Proposal on Lane Changes under RMF and Summary of a Study

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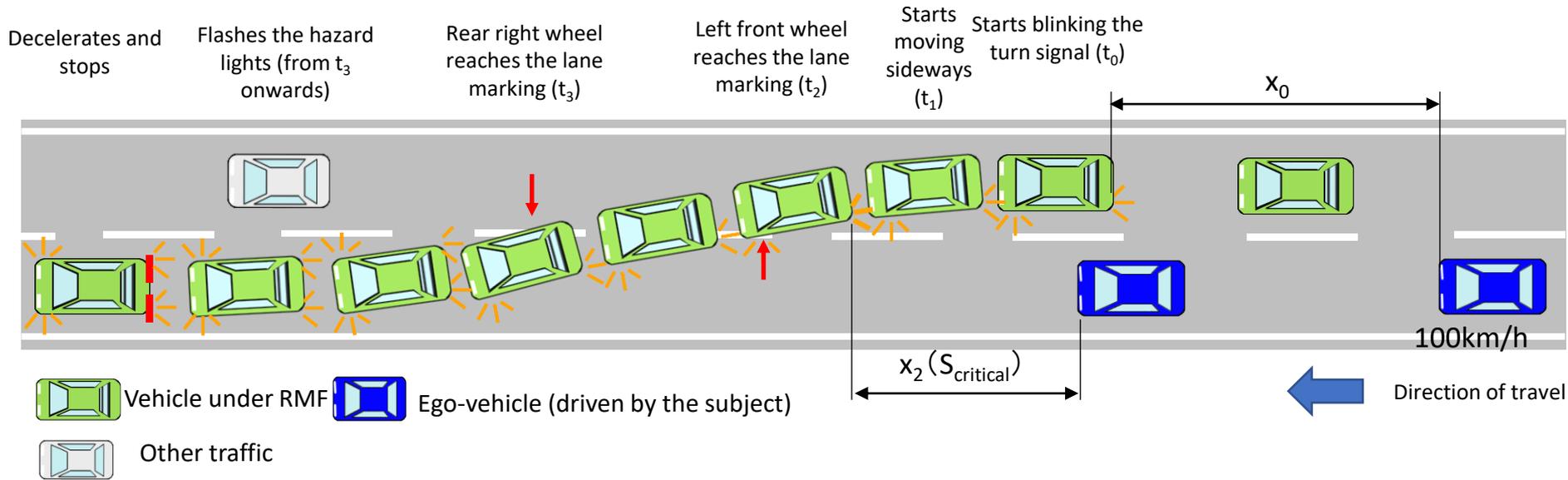## National Traffic Safety and Environment Laboratory

Proposal

Based on the results of a study on lane changes under RMF, Japan proposes adding the following requirements :

5.1.6.3.6.6.x.1. In cases where the vehicle decelerates during a lane change procedure, the deceleration shall not exceed 2m/s^2, except for the purpose of avoiding or mitigating the risk of an imminent collision.

5.1.6.3.6.6.x.2. In cases where the vehicle starts to decelerate or increase deceleration at the end of the lane change procedure with a headway time of less than [2] seconds for the vehicle behind, the vehicle shall not decelerate for at least 2 seconds after the completion of the lane change procedure, except for the purpose of avoiding or mitigating the risk of an imminent collision.

Objectives and Summary of the Study

- Regarding a situation where a vehicle under RMF changes lanes on expressways from a fast lane to a slow lane and then decelerates and stops in its lane*, we have conducted an experiment on an expressway with two lanes to understand the behaviour the driver of the vehicle behind would take to avoid collision.

    *It was assumed that there was no hard shoulder in the vicinity where drivers could retreat.

- To change lanes while under RMF, the preceding vehicle used one of the three methods below:
  - ✓ Method 1
    From a situation in which there was no difference in speed from the following vehicle, the vehicle began to decelerate while starting lane change procedure (LCP) and, upon the completion of LCP, stopped in the slow lane.
  - ✓ Method 2
    From a situation in which there was a fairly large difference in speed from the following vehicle, the vehicle performed LCP at a steady speed and, upon the completion of LCP, decelerated and stopped in the slow lane.
  - ✓ Method 3
    From a situation in which there was no difference in speed from the following vehicle, the vehicle performed LCP at a steady speed and, upon the completion of LCP, decelerated and stopped in the slow lane.

- The experiment was conducted on a driving simulator with the participation of 20 non-professional drivers in their 20s to 50s as subjects.
- The result of the experiment showed certain events that could cause a safety issue.

Decelerates and stops

Flashes the hazard lights (from t_3 onwards)

Rear right wheel reaches the lane marking (t_3)

Left front wheel reaches the lane marking (t_2)

Starts moving sideways (t_1)

Starts blinking the turn signal (t_0)

x_0

x_2 ($S_{critical}$)

100km/h

Vehicle under RMF

Ego-vehicle (driven by the subject)

Other traffic

Direction of travel

- The lane change procedure (LCP) was defined as a process that started at the point in time t_0 (when the preceding vehicle started blinking the turn signal) and ended at the point in time t_3 (when it ended blinking the signal).
- After t_3, the preceding vehicle kept flashing hazard lights.
- The time lapses were unified: between the points in time t_0-t_1 (when the vehicle starts moving sideways) to 1 s, between the points of time t_1-t_2 (sideway motion in its lane) to 2 s, and between the points of time t_2- t_3 (lane change manoeuvre) to 3 s.
- The speed of the following vehicle at the point in time t_0 was unified to 100 km/h.

