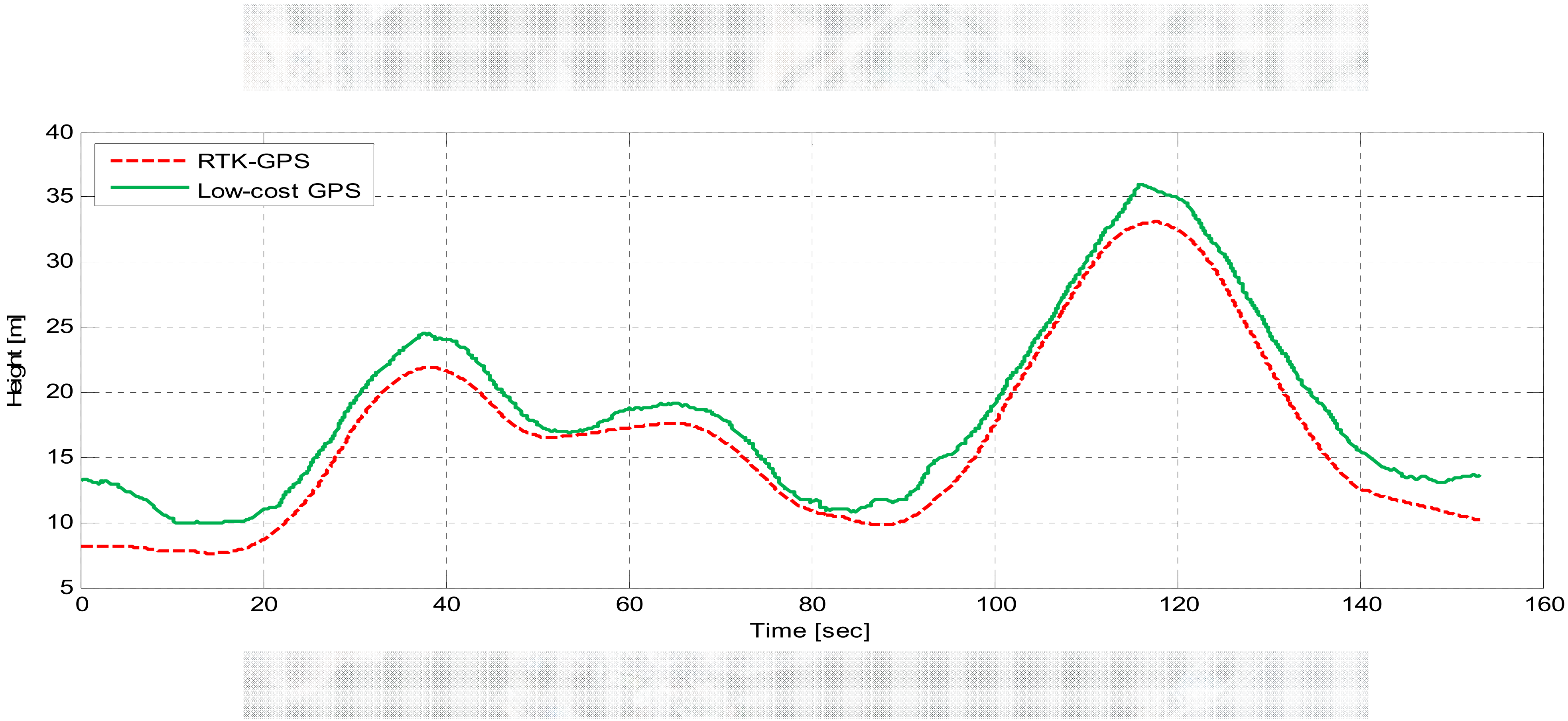
# Previous Studies

- Ohnishi, Hiroshi, et al.,
  "A study on road slope estimation for automatic transmission control," in 2000 JSAE Review
  → On-board sensor based estimation

