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Japanese Study on Lane Changes during MRM

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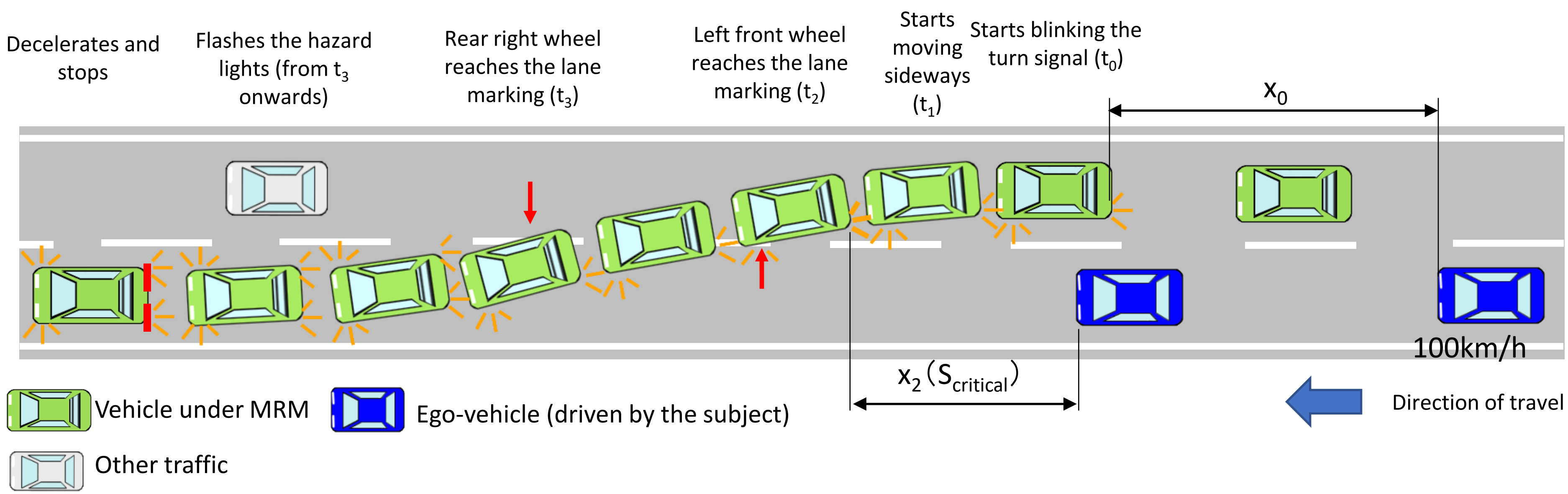
Objectives and Summary of the Study

- Regarding a situation where a vehicle under MRM changes lanes on expressways from the second lane to the first 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 MRM, 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 first 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.

Experimental Method (Summary of the Experimental Situations)



- 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.

Experimental Method (Experimental Setups)

✓ Method 1

- The speed of the vehicle under MRM 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. In the equation, the values of V_{MRM} are changed with time depending on the condition of deceleration.

✓ Method 2

- The speed of the vehicle under MRM 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 MRM 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)

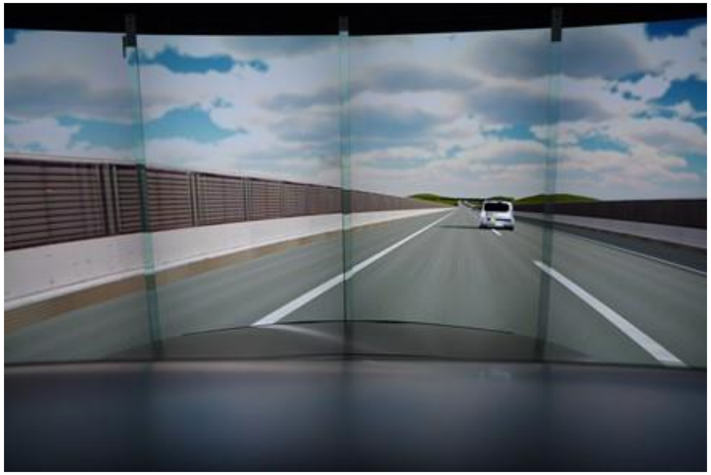
$$\mathbf{S_{critical} = (V_{rear} - V_{MRM}) * t_B + (V_{rear} - V_{MRM})^2 / (2 * a) + V_{MRM} * t_G}$$