✓ Method 1
  - The speed of the vehicle under RMF at the point in time t_0 was 100 km/h and the deceleration was set in 4 conditions between 1 m/s^2 and 4 m/s^2.
  - x_0 and x_2 were set by calculation using the parameters (t_B, a, t_G) in the $S_{critical}$ equation for vehicles of Category C under R79 ACSF.

✓ Method 2
  - The speed of the vehicle under RMF at the point in time t_0 was 50 km/h, and the timing it started deceleration was set in 5 conditions between "at the same time as t_3" and "4 s after t_3" (the deceleration was fixed at 4 m/s^2).
  - x_0 and x_2 were set by calculation using the parameters (t_B, a, t_G) in the $S_{critical}$ equation for vehicles of Category C under R79 ACSF.

✓ Method 3
  - The speed of the vehicle under RMF at the point in time t_0 was 100 km/h, and the timing at which it started deceleration was set in 4 conditions between "at the same time as t_3" and "3 s after t_3" (the deceleration was fixed at 4 m/s^2).
  - x_0 and x_2 were set at 27.8 m (equivalent to a headway time of 1 s)

$$S_{critical} = (V_{rear} - V_{RMF}) * t_B + (V_{rear} - V_{RMF})^2 / (2 * a) + V_{RMF} * t_G$$

$S_{critical}$: Minimally required relative distance in [m] to the following vehicle at the point in time t_2.
V_{rear}: Speed of the following vehicle at the point in time t_2 [m/s].
V_{RMF}: Speed of the vehicle under RMF [m/s]
t_B: The timing at which the following vehicle started deceleration (0.4 s after t_2 in the figure)
a: Deceleration of the following vehicle (3 m/s^2)
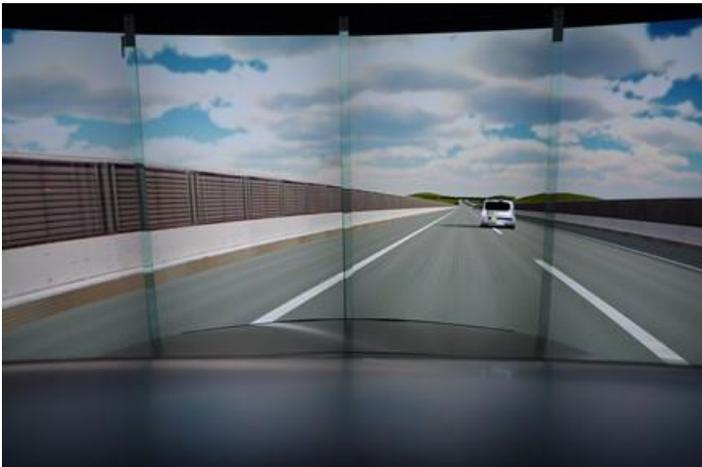t_G: Minimum headway time (1 s)

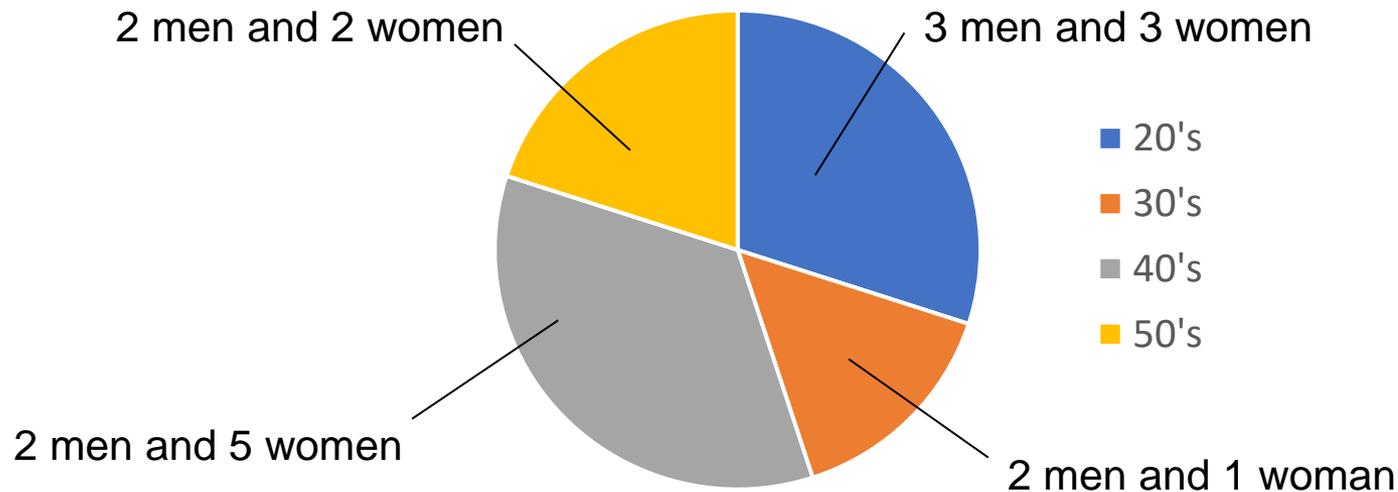External view of the DS

Driver's seat

A scene from the simulator screen images

- Used the body of a compact car
- Seventeen 55-inch OLED panels were installed around the driver's seat to project traffic situations (The horizontal viewing angle was about 360°.)
- Multiple motion devices enabled the driver to physically experience the vehicle acceleration, etc.