- Peng, H., et al.,
  "Recursive least squares with forgetting for online estimation of vehicle mass and road grade: Theory and experiments," in 2005 Vehicle System Dynamics
  → Power-train model based estimation

- Bae, H. S., et al.,
  "Road grade and vehicle parameter estimation for longitudinal control using GPS," in 2001 IEEE IV
  → GPS based estimation

- **Test Site – Mountain Roads in Yeonjong Island**

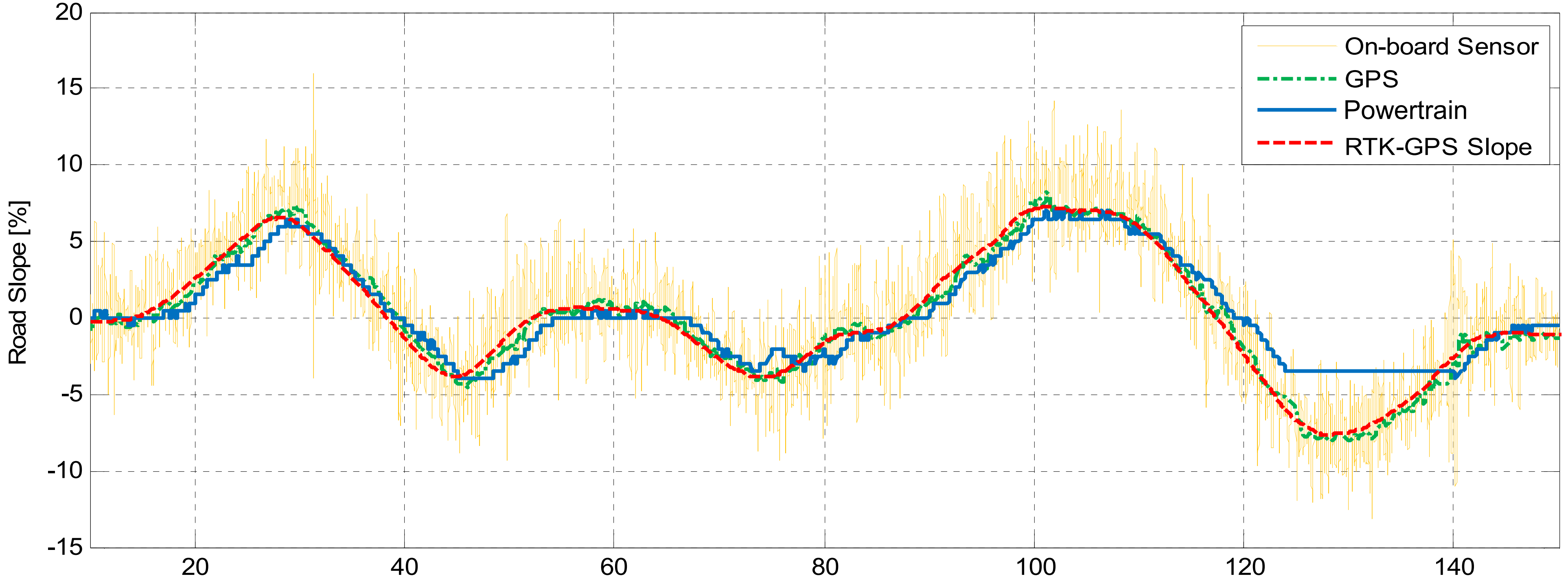



**Test Site**

# Experiments – Variable Slope Condition (II)

## Information Sources for Road Slope

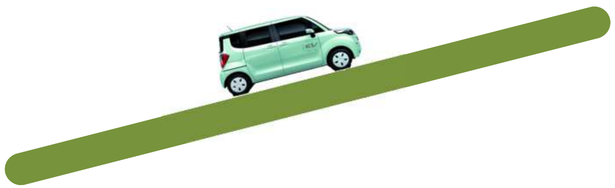
- On-board Sensors
- GPS
- Powertrain Model

