文書No. 08J3-F-93-004

Strategic Innovation Promotion Program（SIP） Automated driving systems／Field operational test ／Next generation transport

Development of sensing and control technology for Docking of Advanced Rapid Transit system

Report of 2017~2018 year

28th,February,2019
JTEKT CORPORATION
R&D Headquarters

Development of sensing and control technology for docking of ART system

>Sensor fusion technology : Vehicle position, surroundings (pedestrian, bicycle and others)
>Control technology : Integrated control of steering and braking

Target | *Development item* | *Technology*

① Smoothness at getting on/off at station

>Get on and off safely
>Shorten staying time at station
Target gap ; 40mm±20mm

② Robust control in various environments

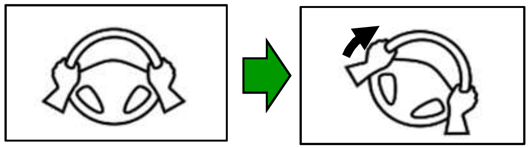
>The best routing for docking even in severe condition
Approaching speed ; 40km/h

③ Smooth braking and steering control

>Prevention of in-car accident
>Passenger comfort
Maximum acceleration ; $1.0 m/s^2$
Maximum jerk ; $1.0 m/s^3$

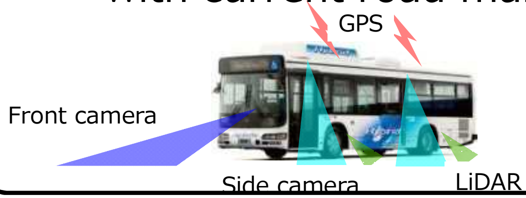
④ Cooperative docking control with driver

>Maneuvering by driver in case



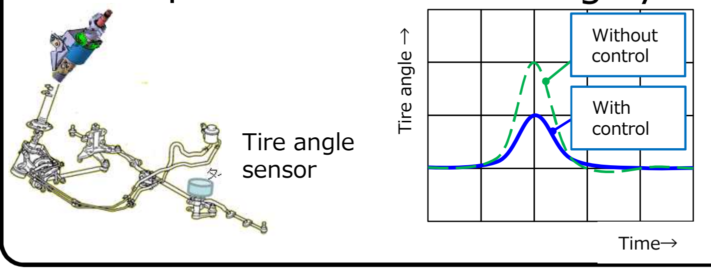
Hands on → Steering

1) Sensor fusion technology compatible with current road marking



>Robustness in various environments
>Small infrastructure investment
>Fast image processing

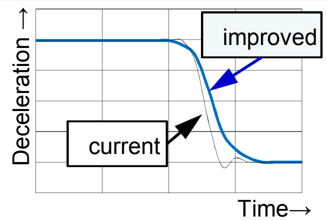
2) Improvement of steering system control performance



>Advanced steering control reducing dead band or delay caused by mechanical issue

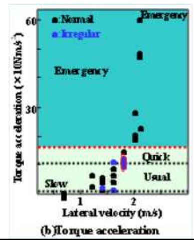
3) Reducing jerk at braking and cornering

>Sophisticated and integrated steering and braking control



4) Harmonizing driver and automated operation

>Precise estimation of driver intention from steering torque or deviation of steering torque



1）Survey on subject about precise docking

・Improvement of system control performance

・Steering ・Braking

・Field Operational Test

- Improvement of steering system control performance
  - Optimization of control gain
  - Optimization of calculating transverse deviation
  - Steering control which compensate the tire angle response to the steering angle behavior.

Optimization of control gain

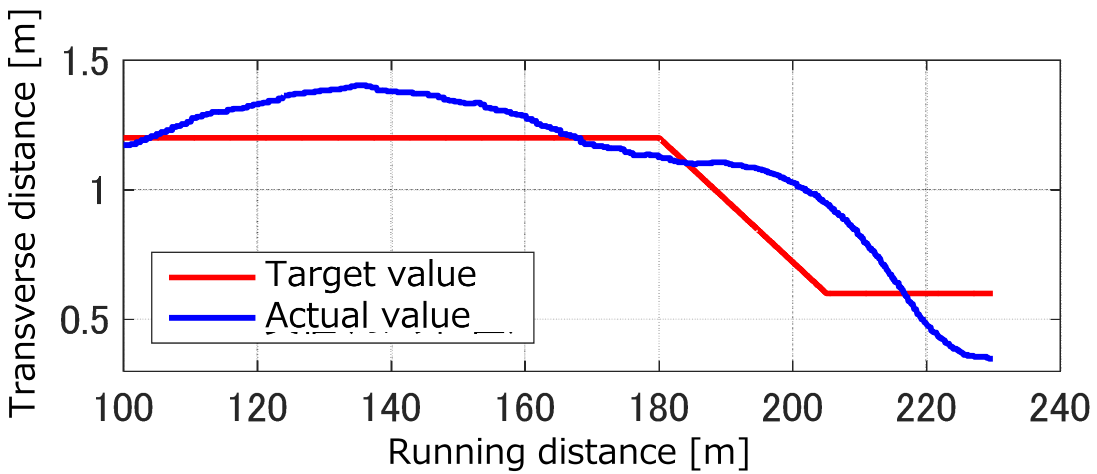
Control gain k2 (term of decreasing transverse deviation)

k2 value was Constant → Switch k2 values (straight / docking)

⇒ Optimum vehicle behavior in each situation

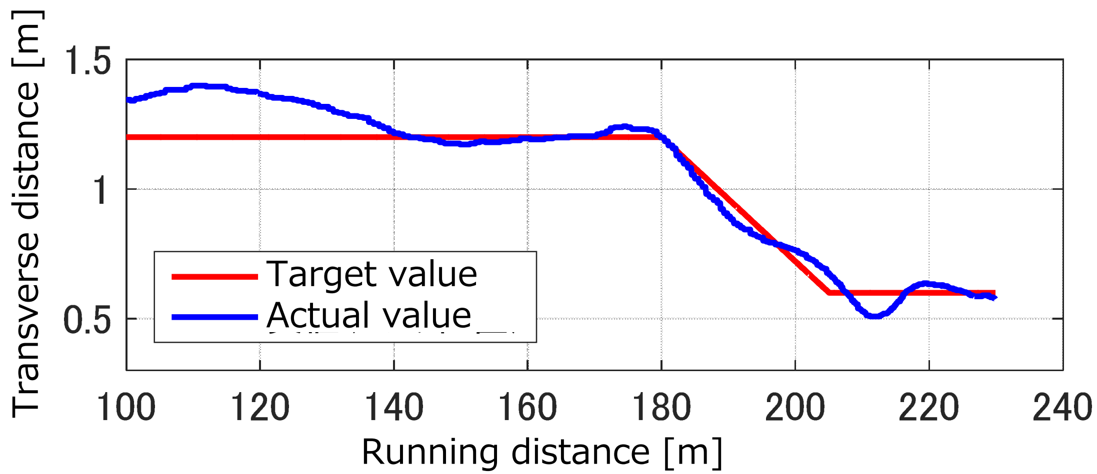
<u>Constant</u>

Optimized gain in straight situation.



<u>Switching (straight / docking)</u>

Optimized gain in each situation.



◎<u>Tracking performance is considerably improved.</u>

Optimization of calculating transverse deviation

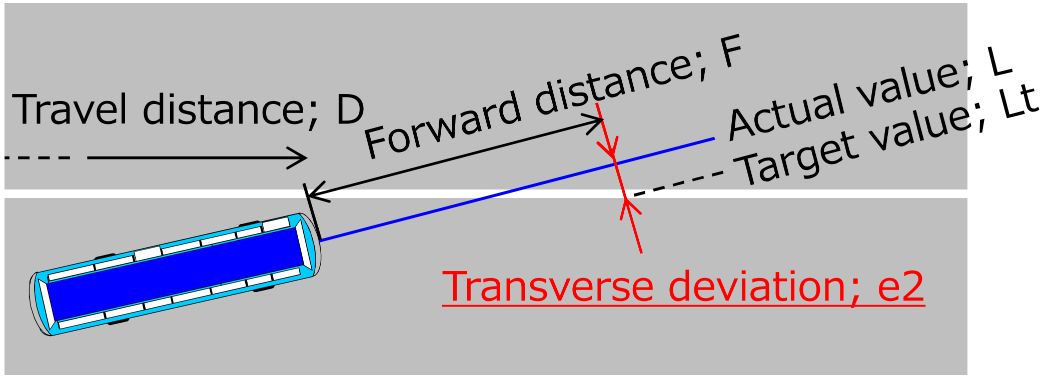
JTEKT Koyo TOYODA

Transverse deviation

①Change calculating position (vehicle forward) for target value.

(Last year, calculating position for actual value was already changed.)

②Optimize calculating position depending on speed, situation (straight/ docking).