- 20 drivers in their 20's to 50's who drive on a daily basis and at least once a year on an expressway participated in the experiment.
- Before starting the experiment, they had some practice run to get used to the driving simulator.
- During the experiment, they used cruise control (CC) to keep the speed approximately constant (but without following distance control function and cutting off CC when applying the brake pedal) from when they started driving till when they reached the scene of the experiment (about 6 min).

2 men and 2 women

3 men and 3 women

■ 20's
■ 30's
■ 40's
■ 50's

2 men and 5 women

2 men and 1 woman

- The timing at which the following vehicle started to brake was, between the 25 and 75 percentiles, earlier than that in the $S_{critical}$ equation (0.4 s after t_2) in Conditions 1 and 2 and equal to or earlier than "0.4 s after t_2" in Condition 3. In contrast, in Condition 4, it was later than "0.4 s after t_2".

  →This seems to indicate that, for the driver of the following vehicle, the longer the relative distance to the preceding vehicle, the longer it took them to conclude that this was a collision they needed to avoid.

$*$: p<0.05   (20 subjects each)

Timing at which the following vehicle started braking [s]

$←t_3$
$←t_2$
$←t_1$
$←t_0$

Maximum value
75 % ile
Median value
25 % ile
Minimum value
× Mean value
◆ Outlier

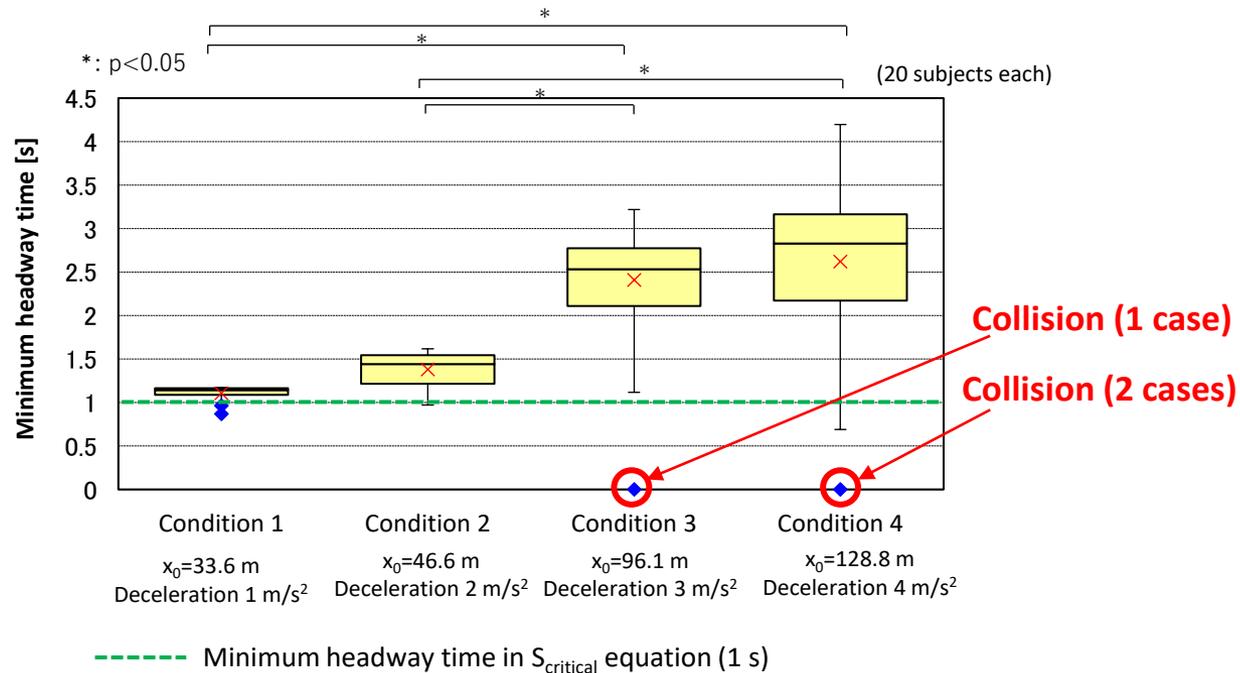| Condition 1	Condition 2	Condition 3	Condition 4
x_0=33.6 m	x_0=46.6 m	x_0=96.1 m	x_0=128.8 m
Deceleration 1 m/s²	Deceleration 2 m/s²	Deceleration 3 m/s²	Deceleration 4 m/s²

- Speed at the point in time t_0
  Vehicle under RMF: 100 km/h
  Following vehicle: 100 km/h
- When the vehicle under RMF started deceleration: t_0