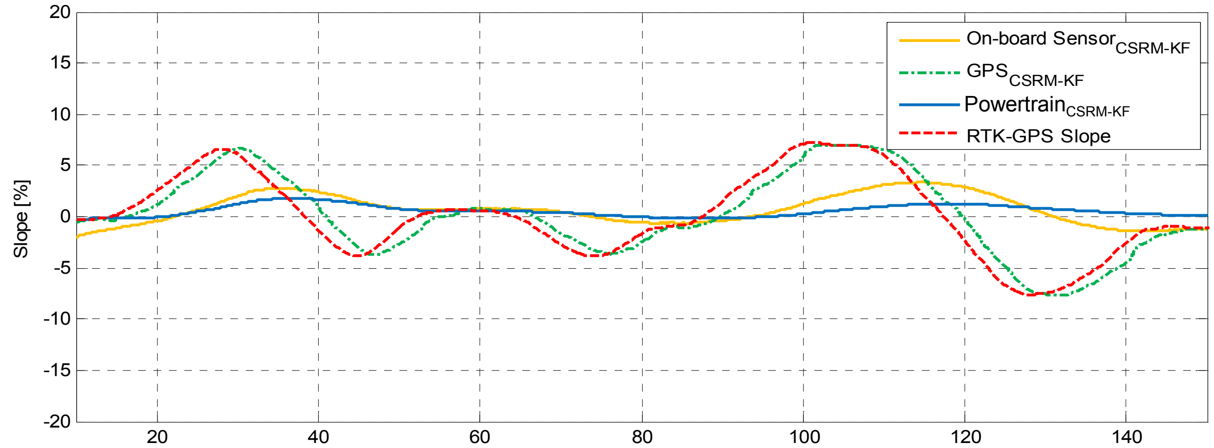


# Experiments – Variable Slope Condition (III)

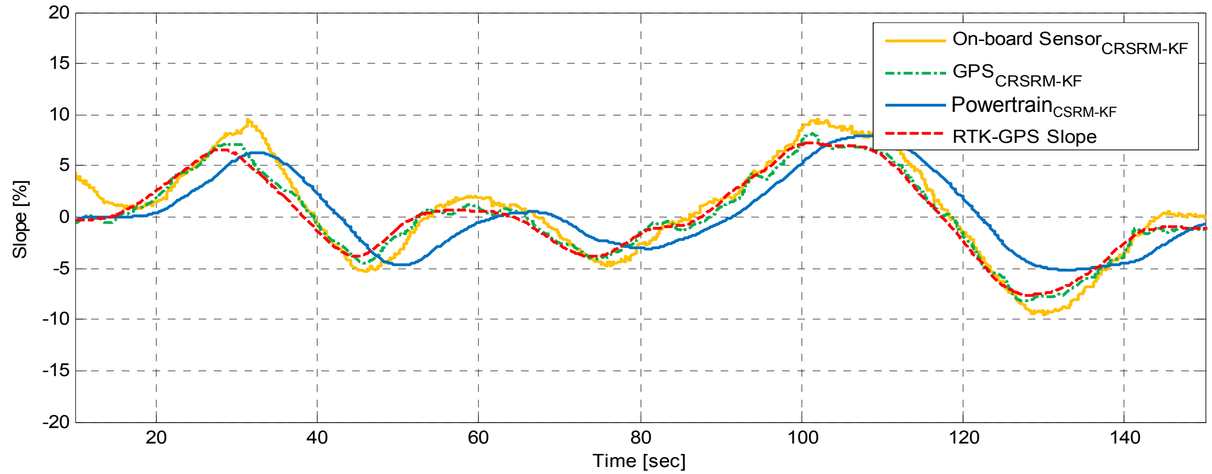
## Slope Estimation with Single-Model Kalman Filter