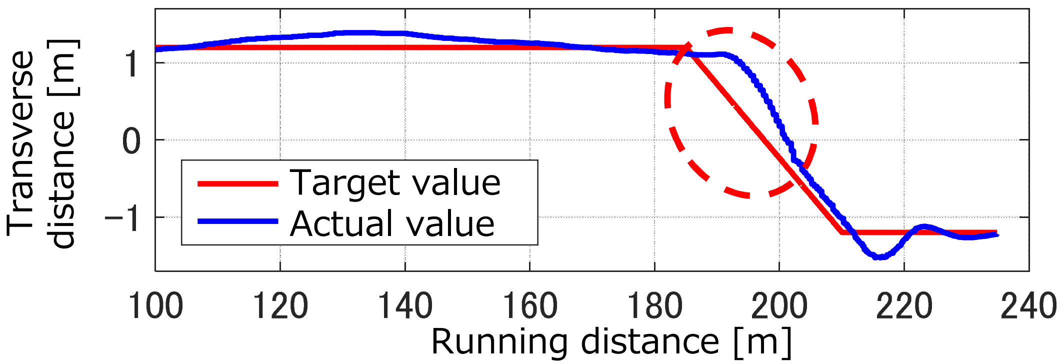
$$e2 = Lt(D+F) - L(D+F)$$

- $e2$: Transverse deviation
- Lt: Target value
- D: Travel distance
- L: Actual value
- F: Distance between calculating position and vehicle front

Effect of changing calculating position (target value)

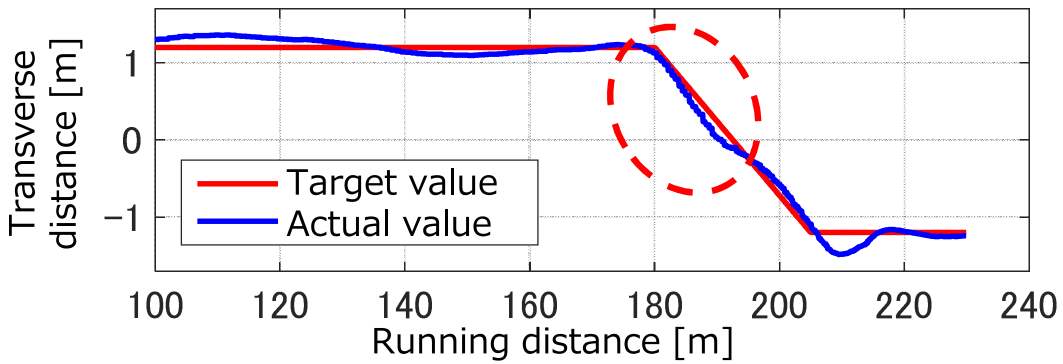
Calculated at vehicle front

$$e2 = Lt(D\ [\ \ ]) - L(D+F)$$



Calculated at vehicle forward position (distance F)

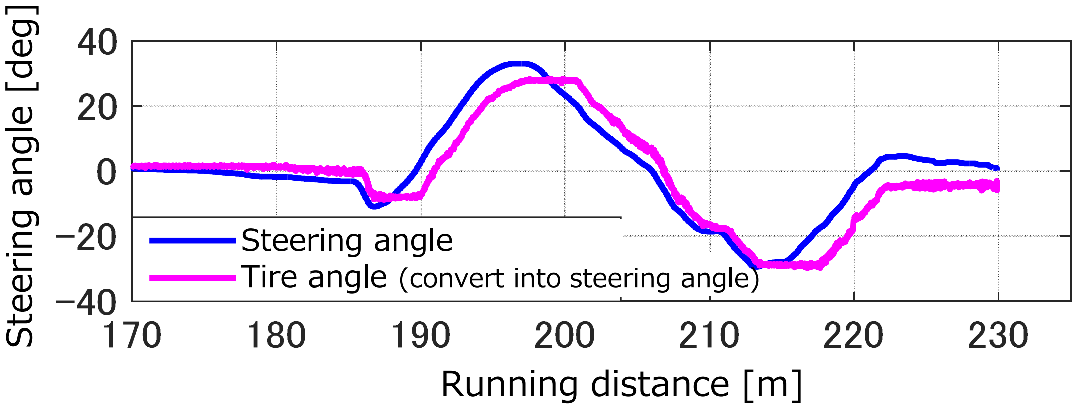
$$e2 = Lt(D + \mathbf{F}) - L(D+F)$$



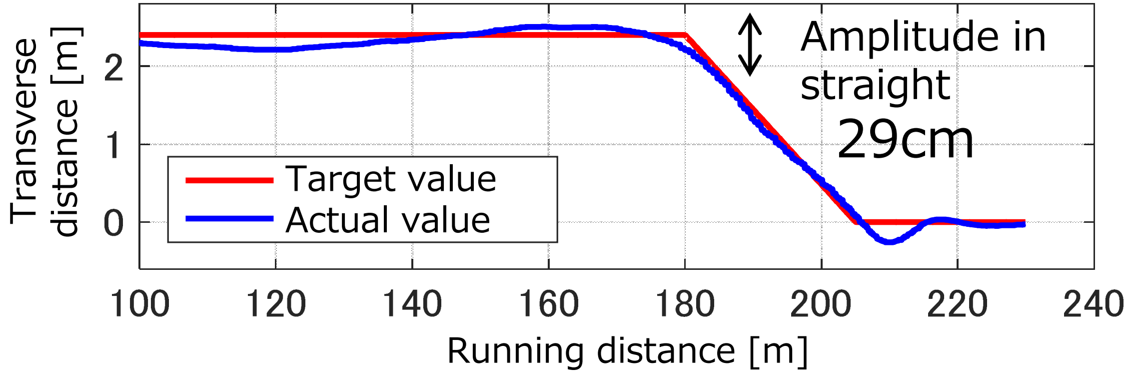
◎ Tracking performance is improved.

Steering control which compensate the tire angle response to the steering angle behavior

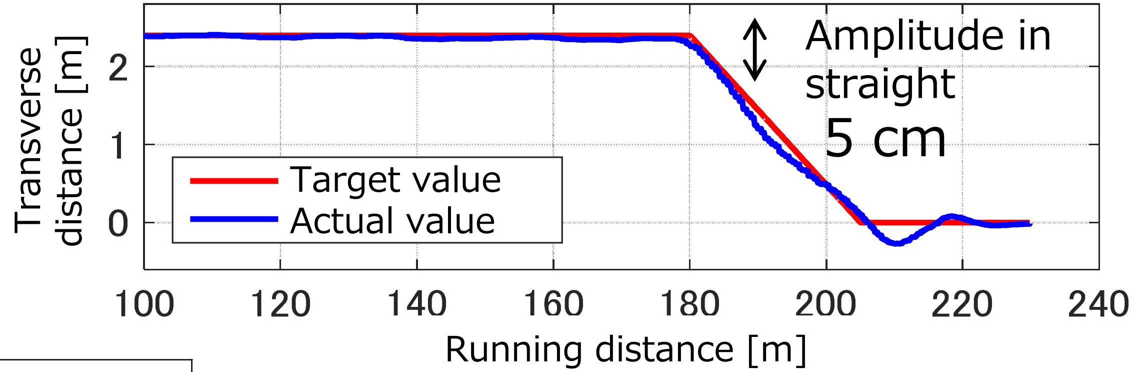
Dead zone between steering angle and tire angle is about 11degrees.
⇒ Correct target steering angle.



Without compensation



With compensation



Results of docking control
(Lateral moving distance is 2.4m.)

	Without compensation (N=15)	**With compensation (N=23)**
OK（both front and middle door)	**30%**	**73%**
NG（NG at least one of the doors)	**70%**	**27%**

Target range: ±20mm.

◎Improved by compensation

- Improvement of braking system control performance
  - Braking control strategy for stopping to the bus stop with high accuracy.
  - Braking performance verification of disc brake system

