Driver Characteristics based Deceleration Model for Smart Regenerative Braking System

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15 November, 2018

ACE Lab control hub

HANYANG UNIVERSITY

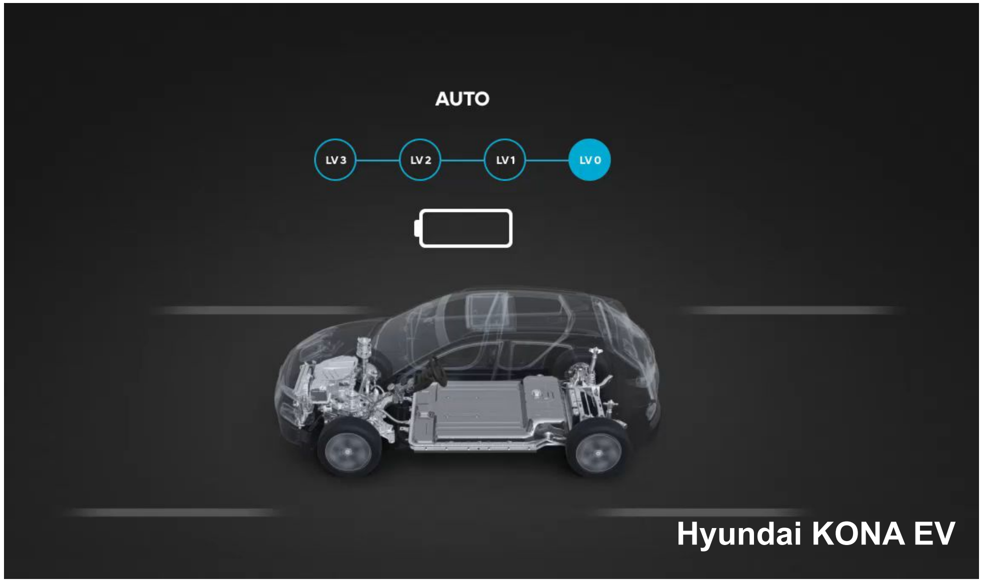
Hanyang University

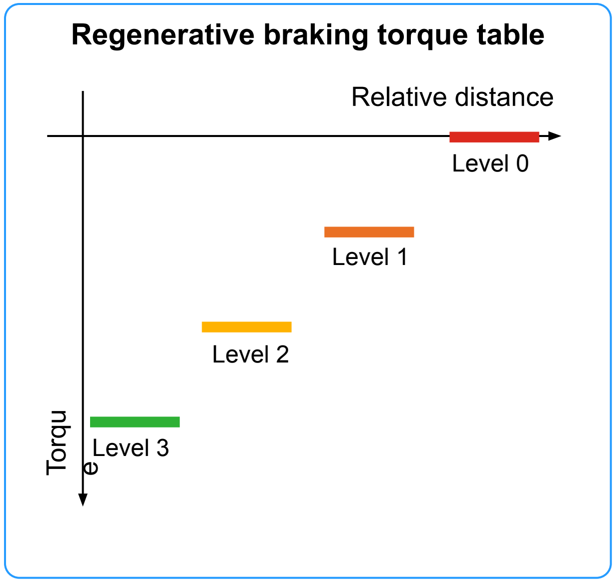
One of the Largest Engineering Schools in Korea (As of the year 2017)

- 476 faculty staff in Engineering including 258 tenure track faculty
- 5300 undergraduate students
- 2300 graduate students
- 390 foreign students

Contents

- **Smart regenerative braking system of the electric vehicle**
  - Automatic control of the regenerative braking according to the driving condition to improve the driving convenience



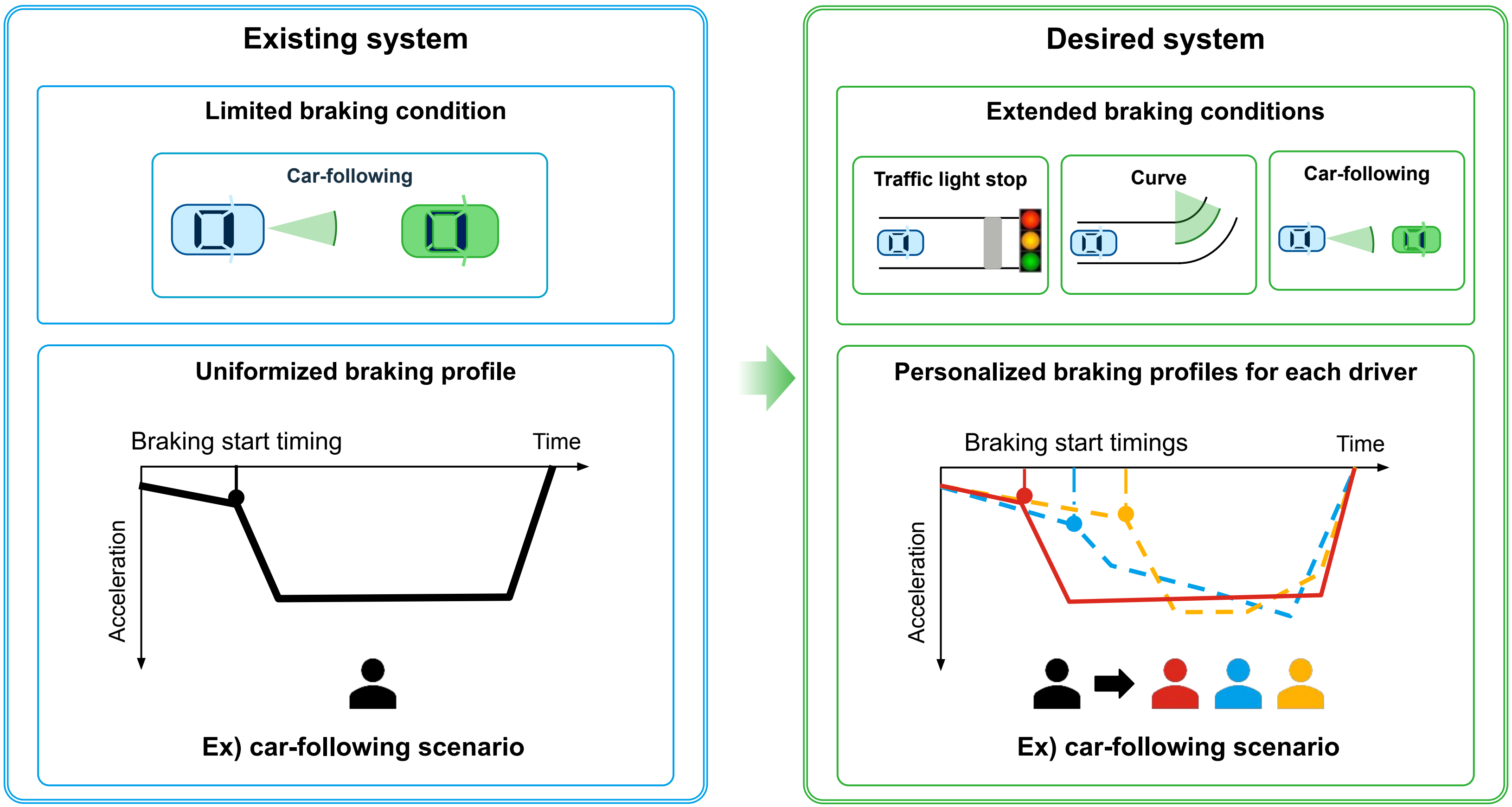


***Example: Smart regenerative braking system in the car-following condition**

Research background (II)