**Constant Slope Model**



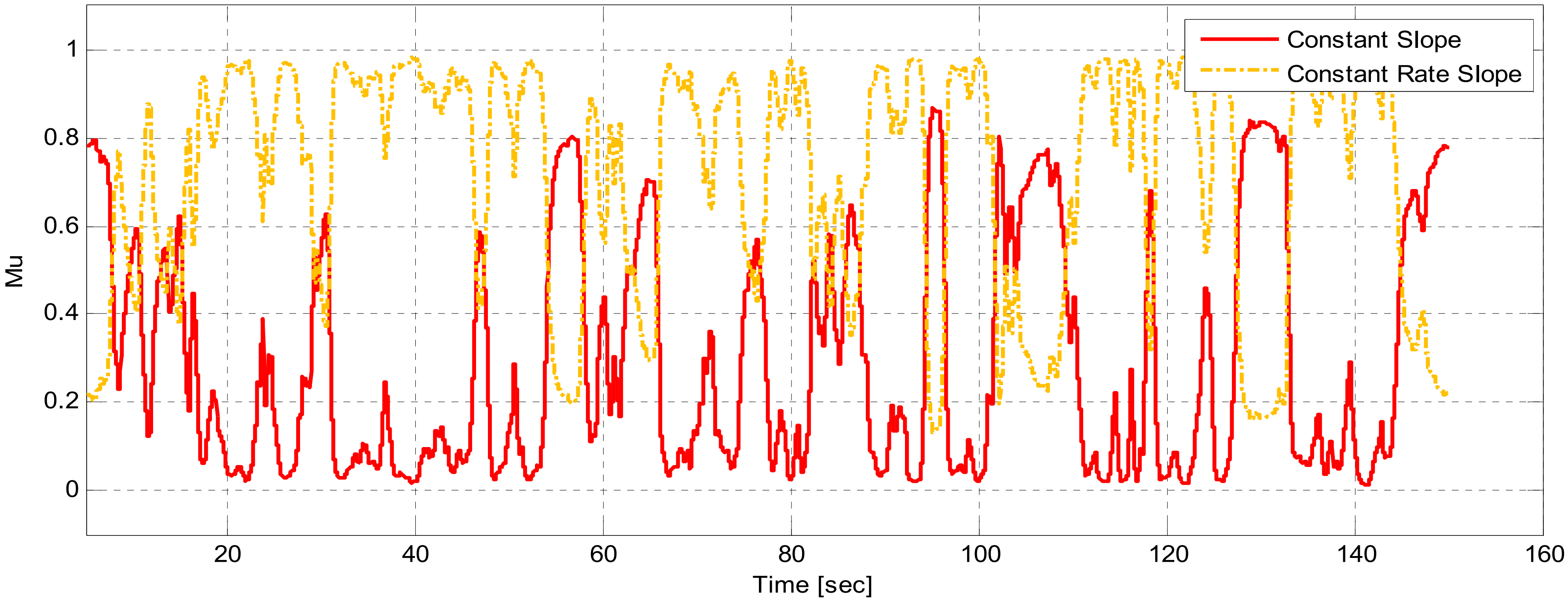



**Constant Rate Slope Model**



# Experiments – Variable Slope Condition (IV)

## Slope Estimation with IMMPDA Filter



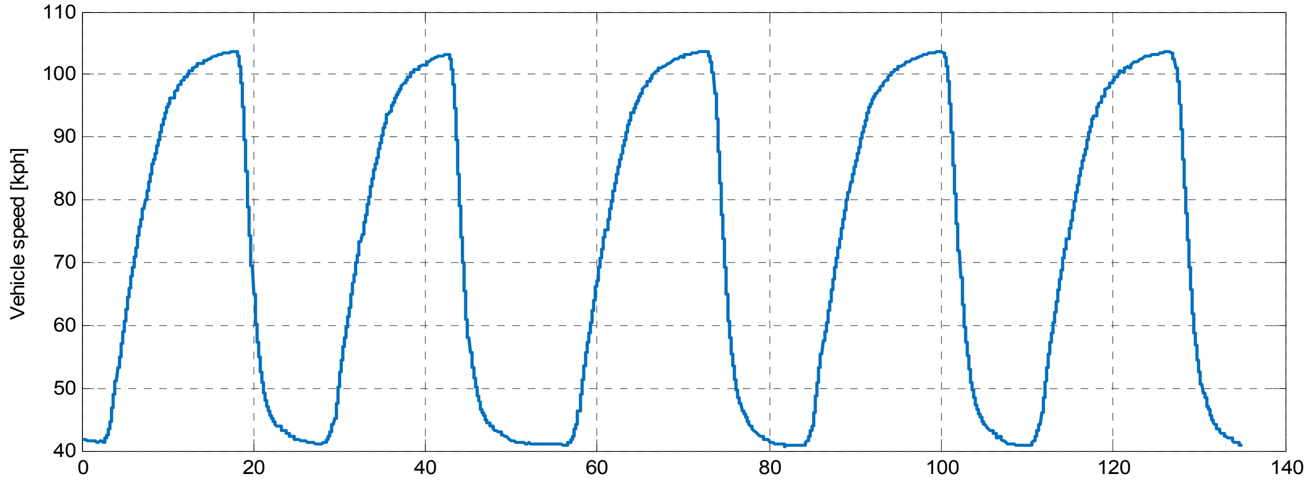

**Model Probability of the IMMPDA filter**

| On-board | GPS | PT | On-board CSRM KF | GPS