-------- The timing at which the following vehicle started deceleration in the $S_{critical}$ equation (0.4 s after t_2)
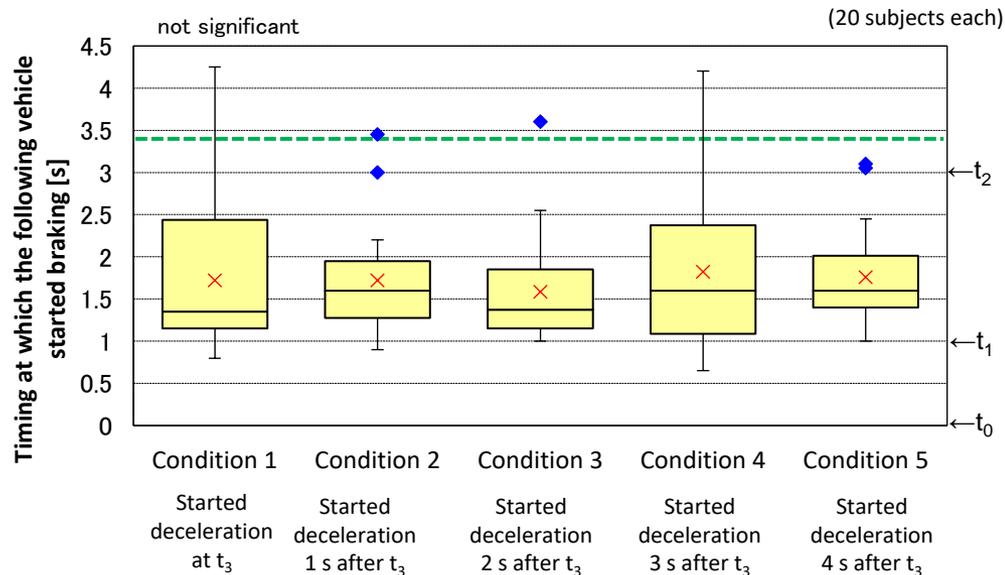
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- In Conditions 3 and 4, the minimum headway time dropped to 0 s and collisions occurred (3 cases).
- Except for the collisions, all conditions showed that the minimum headway time (1 s) in the $S_{critical}$ equation was exceeded for values between the 25 and 75 percentiles.
- For values between the 25 and 75 percentiles, the distribution of the minimum headway time in Conditions 3 and 4 showed that the minimum headway time was longer than that in Conditions 1 and 2.
  - →The reason for what Conditions 3 and 4 showed was presumably that the relative distance (x_0) at the time when the vehicle under RMF started blinking its turn signal was longer than that of Conditions 1 and 2.

*: $p<0.05$ (20 subjects each)

Minimum headway time [s]

Collision (1 case)
Collision (2 cases)

Condition 1	Condition 2	Condition 3	Condition 4
$x_0=33.6$ m	$x_0=46.6$ m	$x_0=96.1$ m	$x_0=128.8$ m
Deceleration 1 m/s²	Deceleration 2 m/s²	Deceleration 3 m/s²	Deceleration 4 m/s²

------ Minimum headway time in $S_{critical}$ equation (1 s)

- The timing at which the following vehicle started braking was, in all conditions between the 25 and 75 percentiles, earlier than that in the $S_{critical}$ equation (0.4 s after t_2).
  →The reason for this was presumably that, with the large speed difference from the vehicle under RMF, it was easy for the driver of the following vehicle to recognize in a shorter time that this was a situation in which they needed to avoid a collision.
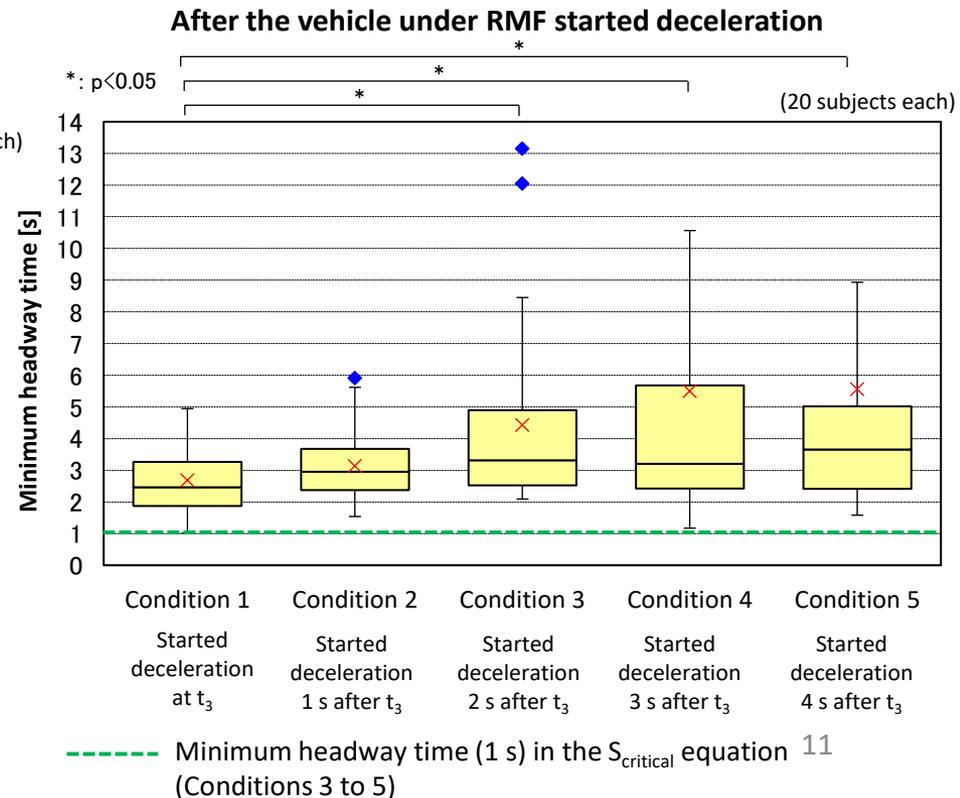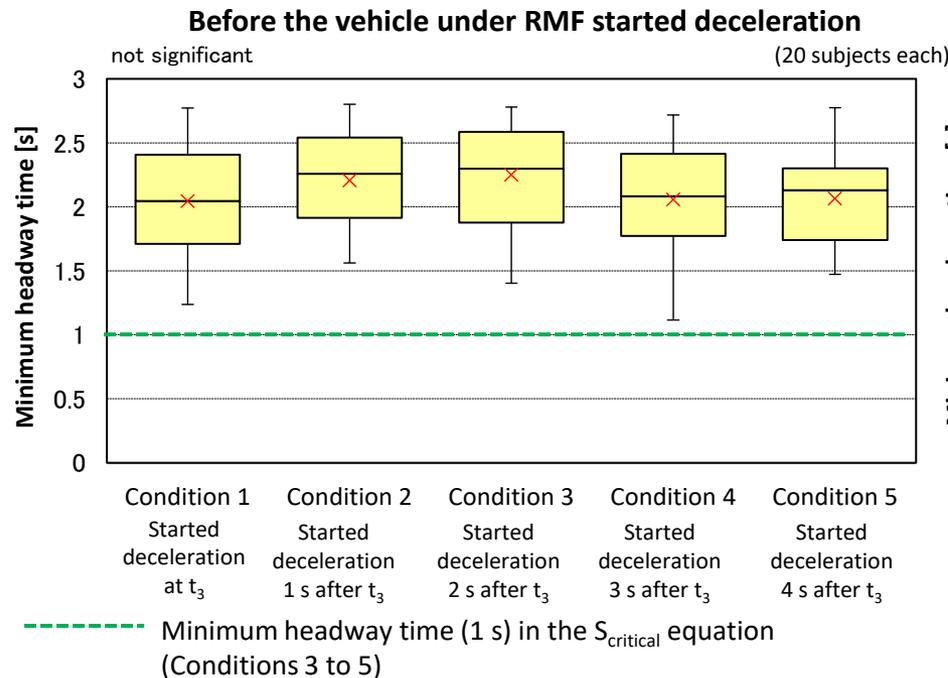
- Speed at the point in time t_0
  Vehicle under RMF: 50 km/h
  Following vehicle: 100 km/h
- Relative distance (x_0) at the point in time t_0: 94.1 m
- Deceleration of the vehicle under RMF: 4 m/s²