■ The necessity of deceleration model

- ► Extension of the braking conditions: traffic light, curve, car-following
- ► Reflection of the driver characteristics to the braking profile

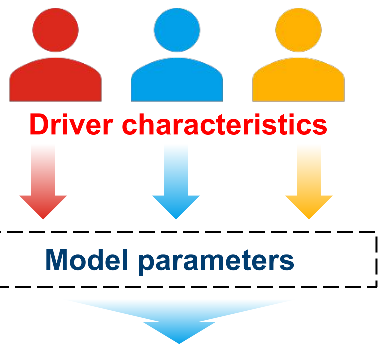


Research objectives

- **Design of the parametric deceleration model based on driver characteristics using intelligent driver model**

Parametric deceleration model

Model equation

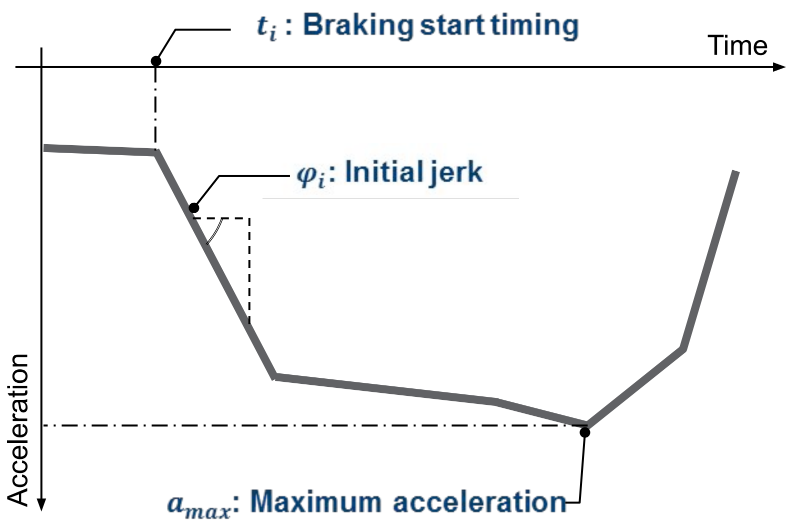


$$a = a_m\left(1-\left(\frac{v}{v_{ref}}\right)^{\delta}-\left(\frac{d_{eff}}{d}\right)^{2}\right)$$

$v_{ref}: f(model\ parameters)$

$d_{eff}: f(model\ parameters)$

Deceleration profile prediction



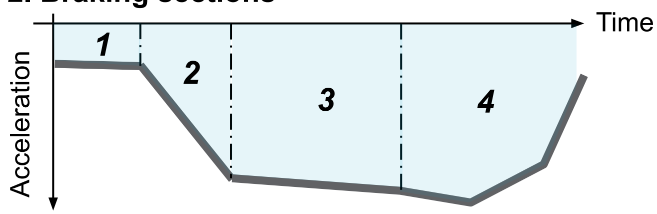
Parametric deceleration model

Overall structure

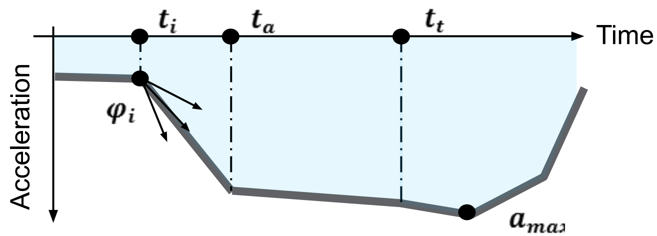
1. Framework

$$a = a_m\left(1-\left(\frac{v}{v_{ref}}\right)^{\delta}-\left(\frac{d_{eff}}{d}\right)^{2}\right)$$

2. Braking sections



3. Model parameters

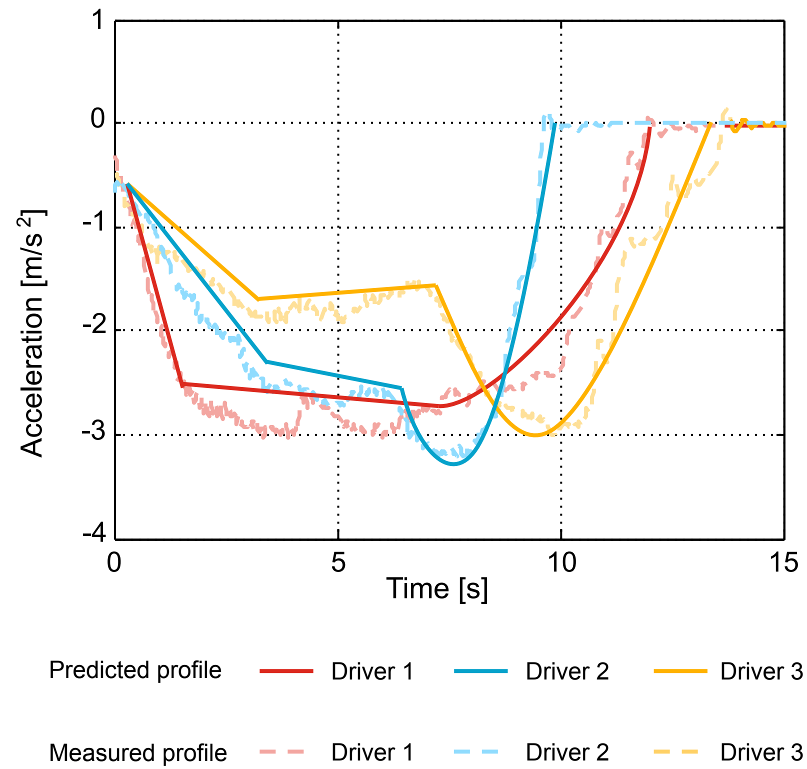


4. Prediction of deceleration profiles

$$a = a_m\left(1-\left(\frac{v}{v_{ref}}\right)^{\delta}-\left(\frac{d_{eff}}{d}\right)^{2}\right)$$

$$v_{ref} = f(sections, parameter)$$
$$d_{eff} = f(sections, parameter)$$

▶ Prediction results



■ Parametric deceleration model based on Intelligent Driver Model*

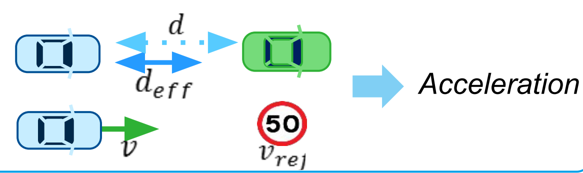
- ► Prediction of acceleration in car-following condition