CSRM KF | PT CSRM KF | On-Board CRSRM KF | GPS CRSRM KF | PT CRSRM KF | CSRM PDAF | CRSRM PDAF | IMM-PDAF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.01 | 1.15 | 1.43 | 3.58 | 1.57 | 3.01 | 2.49 | 1.05 | 2.41 | 2.88 | 1.05 | 1.04 |

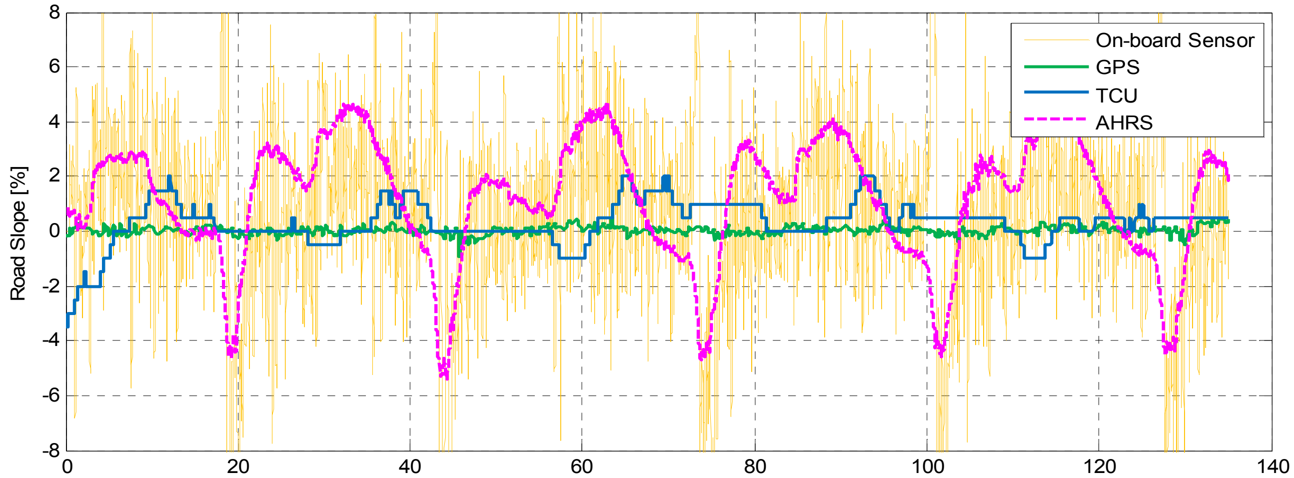
# Experiments – Large Pitch Condition (I)