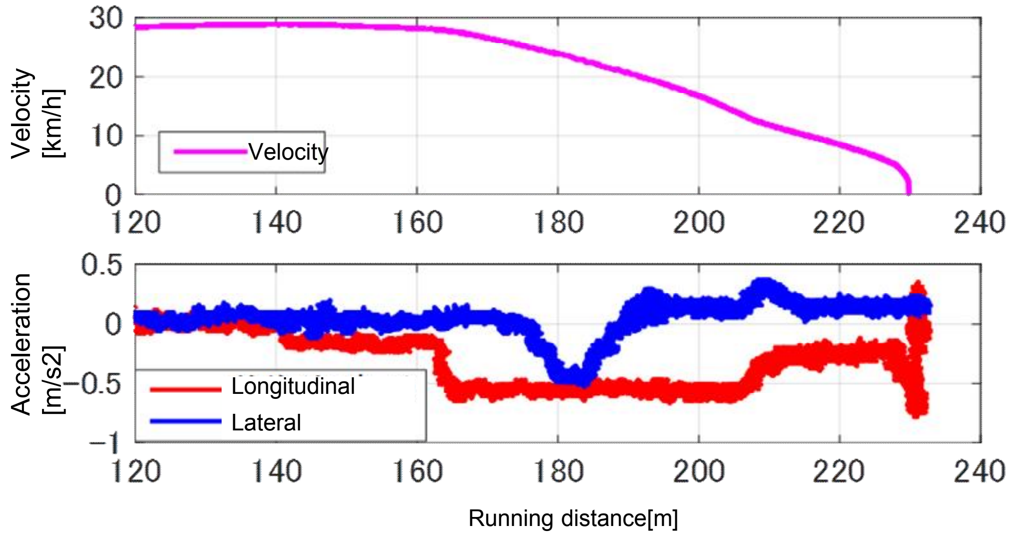
Stop to the bus stop with high accuracy

Braking control method

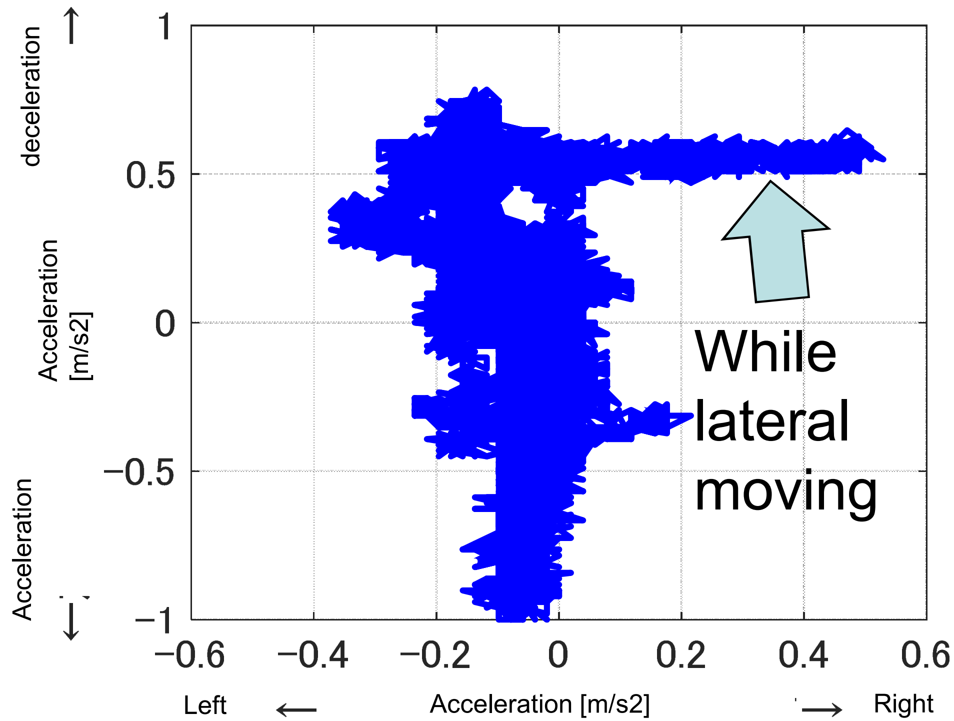
- Calculate target acceleration using assumed stop point.

$$a = \frac{v^2}{2(St - S)}$$

※a : target acceleration, v : velocity
S : runnig distance, St : assumed stoppingpoint



- Set different values of assumed stop point in the first half and the latter half of lateral moving



Result

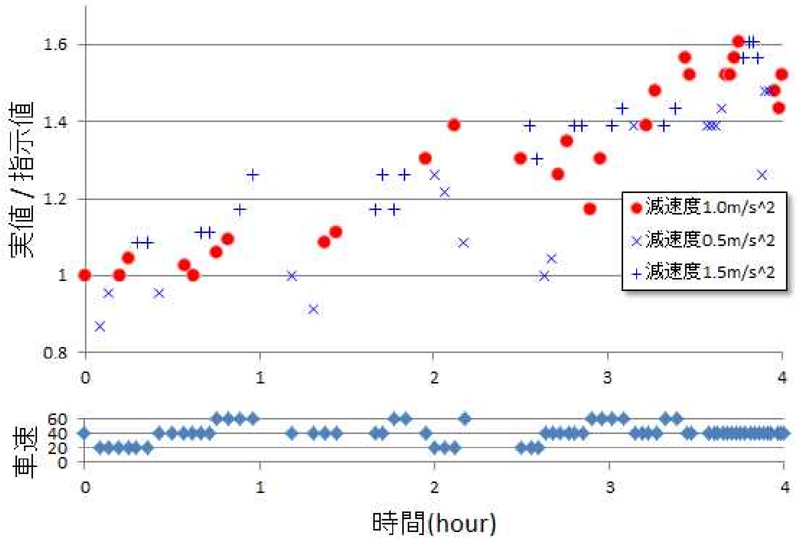
Longitudinal deviation:±0.2m
※Allowable range: ±0.5m

Braking performance verification of disc brake system

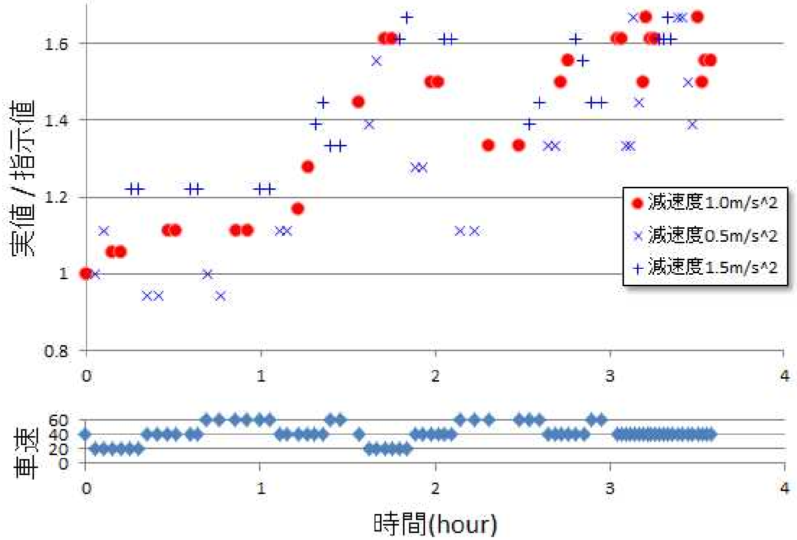
Comparison of braking performance with drum brake and disc brake system

Disc brake system has potential to improve accuracy

- Brake torque of drum brake system had large variation for same command.
  Brake torque of drum brake increased under cyclic operation.
- Brake torque of disc brake system had small variation for same command.
  Brake torque of disk brake system was changed according to vehicle speed.