IDM

Model equation

$$a(k+1) = a_{max}\left(1 - \left(\frac{v(k)}{v_{ref}}\right)^{\delta} - \left(\frac{d_{eff}}{d(k)}\right)^{2}\right)$$

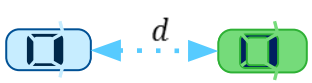
Example



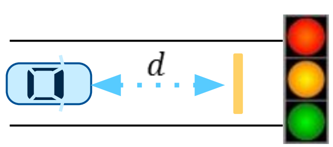
- ► Definition of the distance for each condition to apply the IDM

Deceleration conditions

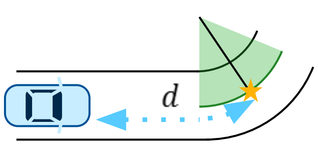
Car-following



Traffic light stop

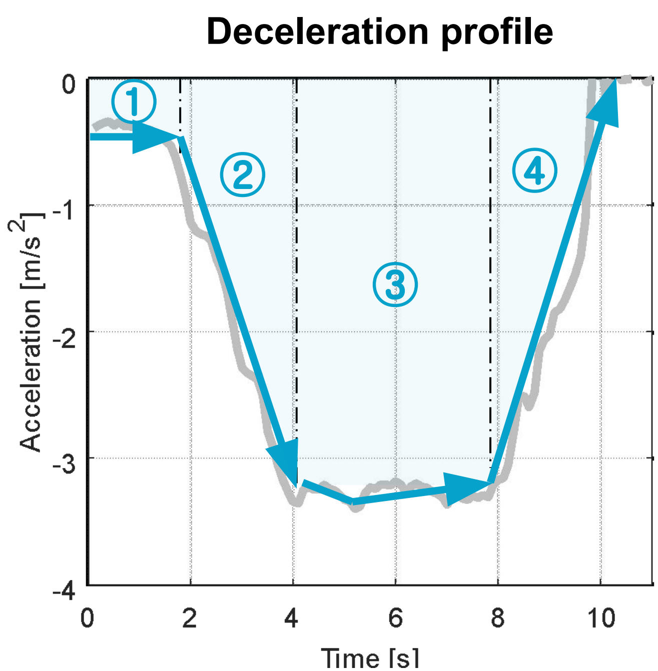


Curve



*Treiber, M., Hennecke, A., and Helbing, D. (2008). Congested Traffic States in Empirical Observations and Microscopic Simulations.

■ Categorization of braking sections to represent braking characteristics



① Coasting section

▶ Time gap of pedal shifting

② Initial section

▶ Step on the brake pedal

③ Adjustment section

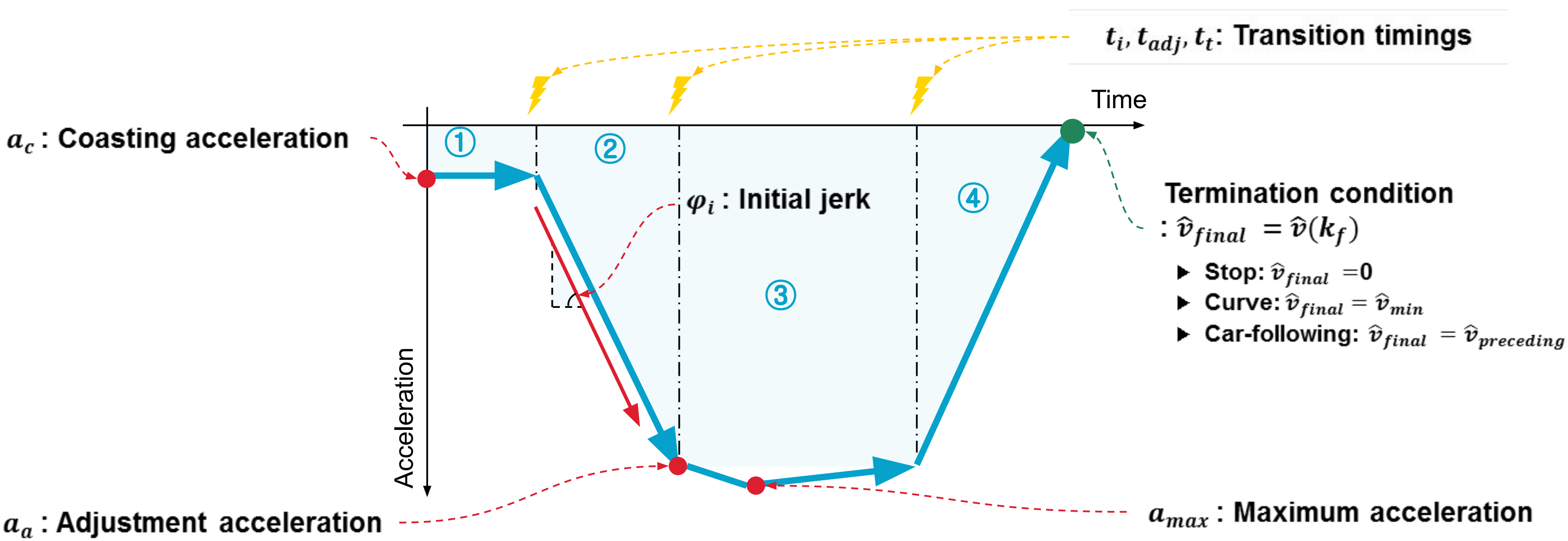
▶ Maintain a braking pedal force to keep the deceleration level

④ Termination section

▶ Control the brake pedal to reach the destination

3. Model parameters

- **Representation of individual driver characteristics**
  - Transition timings of braking sections
  - Acceleration and jerk
  - Termination condition
    - Final velocity condition