## Large Pitch Condition on the Flat Road

Vehicle Speed



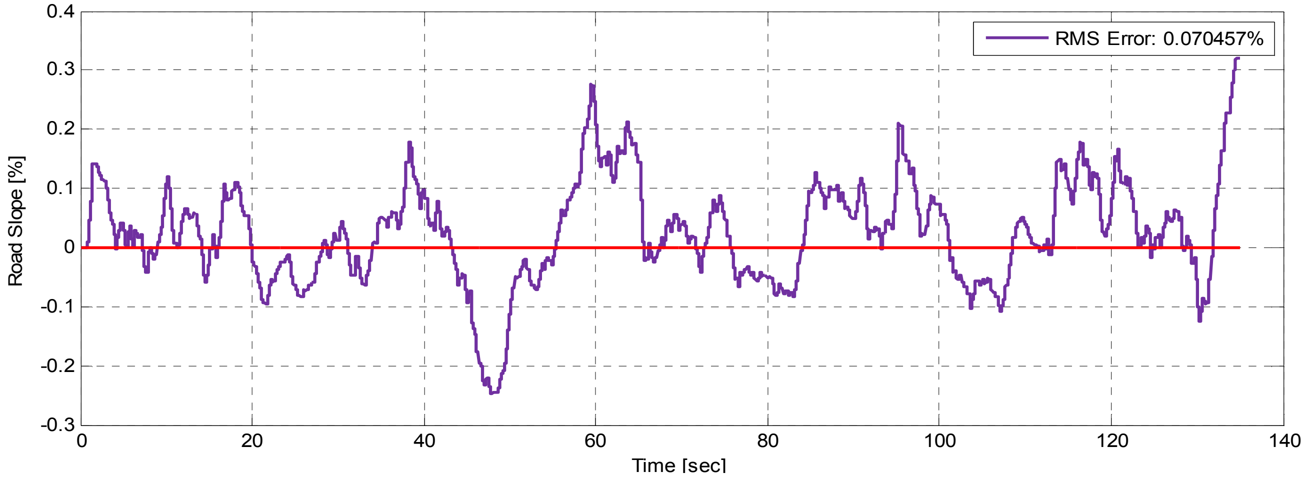

Measurements



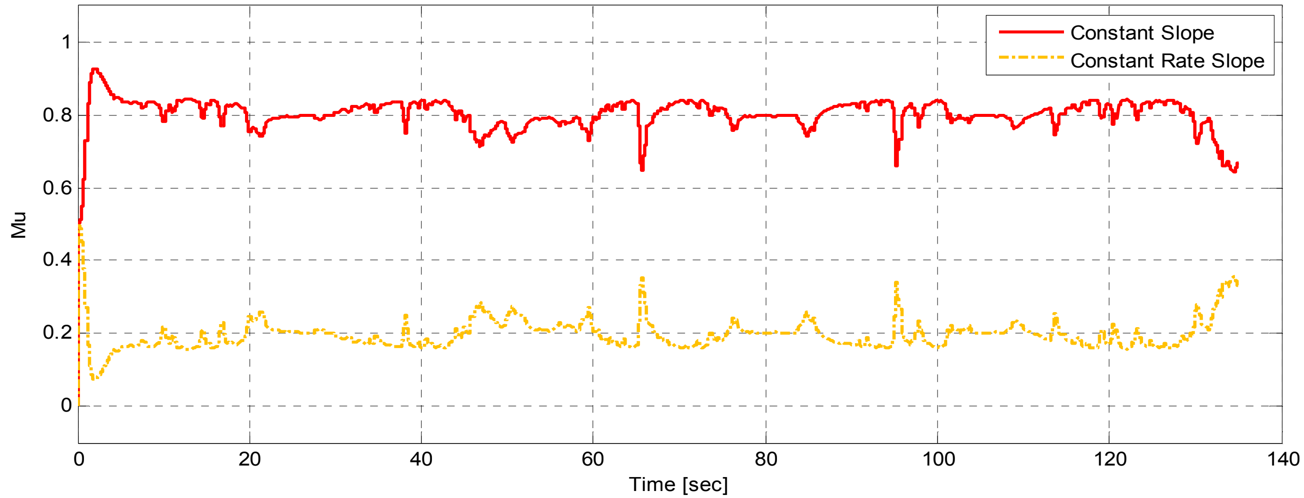
# Experiments – Large Pitch Condition (II)