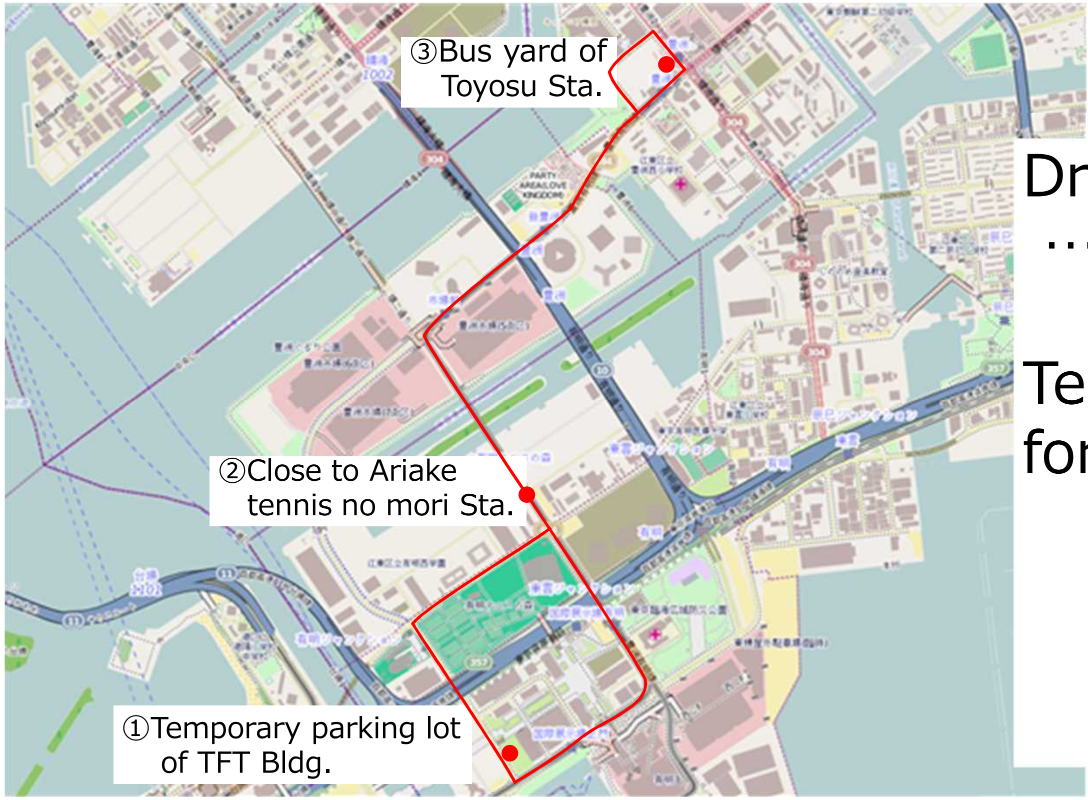
Drum brake system



Disc brake system

Change of deceleration with braking command

Outline of Field Operational Test



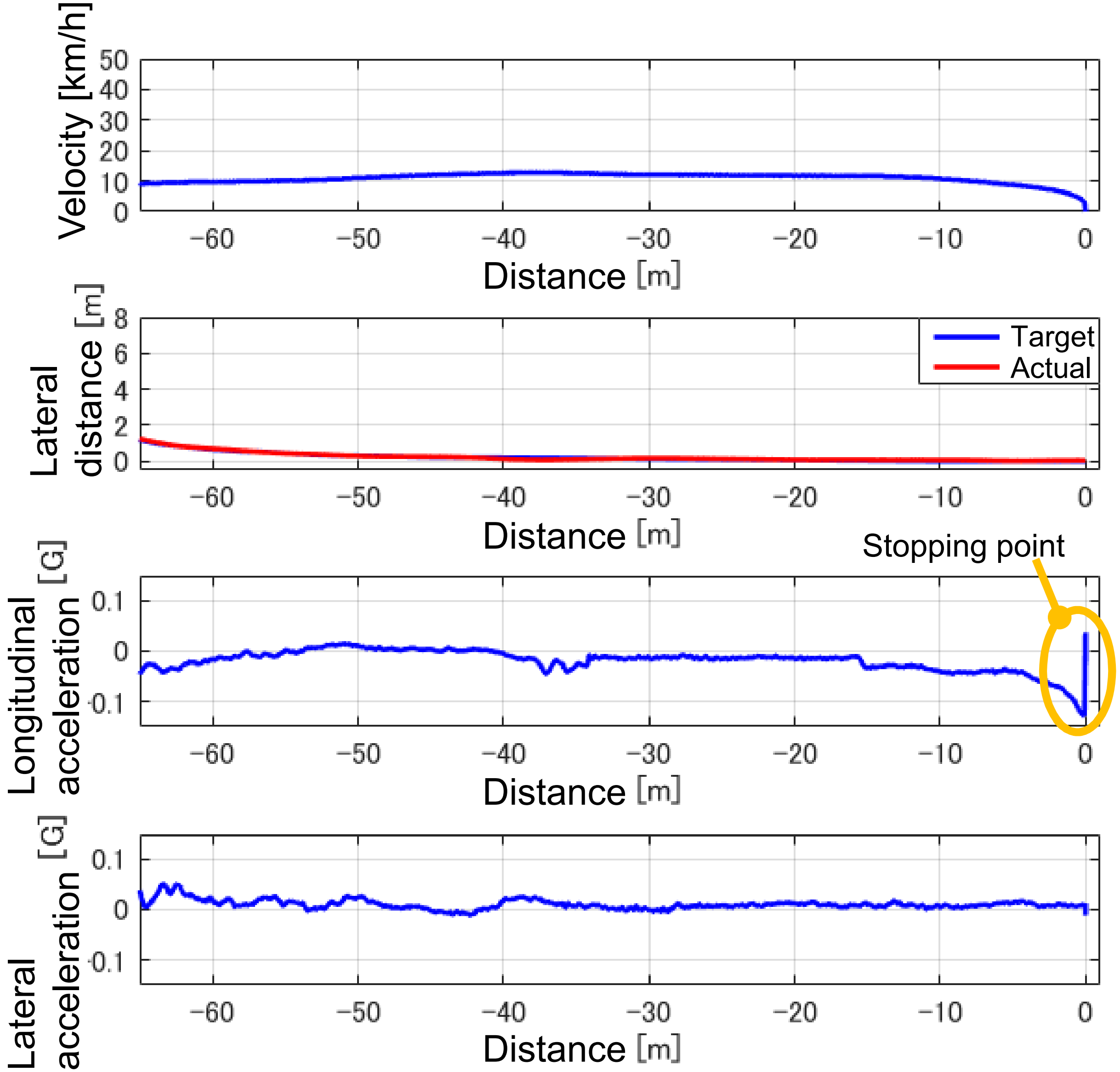
Driving route
…Between TFT Bldg. and Toyosu Sta.

Temporary Bus stops
for evaluation of precise docking
①Temporary parking lot of TFT Bldg.
②Close to Ariake tennis no mori Sta.
(North direction, South direction)
③Bus yard of Toyosu Sta.

Precise docking evaluation

1）Temporary parking lot of TFT Bldg.

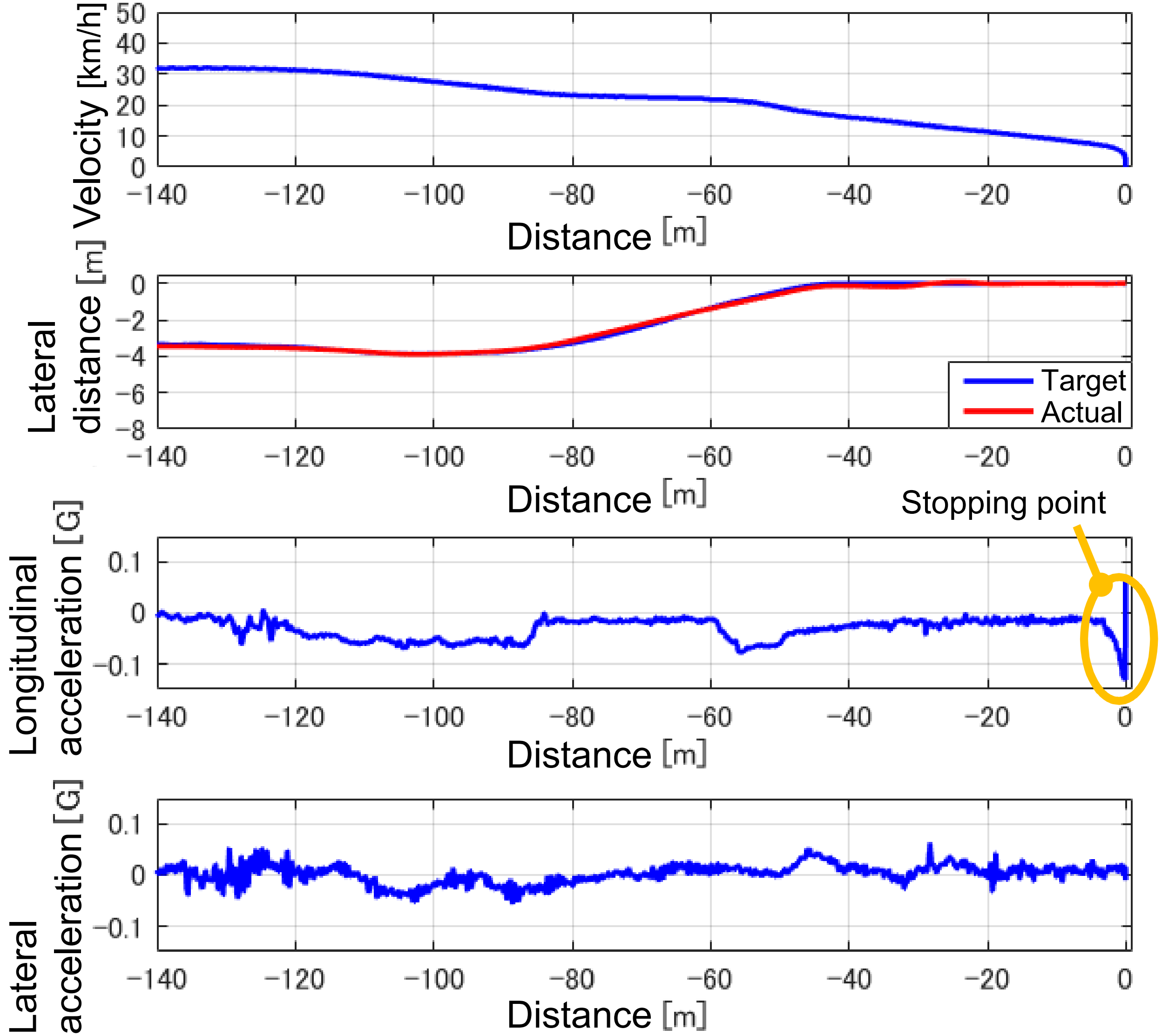
GNSS condition was good sensitivity.
Highly accurate precise docking



Precise docking evaluation

2）Temporary bus stop close to Ariake tennis no mori Sta. (North direction)