4. Prediction of deceleration profiles

① Coasting section

- $d_{eff}(k) = 0,\ v_{ref}(k) = \hat{v}(k)/\left(1 - \frac{a_c}{a_m}\right)^{\frac{1}{\delta}}$

② Initial section

- $d_{eff}(k) = 0,\ v_{ref}(k) = \hat{v}(k)/\Gamma(k)$
- $\Gamma(k) = \left(\Gamma(k-1)^{\delta} - \frac{\varphi_i T_s}{a_m}\right)^{\frac{1}{\delta}}$

③ Adjustment section

- $d_{eff}(k) = \hat{d}(k) + K_a(\hat{a}_{ref}(k) - \hat{a}(k))$
- $v_{ref}(k) = \hat{v}(k)/\left(-\frac{a_a}{a_m}\right)^{\frac{1}{\delta}}$

④ Termination section

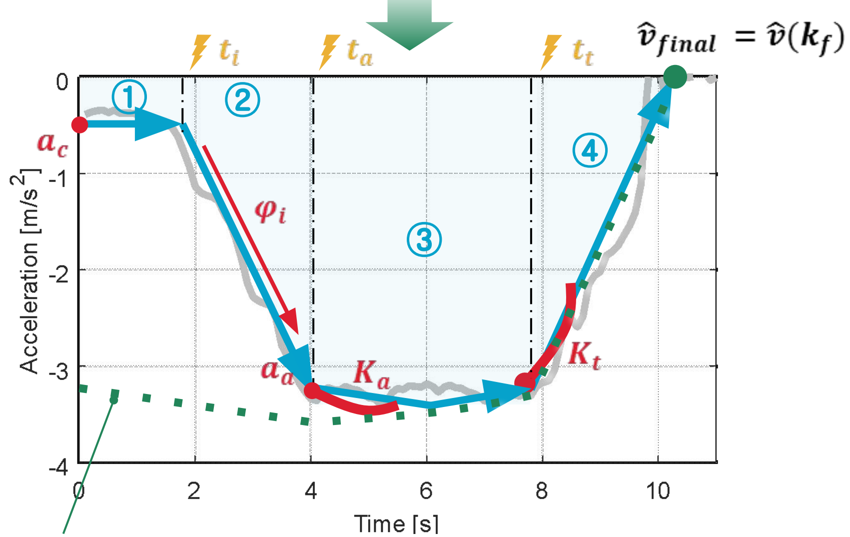
- $d_{eff}(k) = \hat{d}(k) + K_t(\hat{a}_{ref}(k) - \hat{a}(k))$
- $v_{ref}(k) = \hat{v}(k)/\left(-\frac{a_a}{a_m}\right)^{\frac{1}{\delta}}$

$d_{eff}(k)$
$v_{ref}(k)$

Framework: IDM

$$\hat{a}(k+1) = a_m\left(1 - \left(\frac{\hat{v}(k)}{v_{ref}(k)}\right)^{\delta} - \left(\frac{d_{eff}(k)}{\hat{d}(k)}\right)^{2}\right)$$

$$v_{ref}(k) = f(section, parameter)$$
$$d_{eff}(k) = f(section, parameter)$$

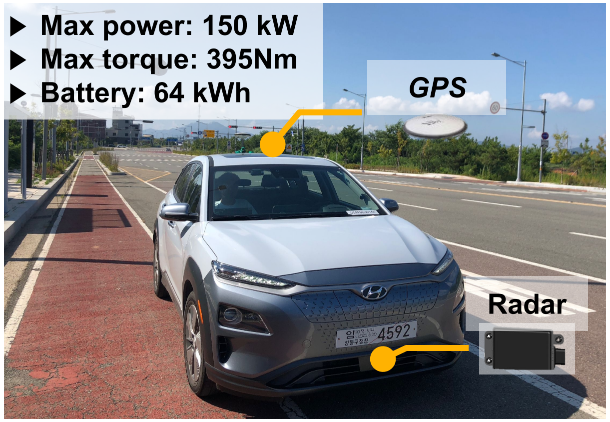


- Guarantee termination condition: $\hat{v}_{final} = \hat{v}(k_f)$
- $\hat{a}_{ref}(k+1) = \frac{\hat{v}_{final}^2 - \hat{v}(k)^2}{2\hat{d}(k)}$, (Constant acceleration model)