not significant   (20 subjects each)

Timing at which the following vehicle started braking [s]

Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Started deceleration at t_3	Started deceleration 1 s after t_3	Started deceleration 2 s after t_3	Started deceleration 3 s after t_3	Started deceleration 4 s after t_3

-------- The timing at which the following vehicle starts deceleration in the $S_{critical}$ equation (0.4 s after t_2)
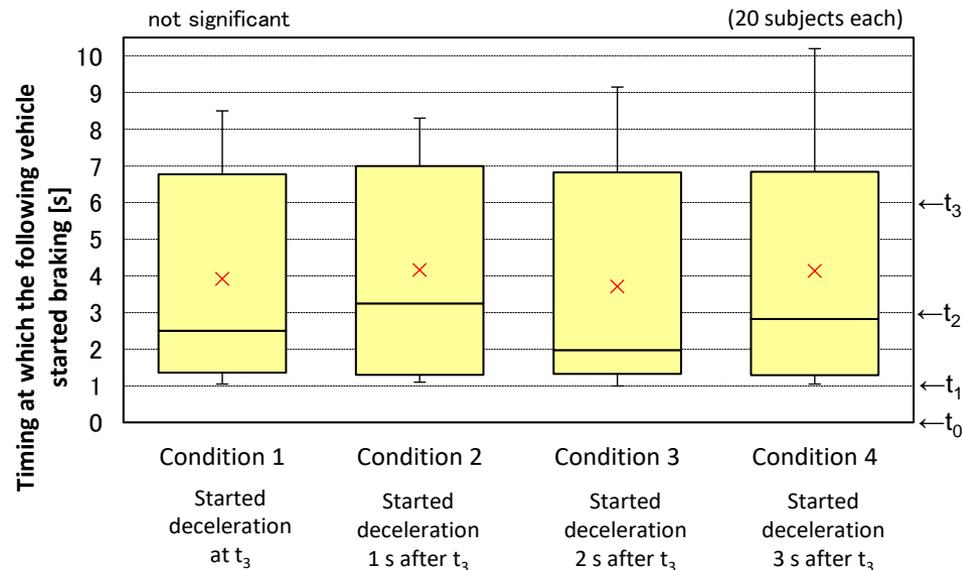
- In the section before the vehicle under RMF started deceleration, the minimum headway time was longer than that in the $S_{critical}$ equation (1 s) between the 25 and 75 percentiles in all conditions.

- In the section after the vehicle under RMF started deceleration, too, the minimum headway time was longer than 1 s between the 25 and 75 percentiles in all conditions. Further, in Conditions 3 to 5, where the hazard lights kept flashing from t_3 until the vehicle started deceleration, the minimum headway time was longer than in Condition 1 (a significant difference).