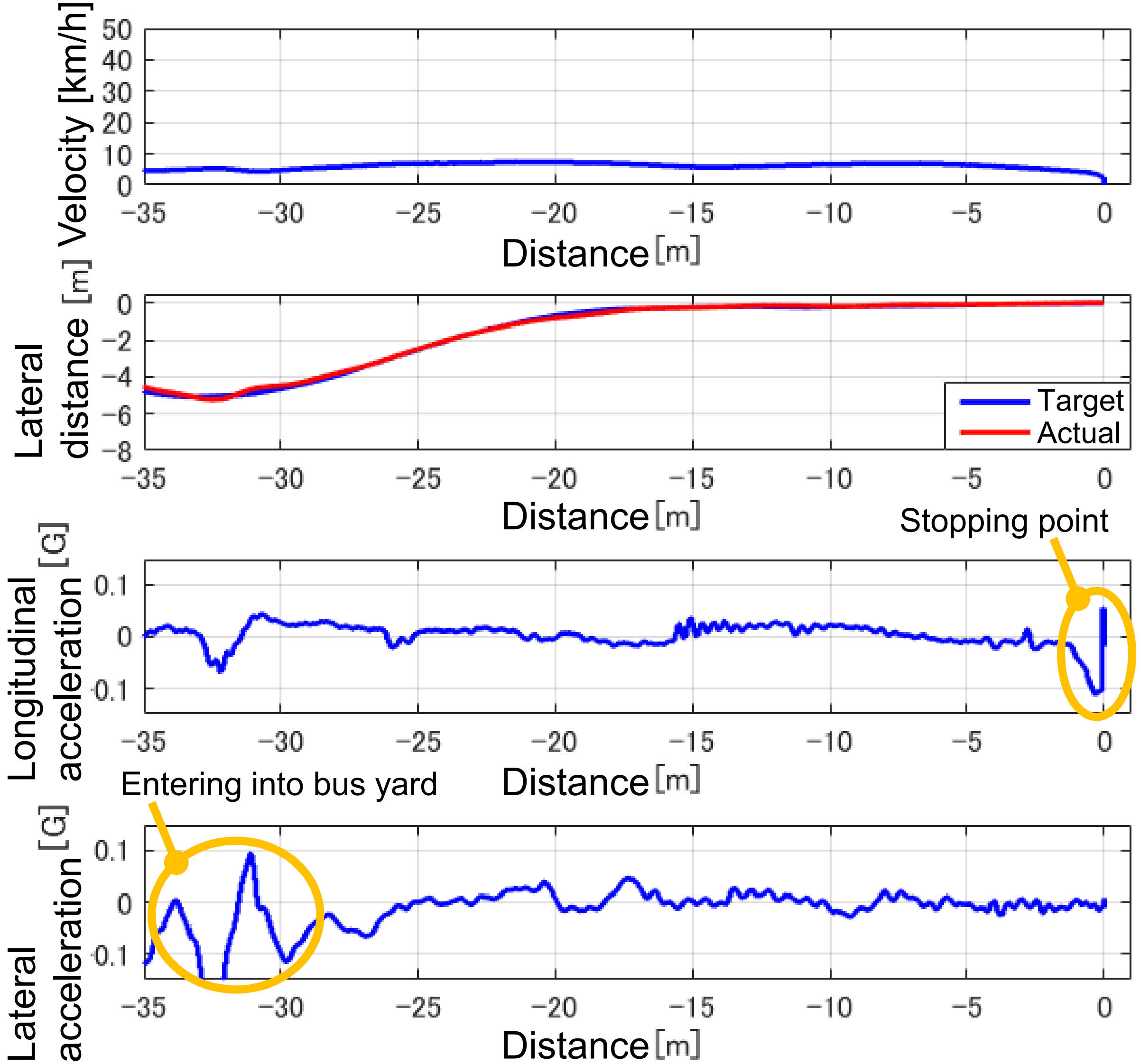
Highly accurate precise docking. However, recovery time of GNSS signal should be considered.
Accuracy of stopping position and small longitude acceleration should be improved.



Precise docking evaluation

3）Bus yard of Toyosu Sta.

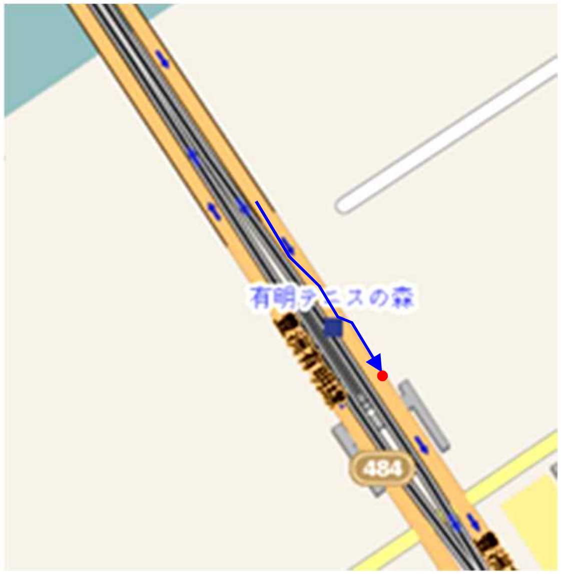
Under short approach line condition, minimum clearance was achieved considering distance to pillar.
Temporary platform was placed at ART experience event.

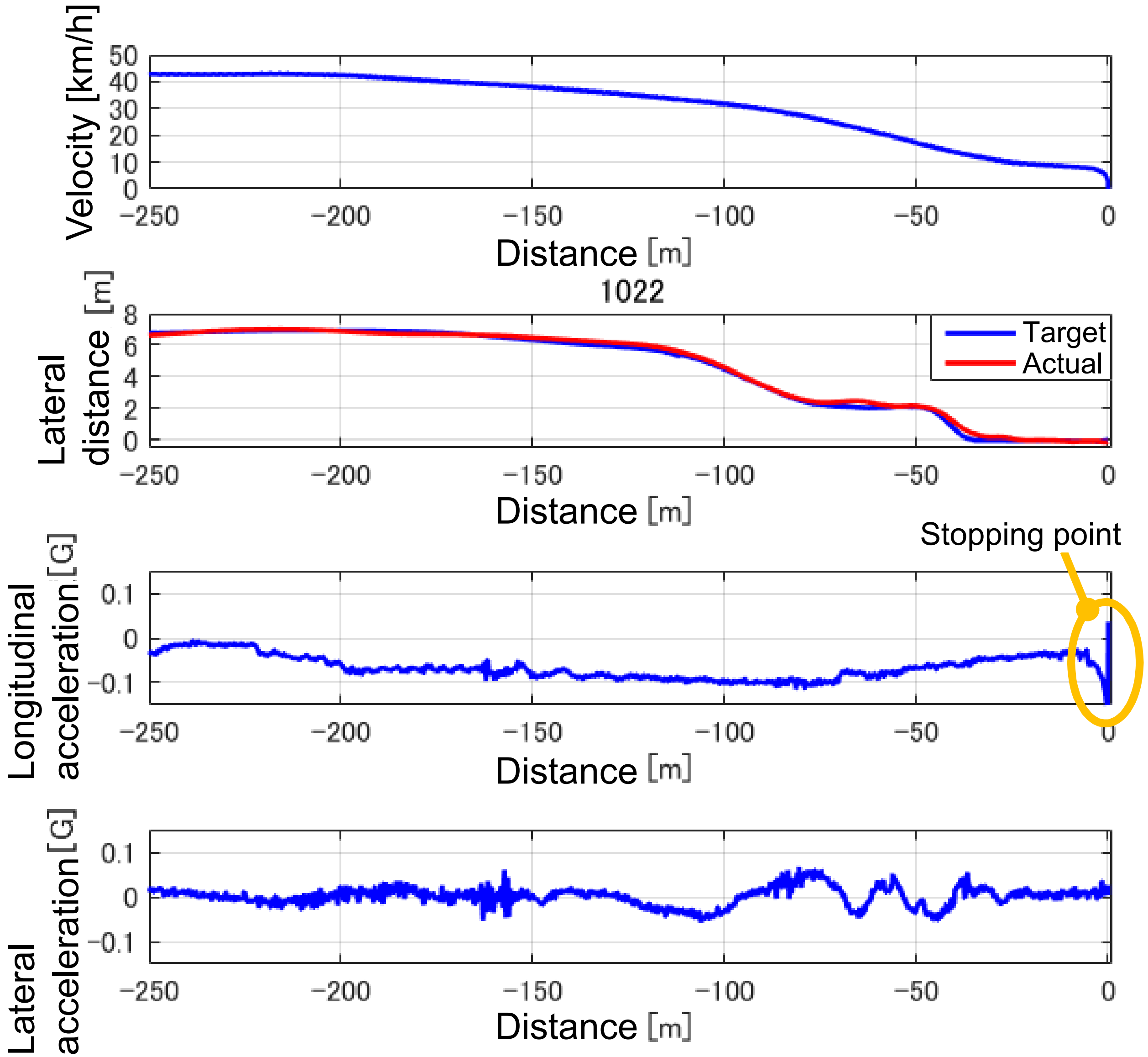


Precise docking evaluation

4）Temporary bus stop close to Ariake tennis no mori Sta. (South direction)

Under descending slope, smooth and precise docking was achieved from high vehicle speed.