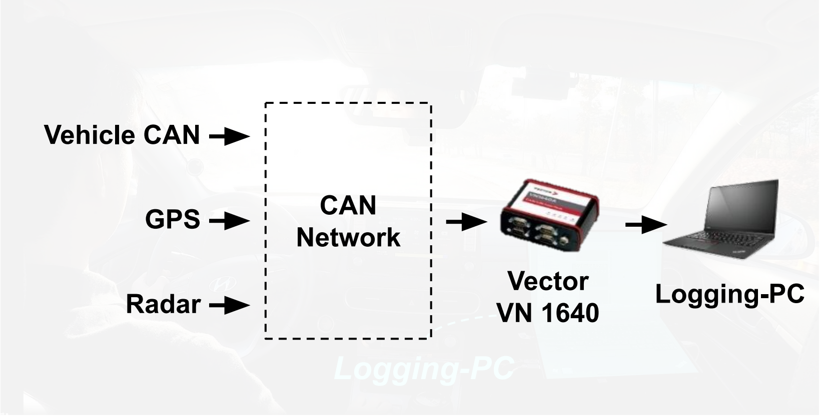
Validation

Simulation environment

■ Vehicle experimental conditions



▶ KONA EV with GPS



▶ Data acquisition environment

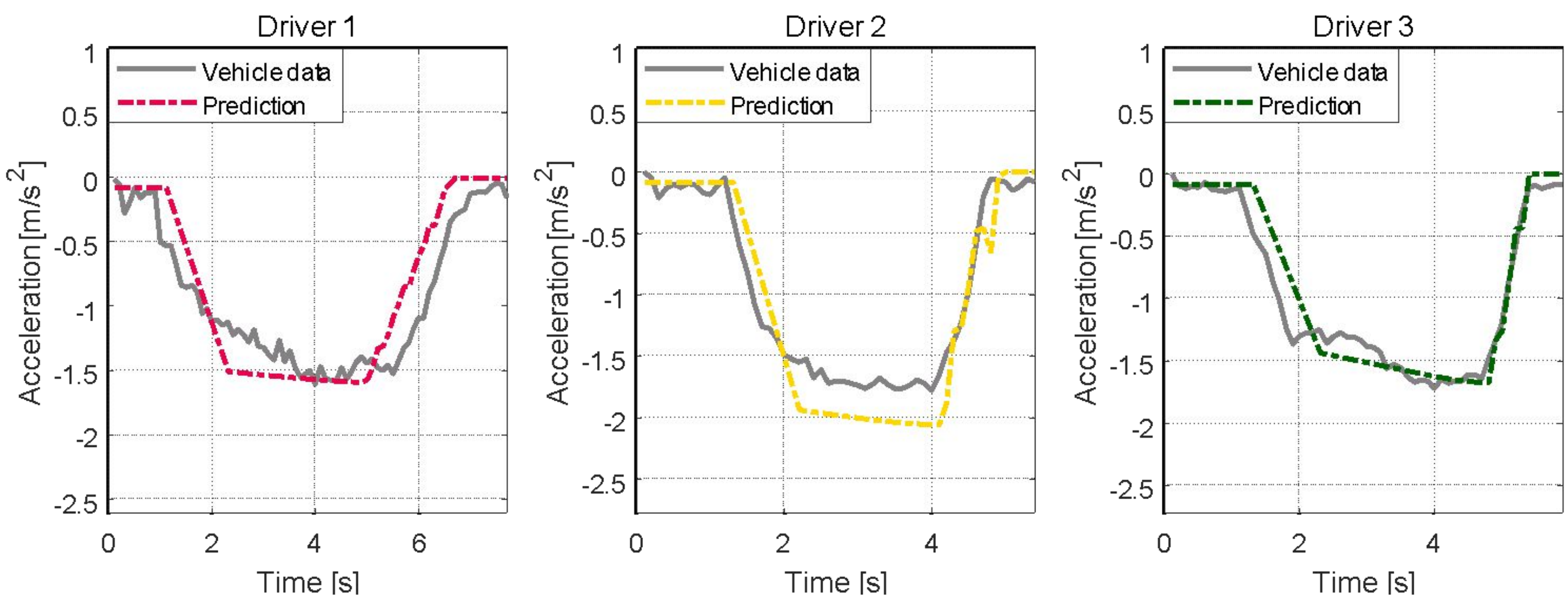
▶ Three test drivers

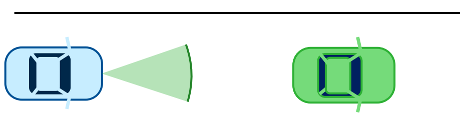
▶ Test site: Incheon, Korea

Modeling results for each condition

■ Comparison between the real-driving data and the prediction results

▶ Car-following

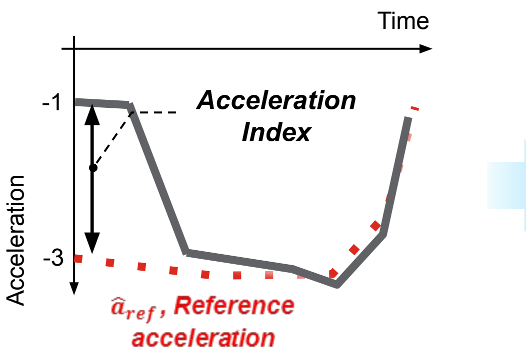




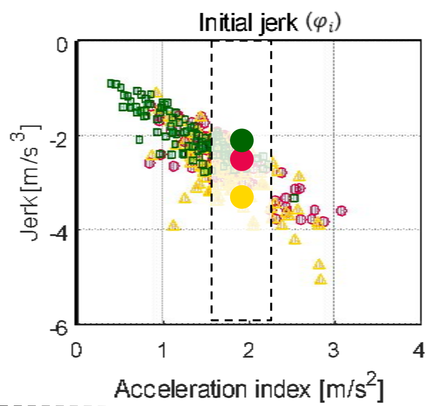
- The number of cases for each driver: 51
- Root Mean Squared Error: 0. 3934 [m/s^2]

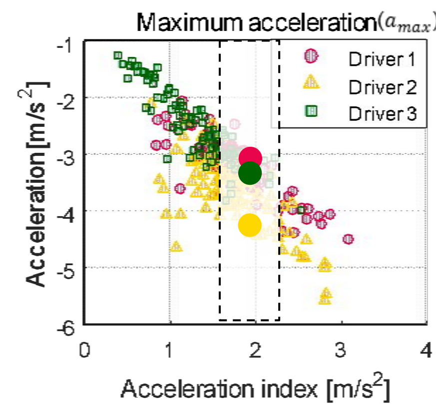
Driver characteristics analysis

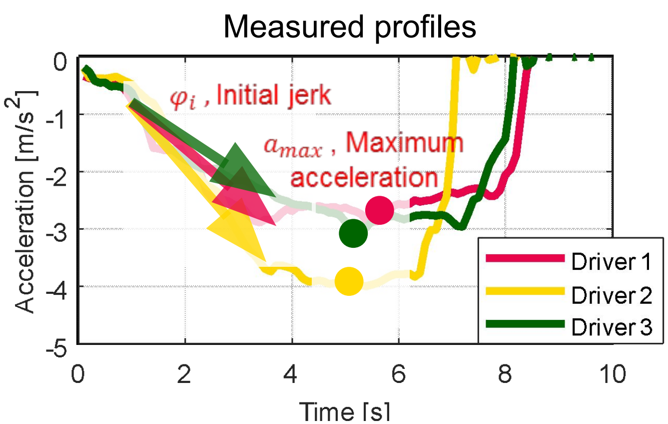
Analysis of the driver characteristics based on model parameters

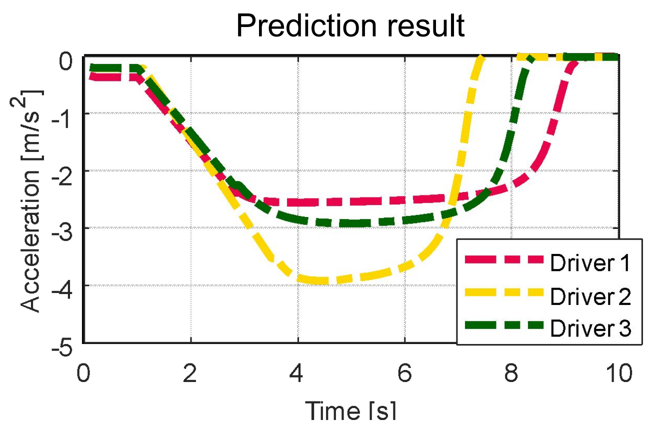


▶ *Indicate the initial deceleration situation*









Conclusion

Conclusion

- **The existing smart regenerative braking system causes discomfort for drivers since it only uses the uniformized braking profile regardless of driver characteristics**

- **Parametric driver model based on intelligent driver model was proposed to predict the personalized deceleration profiles**
  - It can extend the braking conditions
  - It uses several model parameters and braking sections to represent each driver's characteristics