## Large Pitch Condition on the Flat Road

**RMS Error**




**Model Probability**



# 3D map construction based on road slope information

# Map Generation Based on Optimal Smoothing (I)

## 1. System Model

$$x_k = F_{k-1}x_{k-1} + G_{k-1}u_{k-1} + w_{k-1} \qquad \text{where } w_{k-1} \sim \left(0, Q_k\right)$$

$$y_k = H_k x_k + v_k \qquad \text{where } v_{k-1} \sim \left(0, R_k\right)$$

## 2. Initialize the forward filter

$$\hat{x}_0^f = E\left(x_0\right), \quad P_0^f = E\left[\left(x_0 - \hat{x}_0^f\right)\left(x_0 - \hat{x}_0^f\right)^T\right]$$

## 3. Execute the standard forward Kalman filter, K = 1, … ,N

$$\hat{x}_k^{f-} = F_{k-1}\hat{x}_{k-1}^{f+}$$

$$P_k^{f-} = F_{k-1}P_{k-1}^{f+}F_{k-1}^T + Q_{k-1}$$

$$K_k^f = P_k^+ H_k^T R_k^{-1}$$

$$\hat{x}_k^{f+} = \hat{x}_k^{f-} + K_k^f\left(y_k - H_k\hat{x}_k^{f-}\right)$$

$$P_k^{f+} = \left(I - K_k H_k\right)P_k^{f-}$$

## 4. Initialize the RTS smoother

$$\hat{x}_N^b = \hat{x}_N^f, \quad P_N^b = P_N^f$$

## 5. Execute the RTS smoother, K = N-1, … ,0

$$K_k = P_k^{f+}F_k^T\left(P_{k+1}^{f-}\right)^{-1}$$

$$\hat{x}_k = \hat{x}_k^{f+} + K_k\left(\hat{x}_{k+1} - \hat{x}_{k+1}^{f-}\right)$$

$$P_k = P_k^{f+} - K_k\left(P_{k+1}^{f-} - P_{k+1}\right)K_k^T$$

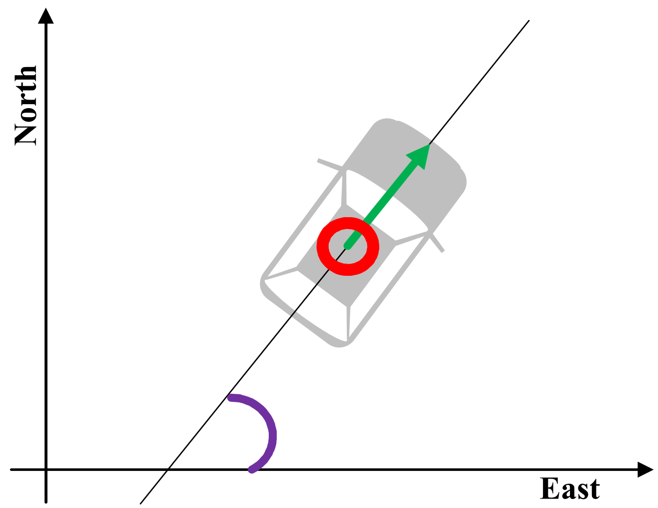
# Map Generation Based on Optimal Smoothing (II)