2)Investigation for minimized infrastructure equipment

- Detection of painted line edge
- Detection of curbstone edge
- Integrated detection of line and curbstone

Issues in sensing for control technology of precise docking

・In order to realize the accuracy of 40±20mm, resolution is insufficient in sensing with GPS or front camera image
・Additional infrastructure equipment is necessary (For example; Specific guidance lines on road or magnetic markers)
Also, it is difficult to avoid with obstacles such as cars parked on the street

→By using side camera, boundary and position detection of painted line or curbstone to improve accuracy

→Final target is minimization of infrastructure equipment and achievement of target accuracy for precise docking by integrating multiple sensing

Cars parked near the bus stop

Detection of line edge

Monocular camera on the bus → **Line edge detection**

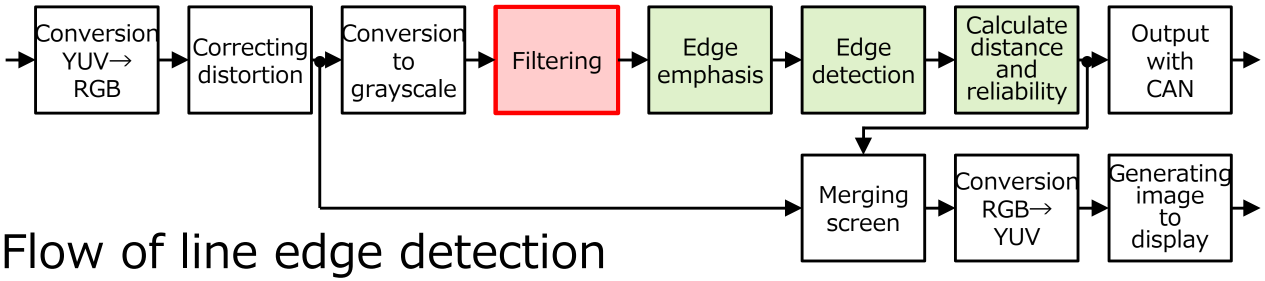
→In some case, detection was failed.
Related factors: Blur of lines・road condition (wet or dry)

→Improvement of detection algorithm (Filtering)

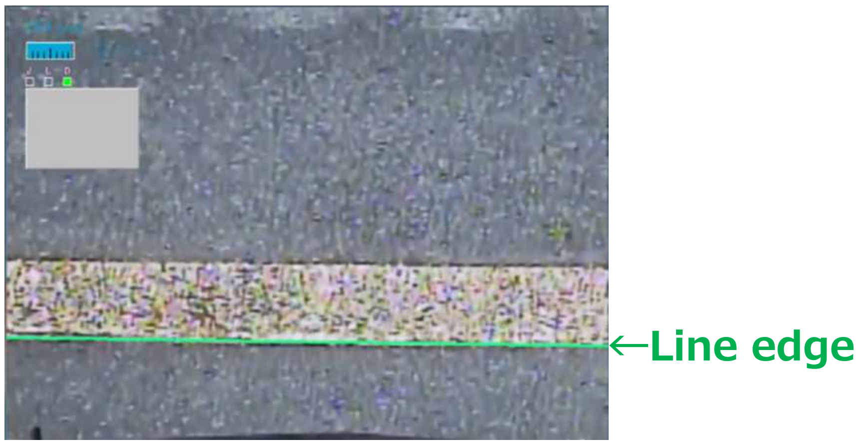
→Improved tolerance against blur of lines and wet surface

→Measurement variation was suppressed to about 10 mm

Side camera（Monocular)



Flow of line edge detection



The result of detecting the line

The result of detecting the lateral displacement

Actual value of displacement	Detection result by side camera	**Detection error**
732 mm	731 mm	**-1 mm**
740 mm	739 mm	**-1 mm**
760 mm	767 mm	**7 mm**
775 mm	773 mm	**-2 mm**

Detection of curbstone edge of bus stop

In many cases there is no line
near the bus stop
↓
Detection target is changed to curbstone edge
↓
Identification by monocular camera is difficult
↓
Detection of curbstone edge by stereo camera

Bus stop
(The front of Toyosu station)

Camera mounting position
(Over the center door)

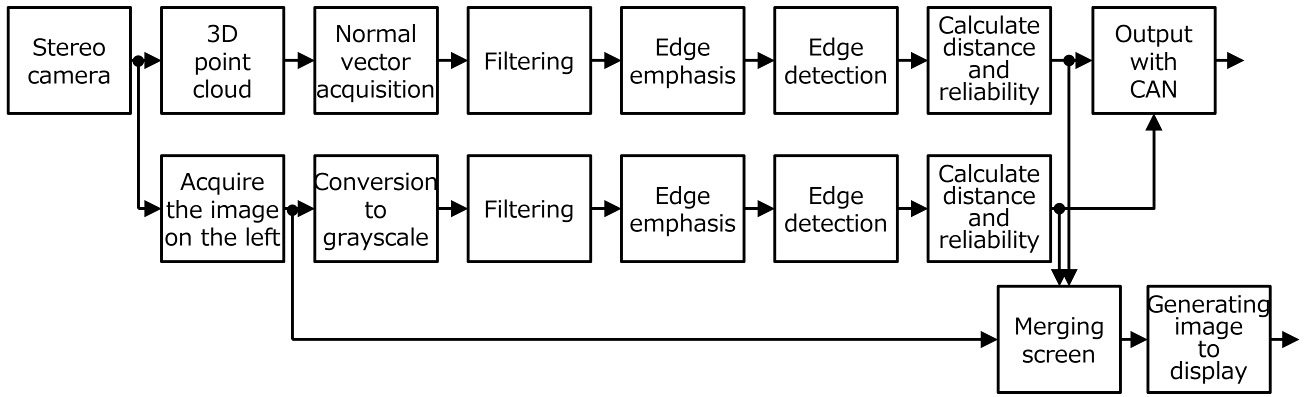
Side camera
(Stereo camera)

Integrated detection of line and curbstone

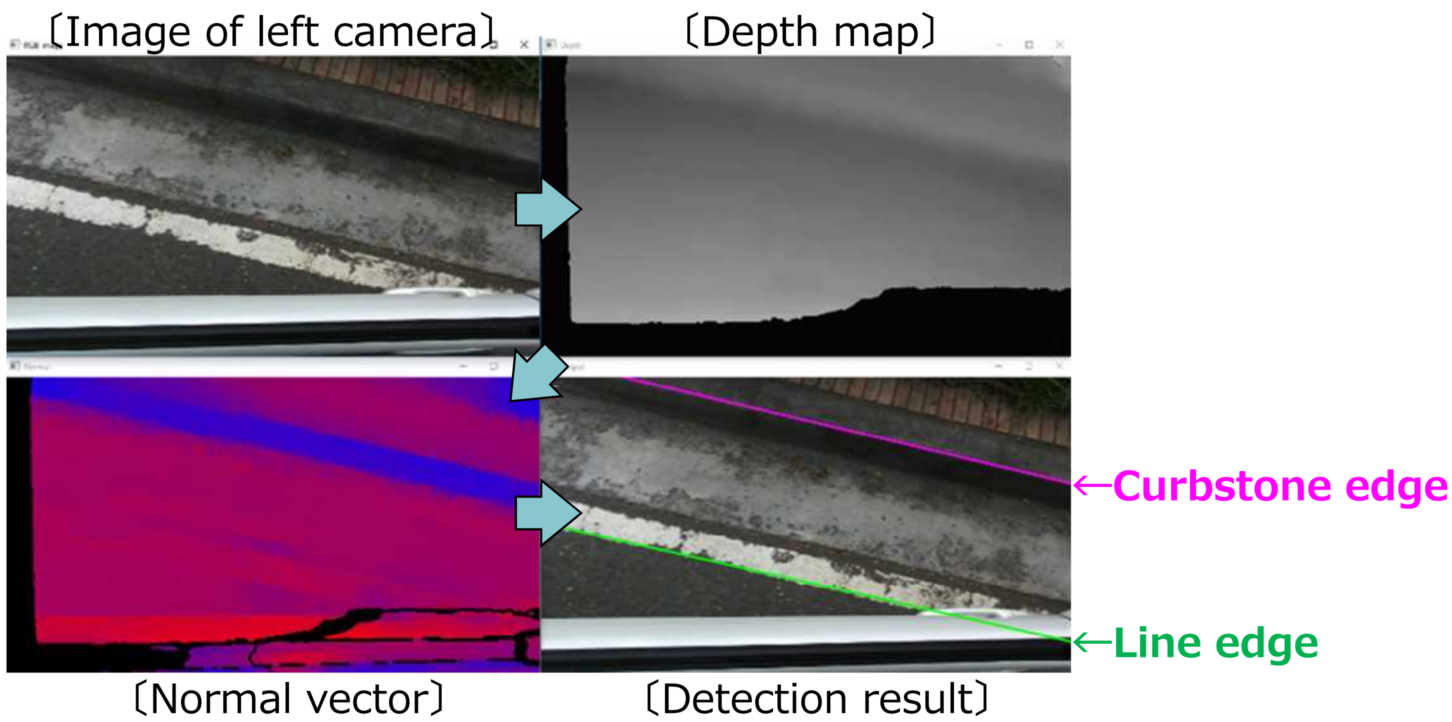
Integrated detection of line and curbstone was tried near the bus stop