- **The proposed method was evaluated with real driving data and driver characteristics were analyzed**

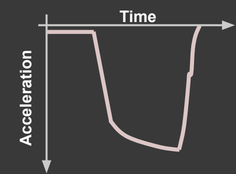
Future work

■ The new smart regenerative braking system overview

Driving state manager

- Determine the driving state based on the on-board sensor and ITS information

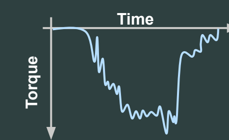
Deceleration model



Car-following
Traffic light
Curve

- Predict personalized deceleration profile for regenerative braking torque control

Regenerative braking torque control



- Control the regenerative braking torque with the reference deceleration profile

Driving state

Reference deceleration profile

Embedded system

Hyundai KONA Electric

- ■ Integrate the algorithm in embedded system
- ■ Validate the new smart regenerative braking system through vehicle tests

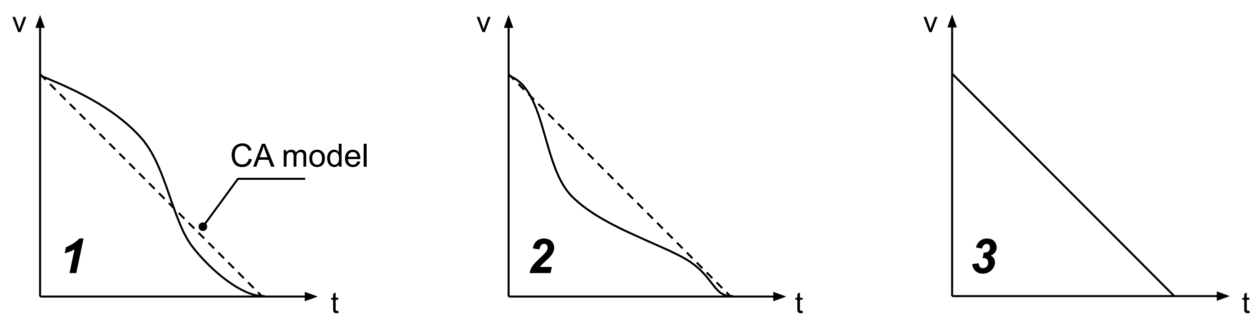
Thank you!

Appendix

Previous research

Analysis of driver characteristics in deceleration

- Braking timings
  - Investigation of braking timing of drivers based on driving style questionnaire
- Speed in curves
  - Design the curve speed model based on acceptable lateral acceleration of each driver
- Braking profiles
  - Deviation from constant acceleration model

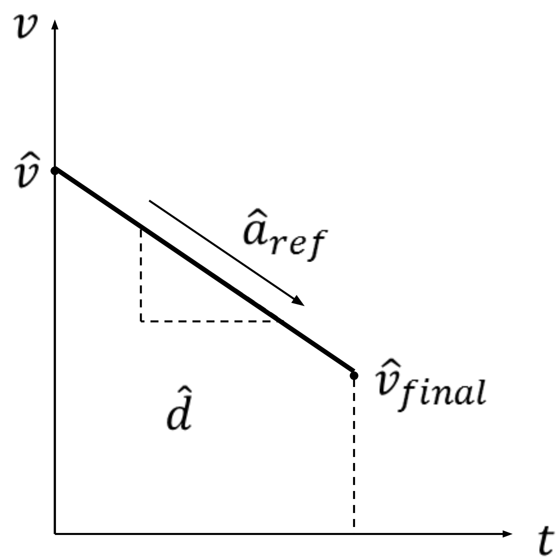


Keisuke Suzuki, Takuya Kakihara, and Yasutoshi Horii. (2016). Investigation of Braking Timing of Drivers for Design of Pedestrian Collision Avoidance System. *J. Mech.*
Reymond, G., Kemeny, A., and Berthoz, A. (2001). Role of Lateral Acceleration in Curve Driving. *Hum. Factors J. Hum.*
Wortman, R. H., and Fox, T. C. (1994). An evaluation of vehicle deceleration profiles. *J. Adv. Transp.*, 28, 3, 203–215.