$S_{critical}$: 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_{MRM}: Speed of the vehicle under MRM [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)

Experimental Method (Driving Simulator Used in the Experiment)

External view of the DS

Driver's seat

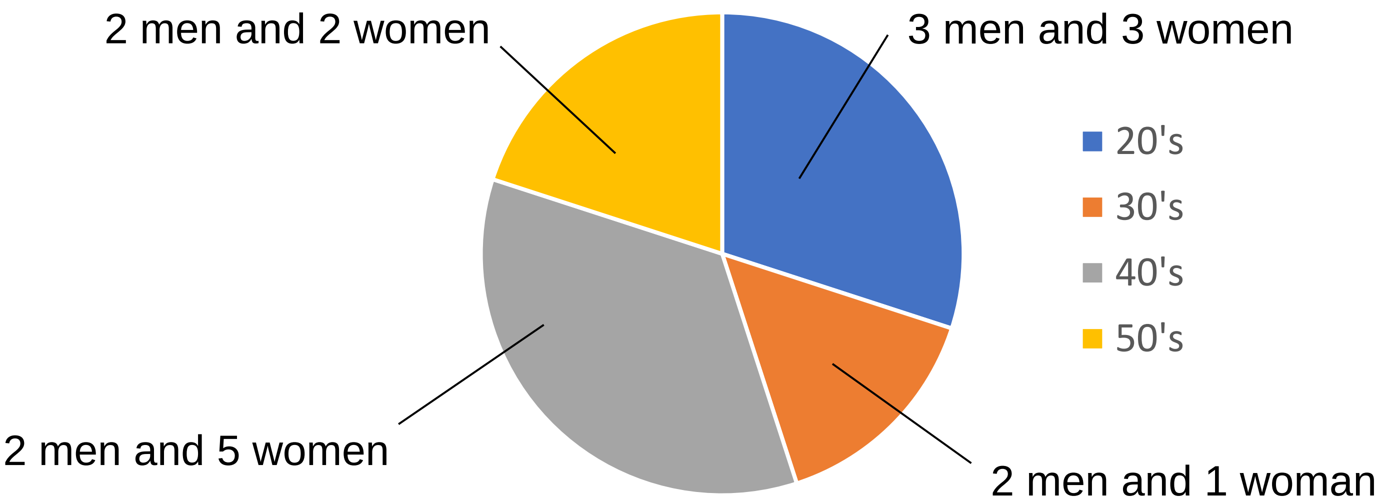


A scene from the simulator screen images

- 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.

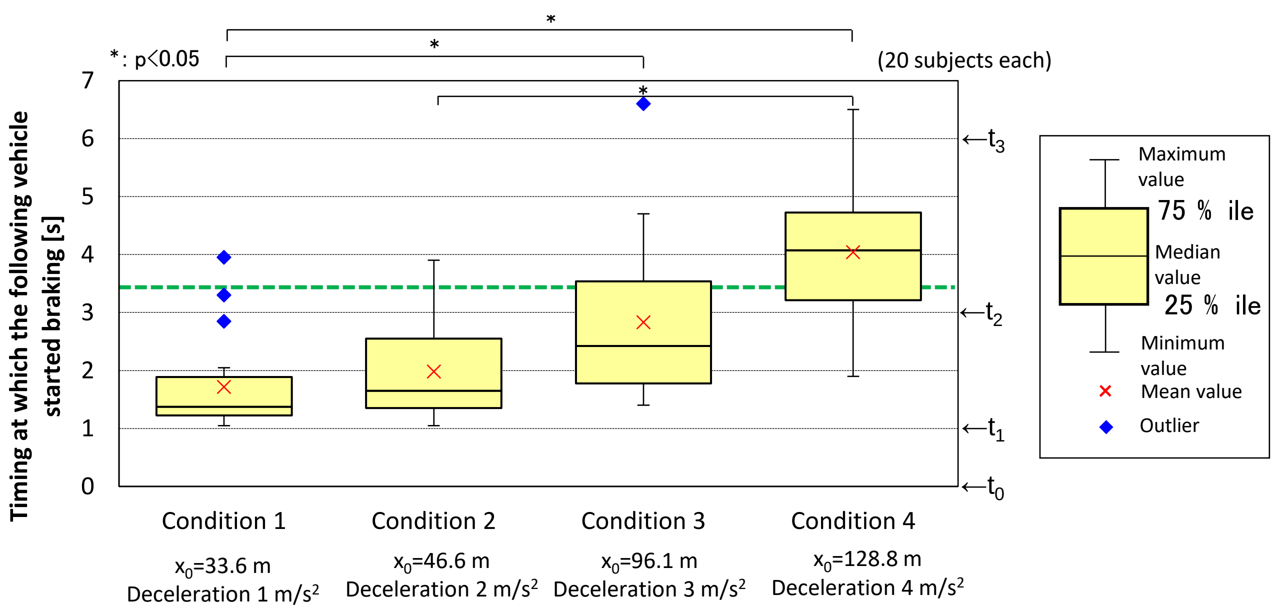
Experimental Method (Composition of the subjects)