↓

Both line and curbstone could be detected



Integrated flow of line and curb detection



Detection result of line and curbstone

Fusion of forward and side cameras

Comparison of painted line edge detection results between front and side cameras

↓

Determination of reliability level

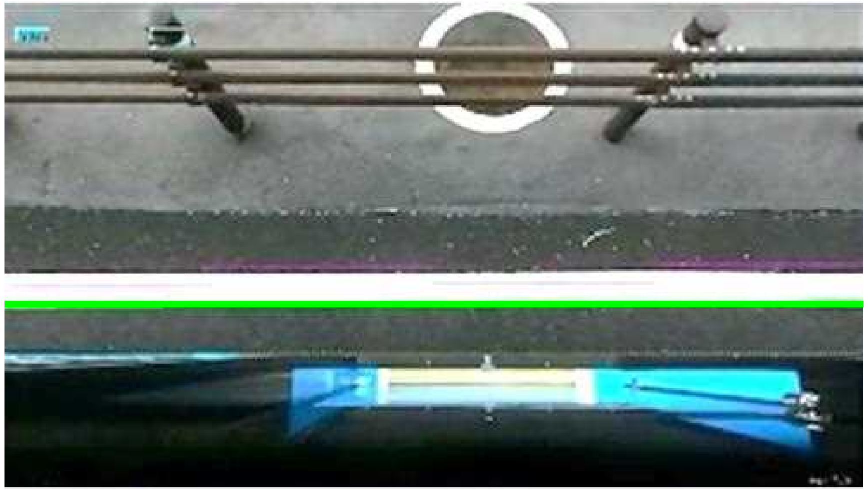
Detection result of painted line edge by front camera

↓

Comparison → Matched → High reliability

↑

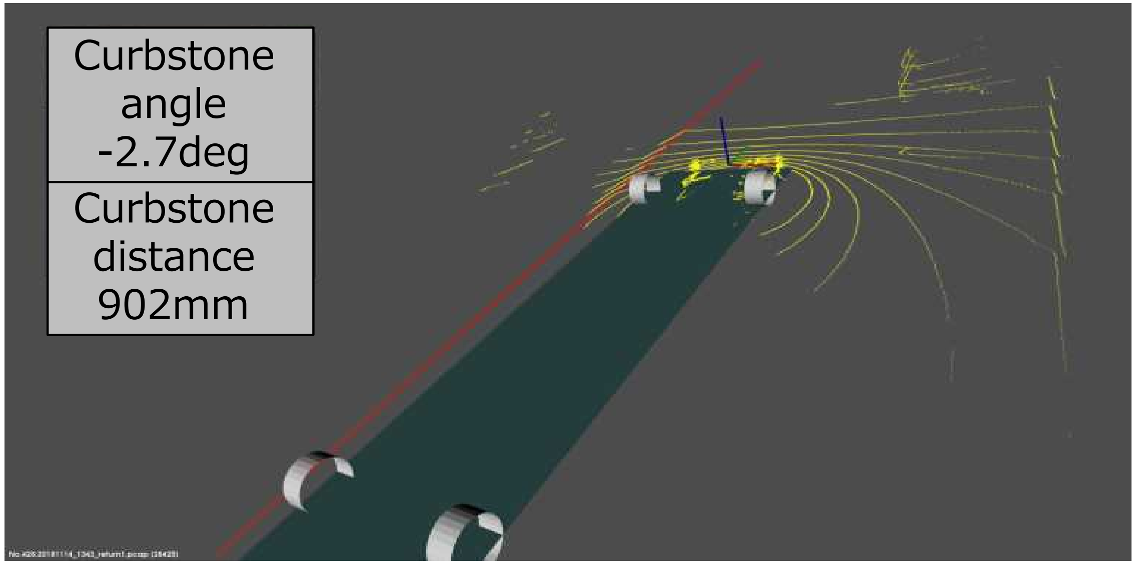
Detection result of painted line edge by side camera



Sensing by LiDAR

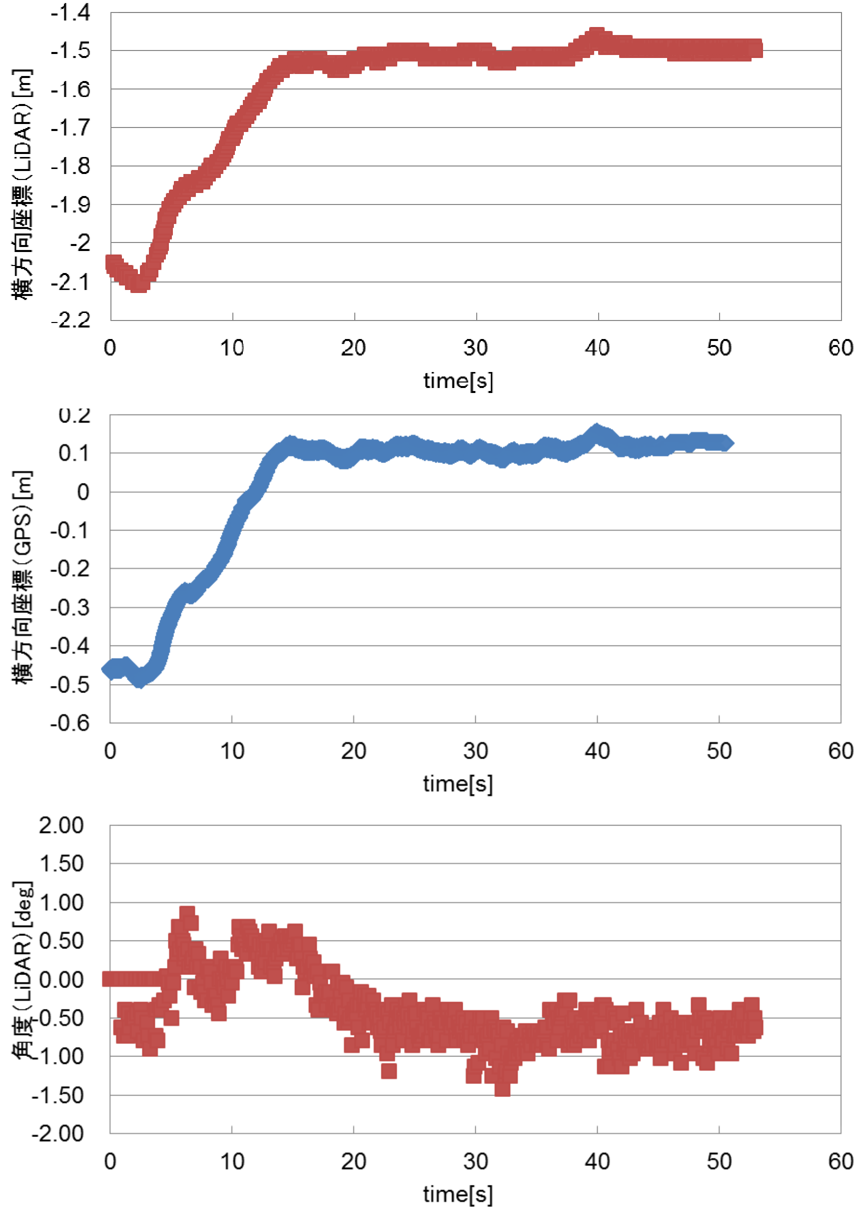
Measurement of distance and angle between sidewalk edge and vehicle by search for vertical plane of curbstone

- Detectable range
  - Distance : about 2.2m
  - Angle : ±45deg
- Accuracy of precise docking (Static condition)
  - Distance : ±17mm
  - Angle : ±0.5deg



Measurement display image by LiDAR

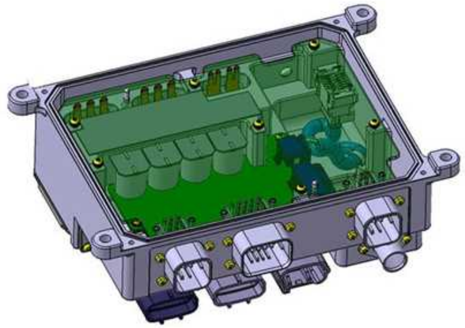
Measurement result



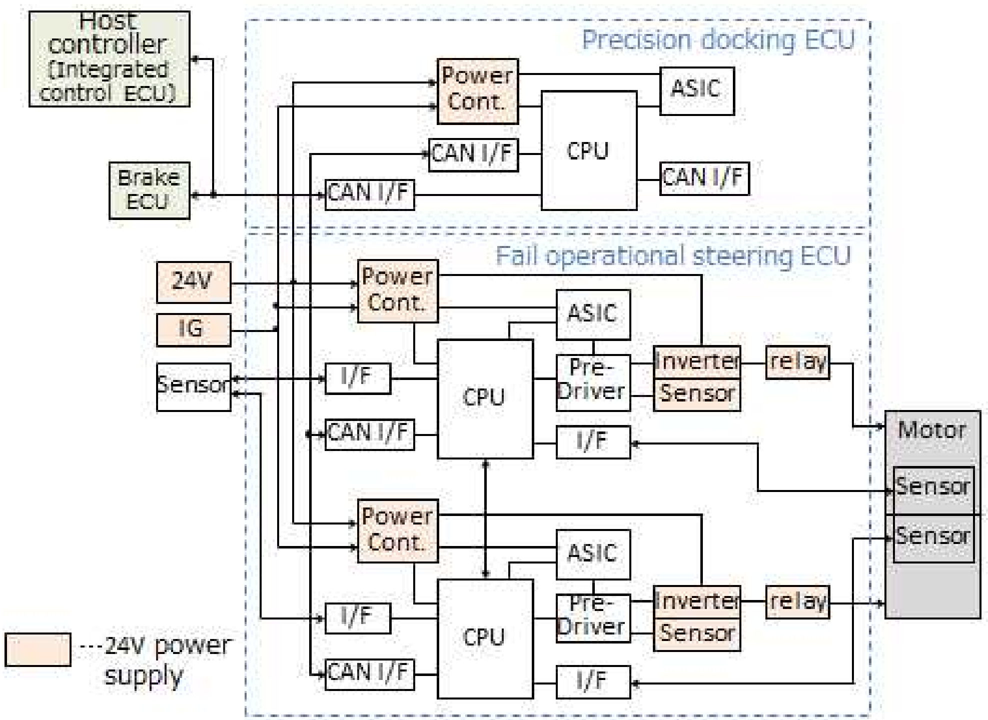
3) Study of ECU configuration considering commonization