Reference acceleration

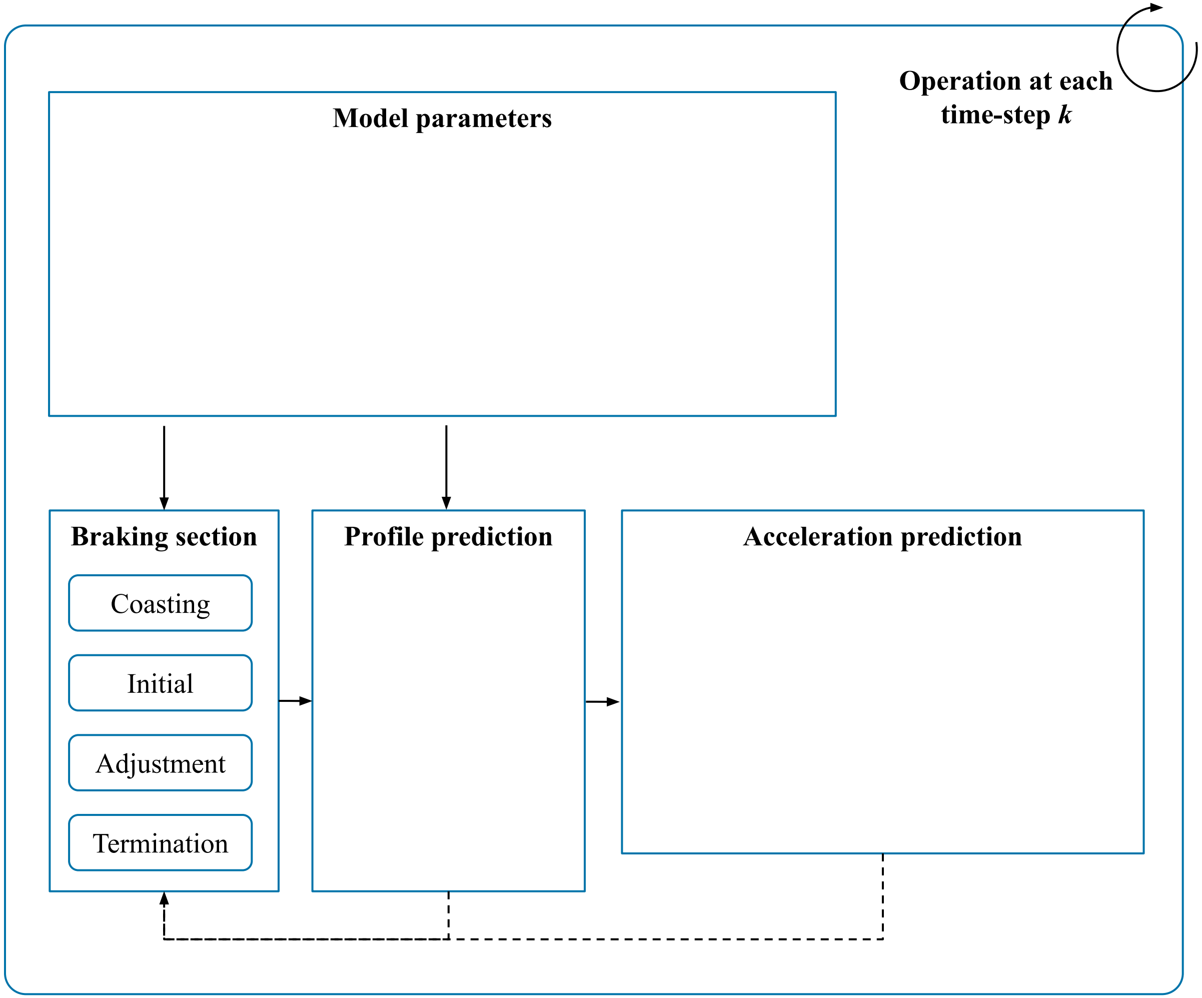
Constant acceleration

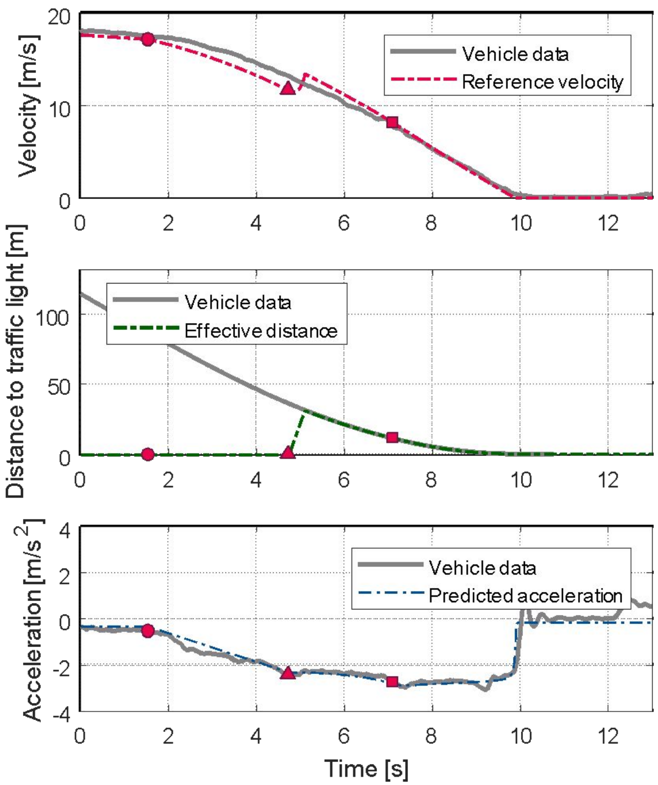
- Acceleration with constant calculated from present velocity and distance
- $\hat{a}_{ref} = \frac{\hat{v}_{final}^2 - \hat{v}^2}{2\hat{d}}$
- $\hat{v}_{final}$
  - Stop: 0
  - Curve: velocity from the acceptable lateral acceleration for each driver
  - Car-following: velocity of preceding vehicle



Prediction process

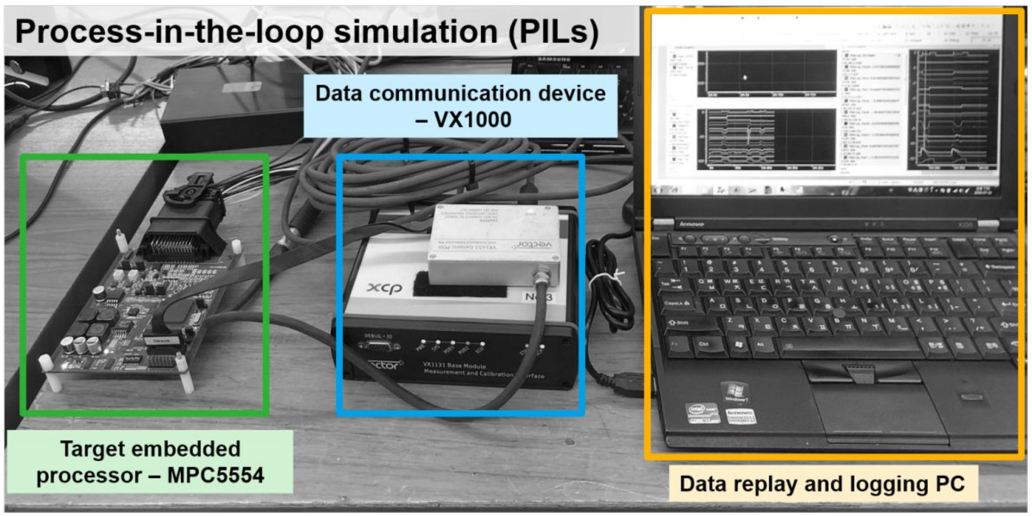
- Profiles update according to **braking sections** and **model parameters**

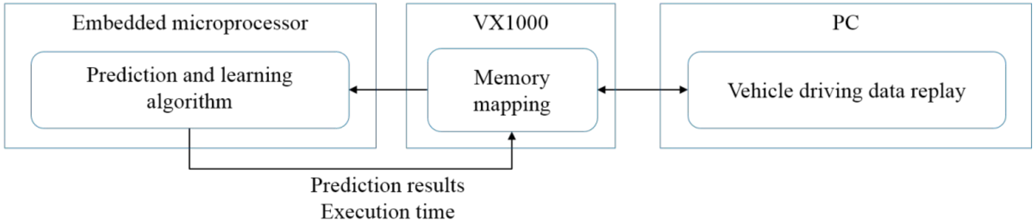




Process in-the-loop simulation (PILS)

- **Verification of real-time performance**
  - Integration to embedded system
  - Embedded system: 32bit microprocessor (NXP)
  - System clock: 256 MHz