Before the vehicle under RMF started deceleration

not significant

(20 subjects each)

Minimum headway time [s]

Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Started deceleration at t_3	Started deceleration 1 s after t_3	Started deceleration 2 s after t_3	Started deceleration 3 s after t_3	Started deceleration 4 s after t_3

- - - - - Minimum headway time (1 s) in the $S_{critical}$ equation (Conditions 3 to 5)

After the vehicle under RMF started deceleration

*: $p < 0.05$

(20 subjects each)

Minimum headway time [s]

Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Started deceleration at t_3	Started deceleration 1 s after t_3	Started deceleration 2 s after t_3	Started deceleration 3 s after t_3	Started deceleration 4 s after t_3

- - - - - Minimum headway time (1 s) in the $S_{critical}$ equation (Conditions 3 to 5)
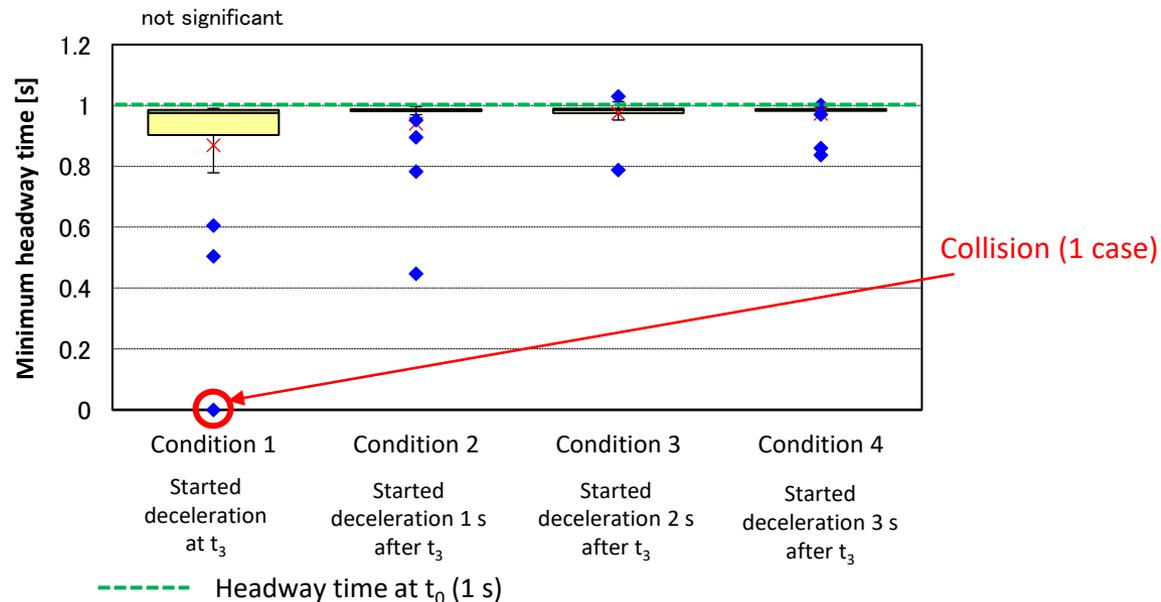
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- The timing at which the following vehicle started braking was more widely distributed than in Methods 1 and 2, ranging roughly from 1.3 s to 7 s between the 25 and 75 percentiles in all conditions.
   → This was presumably because there was no speed difference at t_0 and the relative distance was 27.8 m (equivalent to 1 s of headway time), which, after the vehicle under RMF started LCP, divided the subjects into two groups: those who judged that braking was necessary immediately and those who did not.
- Conditions 3 and 4 revealed that, around 75 percentile (6 to 7 s), some people, in reaction to the flashing hazard lights, started braking even before the vehicle under RMF started deceleration.

- Speed at the point in time t_0
  Vehicle under RMF: 100 km/h
  Following vehicle: 100 km/h
- Relative distance (x_0) at the point in time t_0: 27.8 m
- Deceleration of the vehicle under RMF: 4 m/s^2

not significant   (20 subjects each)

Timing at which the following vehicle started braking [s]

Condition 1	Condition 2	Condition 3	Condition 4
Started deceleration at t_3	Started deceleration 1 s after t_3	Started deceleration 2 s after t_3	Started deceleration 3 s after t_3

←t_3
←t_2
←t_1
←t_0

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- In condition 1, the minimum headway time dropped to 0 s and a collision occurred (1 case).
- In all conditions except for the collision, the headway time was approximately the same as that at t_0 (1 s) between the 25 and 75 percentiles.

Summary of the Experimental Results

✓ Method 1
- The longer the relative distance at the start of LCP and the higher the deceleration, the later the timing at which the following vehicle started braking and the higher the average deceleration became.
- Collisions occurred when the deceleration of the vehicle under RMF was set at 3 to 4 m/s^2 (3 out of 40 cases in total).

✓ Method 2
- The timing at which the following vehicle started braking was earlier than that in the $S_{critical}$ equation and the deceleration was higher than that in the $S_{critical}$ equation.
- When the vehicle under RMF started deceleration after the hazard lights kept flashing for more than 2 s following the completion of LCP, the proportion of subjects increased who decelerated their own vehicle to 50 km/h or less even before the vehicle under RMF started deceleration, and the minimum headway time after the vehicle under RMF started deceleration became longer.

✓ Method 3
- The timings at which the subjects started braking were distributed over a wide range of values (some people did not brake while changing lanes).
- When the vehicle under RMF decelerated upon the completion of LCP, a collision occurred (1 out of 20 cases).
- When the vehicle under RMF started deceleration after the hazard lights kept flashing for more than 2 s following the completion of LCP, some subjects started braking even before the vehicle under RMF started decelerating, resulting in a slightly lower deceleration after starting braking.