ECU configuration

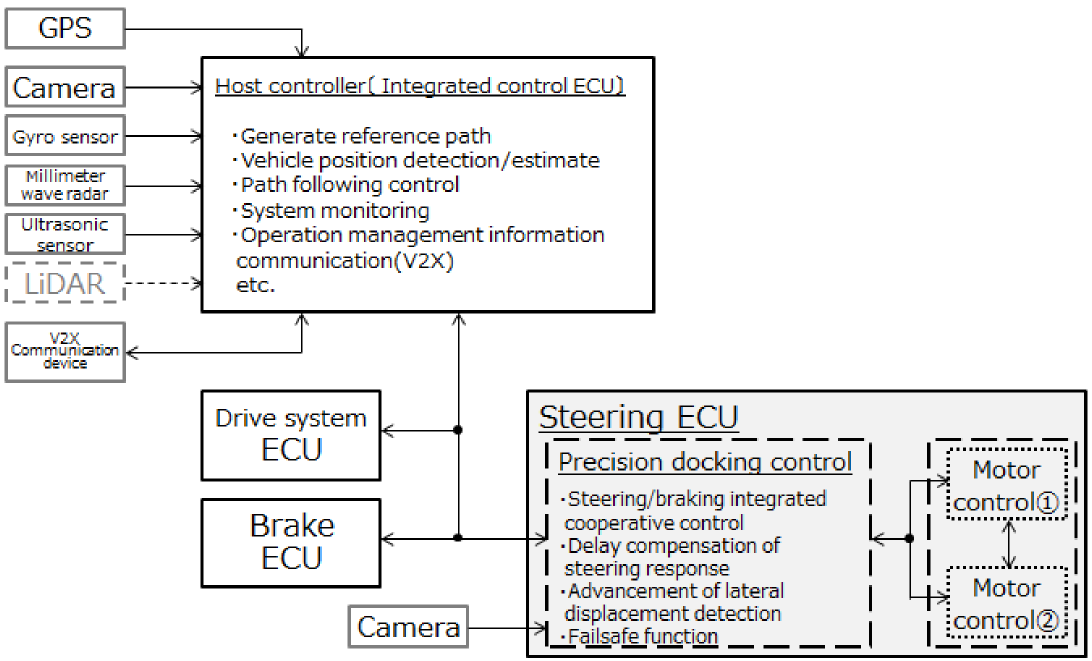
- Fail operational steering ECU in common with passenger car
- Correspond to different power supply voltages
  (Passenger car:12V → Bus:24V)
- Addition of bus specific precise docking control function



Conceptual image of steering ECU



Block diagram of bus steering control system corresponding to automated driving



Outline of bus automated driving system configuration

4) Harmonizing driver and automated operation

Vehicle test with fix professional bus driver

- **Object**

  Achieve the knowledge
  to consider the ideal precise docking

Test field in Univ. of Tokyo

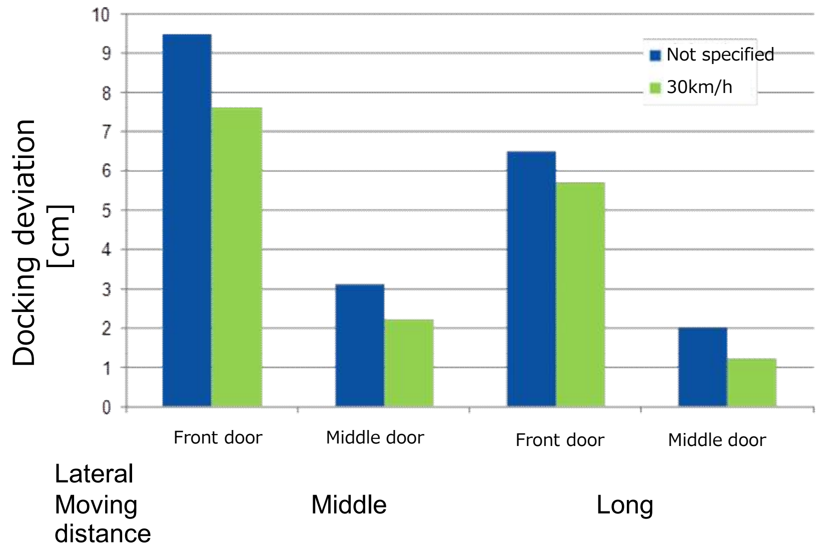
- **Implementation content**

  Acquire the data about driving maneuver, trajectory

  Vehicle : Hino Liesse (Property of Advanced Smart Mobility Co., Ltd.)
  Situation : Docking, Turn at intersection, Parking, Public road
  Data : Position(GPS),Curbstone(LiDAR)
  Painted line (Camera), Veicle behavior(Gyro Sensor)
  Steering angle, torque, Line of sight

- **Analysis example**

  the effect of vehicle velocity before docking
  ・velocity : ①30km/h specified ②not specified
  Result : Docking deviation is smaller
  when ①30km/h is specified.



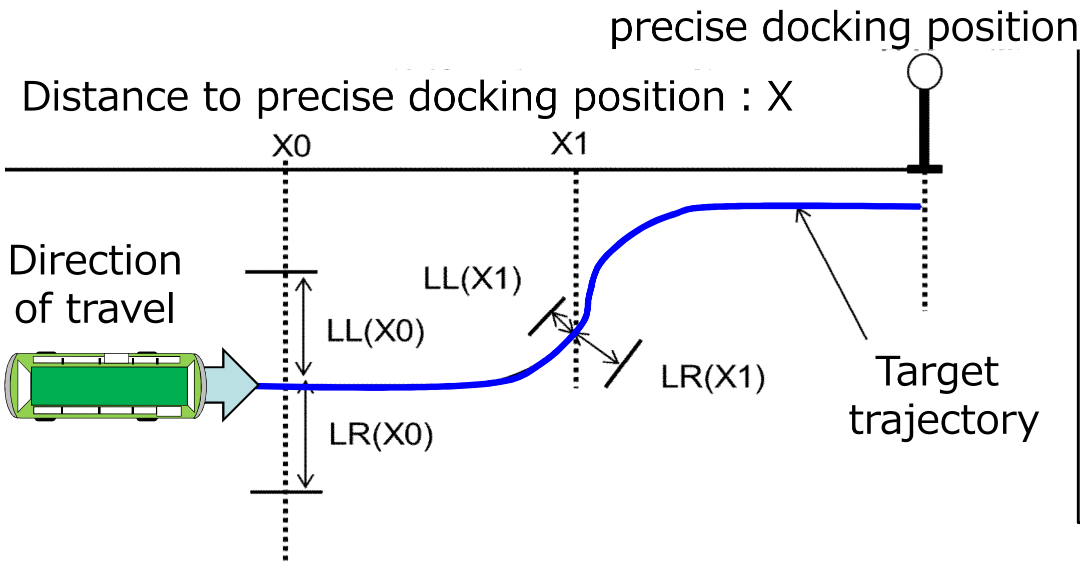
- **Next step**

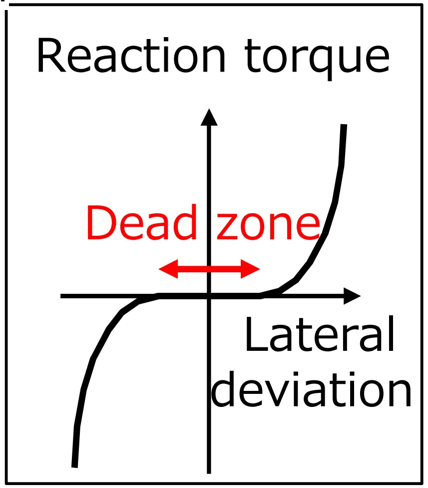
  Analyze the acquired data.
  Estimate the bus driver’s driving behavior.
  Decide the ideal target of precise docking.

Evaluation of the precise docking with guidance torque using DS

※DS : Driving simulator
LKA : Lane keep assistance

Examination of optimum values of control parameters in LKA control with trajectory guidance torque





Experiment with 6 subjects (using DS)

Considering the influence of proficiency of subject for target trajectory

- Preliminary driving with indicating target trajectory
- Preliminary driving with system assistance

(Each 3~5 times)

●Control parameter

<table>
<tr><td>Lateral movement amount</td><td colspan="2">Small</td><td colspan="2">Large</td></tr>
<tr><td>Dead zone</td><td colspan="2">None</td><td colspan="2">With dead zone</td></tr>
<tr><td>Torque gain for lateral deviation</td><td>Small</td><td colspan="2">Medium</td><td>Large</td></tr>
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