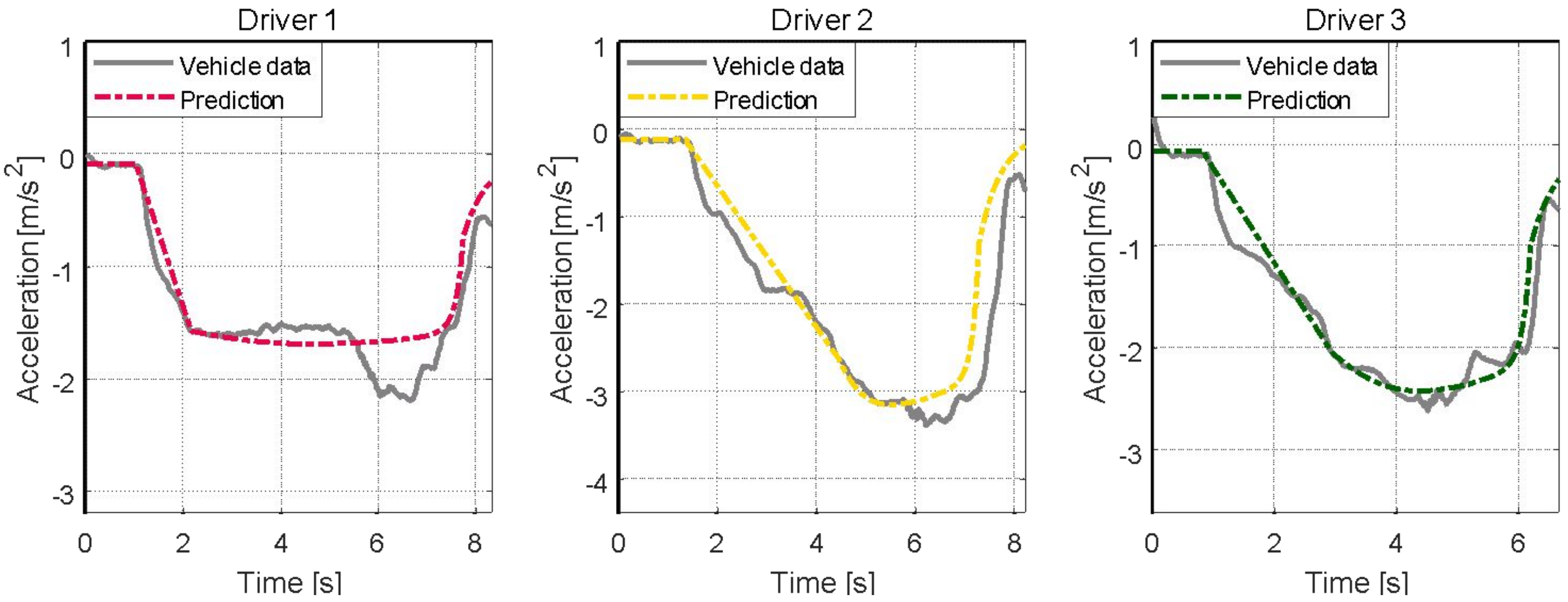


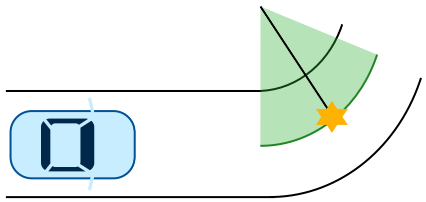


Modeling results for each condition

■ Comparison between the real-driving data and the proposed model

▶ Curve



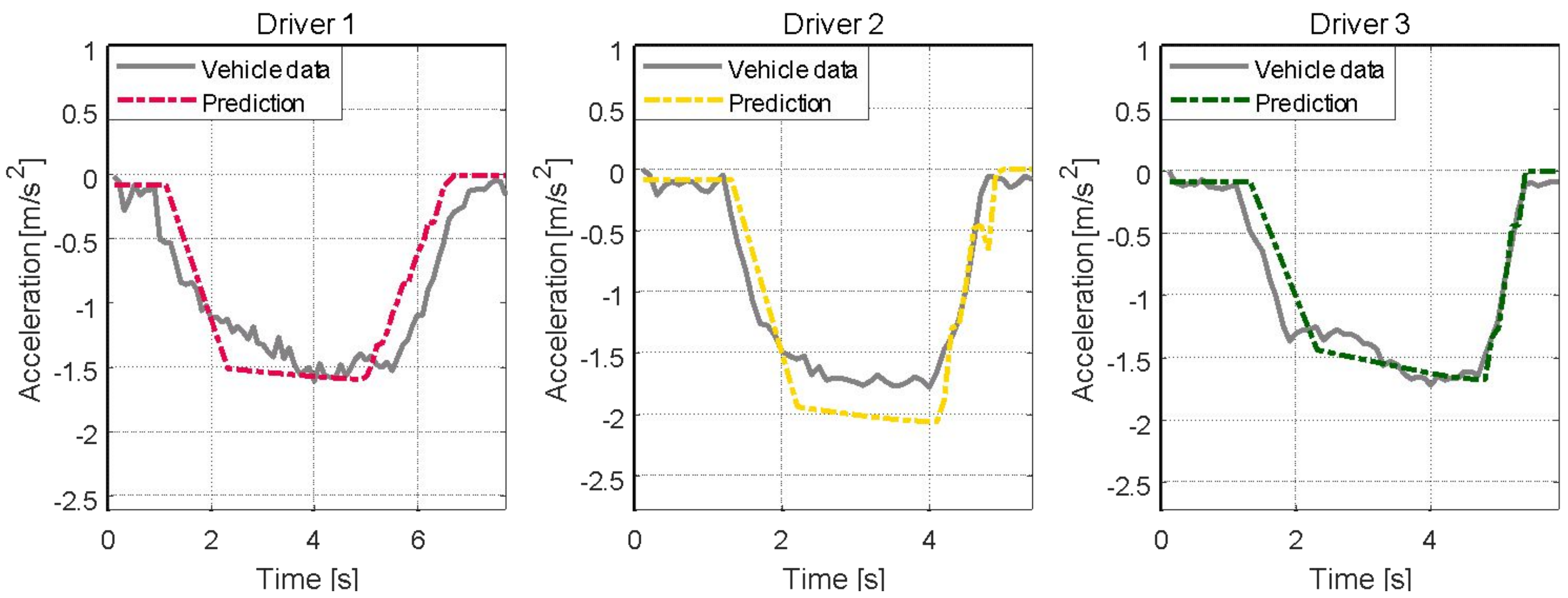


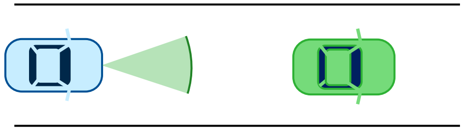
- The number of cases for each driver: 41
- Root Mean Squared Error: 0. 2037 [m/s^2]

Modeling results for each condition

■ Comparison between the real-driving data and the proposed model

▶ Car-following





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