Appendix

Table of Experimental Parameters

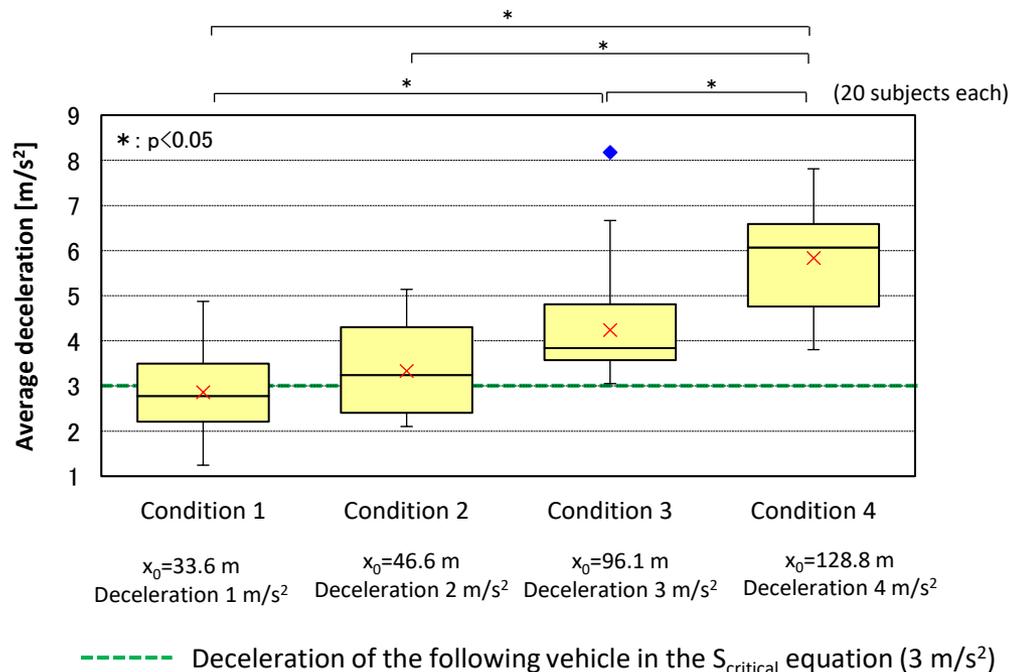| Experimental parameters	Method 1				Method 2 [*2]					Method 3			
	Condition 1	Condition 2	Condition 3	Condition 4	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 1	Condition 2	Condition 3	Condition 4
Speed of vehicle under RMF (at the point in time t_0) [km/h]	100	100	100	100	50	50	50	50	50	100	100	100	100
Speed of the following vehicle (at the point in time t_0) [km/h]	100	100	100	100	100	100	100	100	100	100	100	100	100
The timing at which the vehicle under RMF started slowing down	t_0	t_0	t_0	t_0	t_3	1 s after t_3	2 s after t_3	3 s after t_3	4 s after t_3	t_3	1 s after t_3	2 s after t_3	3 s after t_3
Deceleration of the vehicle with ALKS [m/s^2]	1	2	3	4	4	4	4	4	4	4	4	4	4
Relative distance x_0[*1] (at t_0) [m]	33.6	46.6	96.1	128.8	94.1	94.1	94.1	94.1	94.1	27.8	27.8	27.8	27.8
Relative distance x_2 (at t_2) [m]	29.1	37.6	82.6	110.8	94.1	94.1	94.1	94.1	94.1	27.8	27.8	27.8	27.8

[*1] In the experiment, x_0 was adjusted to be the set value.

[*2] In Method 2, It was assumed that the following vehicle started slowing down 0.4 s after t_2, decelerated at a deceleration of 3 m/s^2, and stopped slowing down when the speed difference with the vehicle under RMF reached 0 km/h, but then resumed slowing down at a deceleration of 3 m/s^2 0.4 s after the vehicle under RMF started slowing down. In this case, in Conditions 1 and 2, the vehicle under RMF started to decelerate before the speed difference reaches 0 km/h, and the minimum headway time was 0 s (collision).