## System model

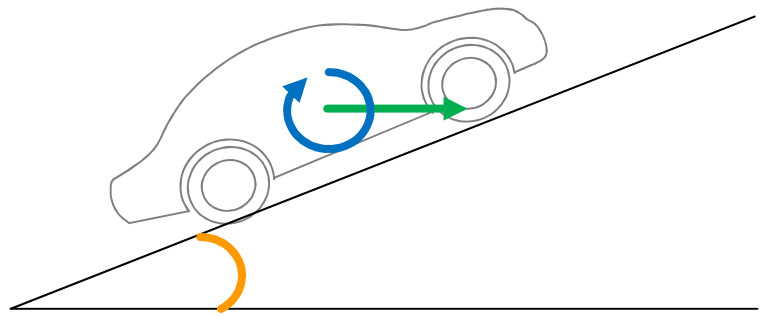
$$x_k = f_{k-1}\left(x_{k-1}, u_{k-1}\right)$$

- $x_1 \rightarrow a_{XY_k} = a_{XY_{k-1}}$
- $x_2 \rightarrow V_{XY_k} = V_{XY_{k-1}} + T \cdot a_{XY_{k-1}}$
- $x_3 \rightarrow q_k = q_{k-1}$
- $x_4 \rightarrow \theta_k = \theta_{k-1} + T \cdot q_{k-1}$
- $x_5 \rightarrow \psi_k = \psi_{k-1} + T \cdot r_{gyro}$
- $x_6 \rightarrow X_k = X_{k-1} + T \cdot V_{XY_{k-1}} \cos\left(\psi_{k-1}\right)$
- $x_7 \rightarrow Y_k = Y_{k-1} + T \cdot V_{XY_{k-1}} \sin\left(\psi_{k-1}\right)$
- $x_8 \rightarrow Z_k = Z_{k-1} + T \cdot V_{XY_{k-1}} \tan\left(\theta_{k-1}\right)$

*Horizontal Alignment*




*Vertical Alignment*



# Map Generation Based on Optimal Smoothing (III)

## Measurement model

$$y_k = h_{k-1}(x_{k-1})$$

$$y_1 \rightarrow \sqrt{V_{X,GPS_k}{}^2 + V_{Y,GPS_k}{}^2} = \hat{V}_{XY_k}$$

$$y_2 \rightarrow \tan^{-1}\left(\frac{V_{Y,GPS_k}}{V_{X,GPS_k}}\right) = \hat{\psi}_k$$

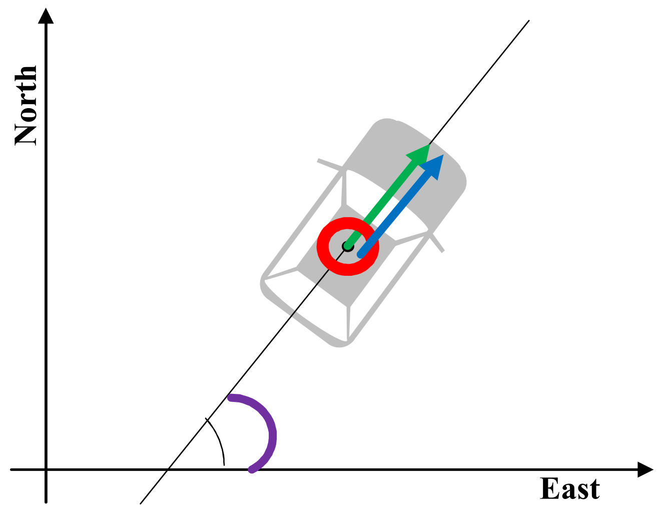
$$y_3 \rightarrow \theta_{InfomrationFusion} = \hat{\theta}_{k-1}$$

$$y_4 \rightarrow X_{GPS_k} = \hat{X}_k$$

$$y_5 \rightarrow Y_{GPS_k} = \hat{Y}_k$$

$$y_6 \rightarrow Z_{GPS_k} = \hat{Z}_k$$

Horizontal Alignment




Vertical Alignment