- The average deceleration of the following vehicle was equal to or lower than the deceleration of the following vehicle in the $S_{critical}$ equation (3 m/s^2) in Conditions 1 and 2 between the 25 and 50 percentiles, and was higher than 3 m/s^2 for 75 percentile. In Condition 3 and 4, it was higher than 3 m/s^2 between the 25 and 75 percentiles, with Condition 4 it being the highest.
  →The reason Condition 4 resulted in higher deceleration was presumably that the vehicle took delay in starting braking compared to in other conditions.
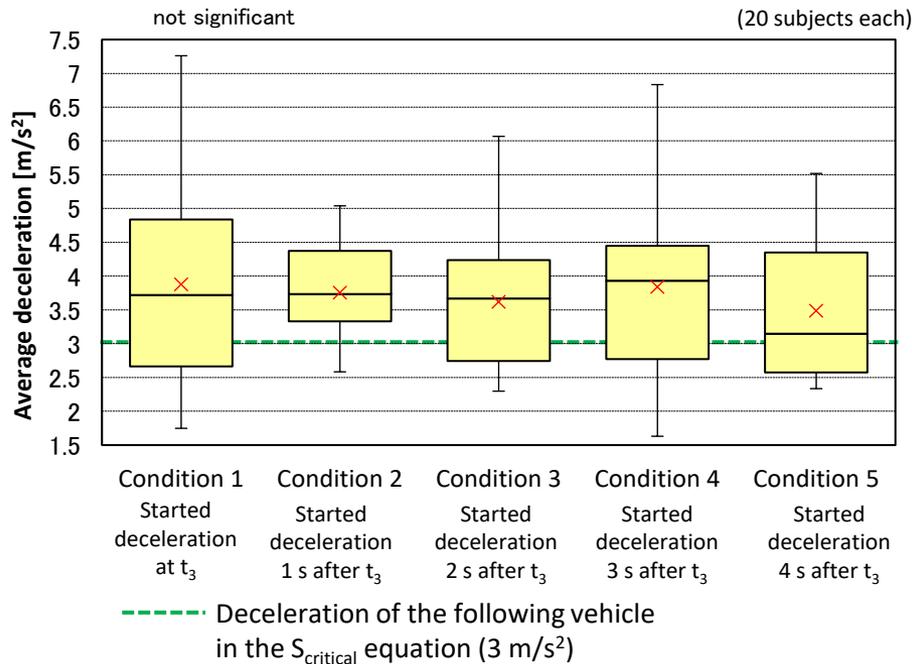
* If the driver applied the brakes more than once, the average deceleration was calculated as the average value of deceleration for the brake operation that caused the highest deceleration (the same method was used for Method 2 and Method 3).
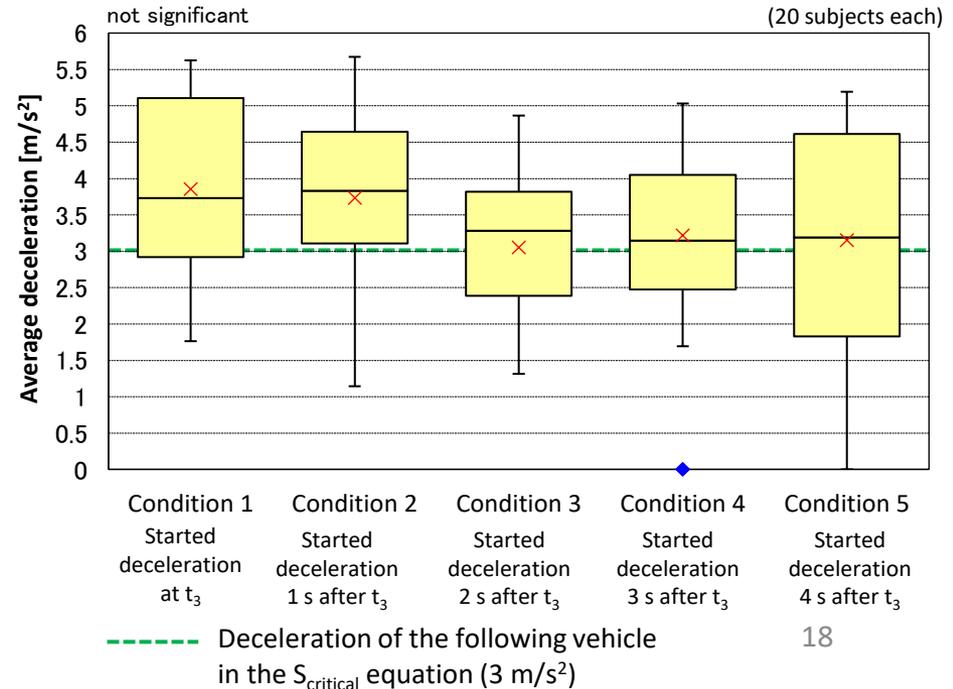

Deceleration of the following vehicle in the $S_{critical}$ equation (3 m/s^2)

- In the section before the vehicle under RMF started deceleration, the average deceleration of the following vehicle was equal to or higher than that in the $S_{critical}$ equation (3 m/s^2) between the 25 and 75 percentiles in all conditions.
- In the section after the vehicle under RMF started deceleration, the average deceleration of the following vehicle was equal to or higher than 3 m/s^2 between the 25 and 75 percentiles in Conditions 1 and 2. In Conditions 3 to 5, it was higher than 3 m/s^2 between the 50 and 75 percentiles, but the average and mean values were generally 3 m/s^2 or less between the 25 and 50 percentiles.
  - →This was presumably because that, in Conditions 3 to 5, the proportion of the drivers increased who reduced their vehicle speed to 50 km/h or less even before the vehicle under RMF started deceleration.

Before the vehicle under RMF started deceleration

After the vehicle under RMF started deceleration

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- The average deceleration of the following vehicle was equal to or higher than that of the vehicle under RMF (4 m/s^2) between the 25 and 75 percentiles in Condition 1.
- Condition 2 was lower than 4 m/s^2 between the 25 and 50 percentiles, but higher than 4 m/s^2 at 75 percentile.
- Condition 3 and Condition 4 were equal to or lower than 4 m/s^2 between the 25 and 75 percentiles.
  - → This was presumably because, in Conditions 3 and 4, some people started braking even before the vehicle under RMF started deceleration reacting to the flashing hazard lights after t_3, which distributed the average deceleration in lower areas.

not significant   (20 subjects each)

Average deceleration[m/s^2]

Condition 1	Condition 2	Condition 3	Condition 4
Started deceleration at t_3	Started deceleration 1 s after t_3	Started deceleration 2 s after t_3	Started deceleration 3 s after t_3

------ Deceleration of the vehicle under RMF (4 m/s^2)