- 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).



Experimental Results (Method 1) - Timing at Which the Following Vehicle Started Braking -

- 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**.



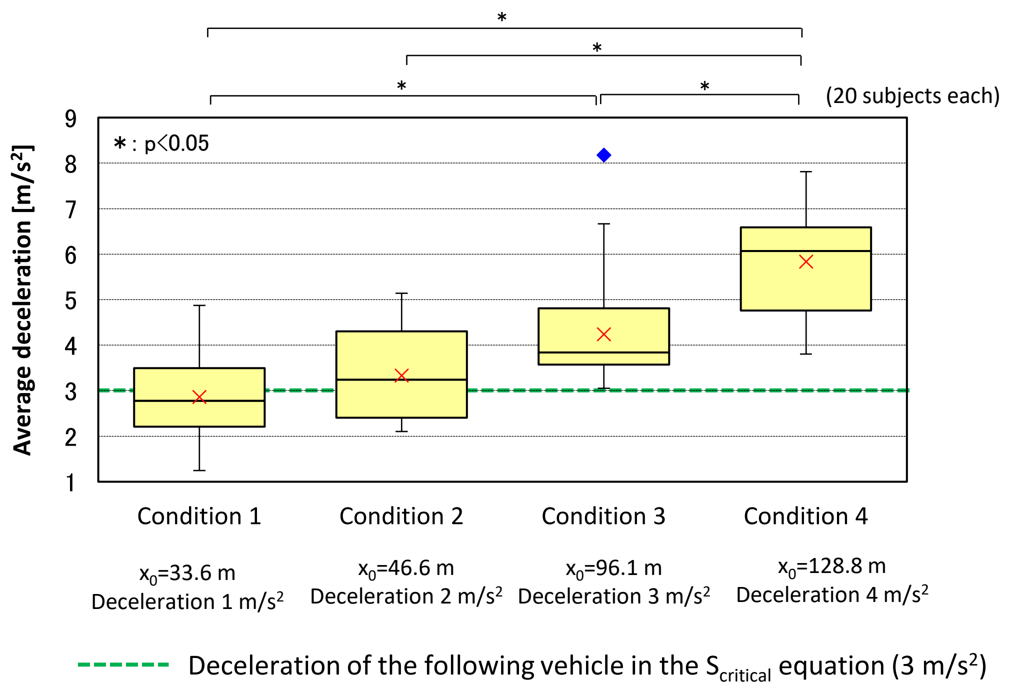
■ Speed at the point in time t_0
Vehicle under MRM: 100 km/h
Following vehicle: 100 km/h
■ When the vehicle under MRM started deceleration: t_0

-------- The timing at which the following vehicle started deceleration in the $S_{critical}$ equation (0.4 s after t_2)

Experimental Results (Method 1) - Average Deceleration* of the Following Vehicle -

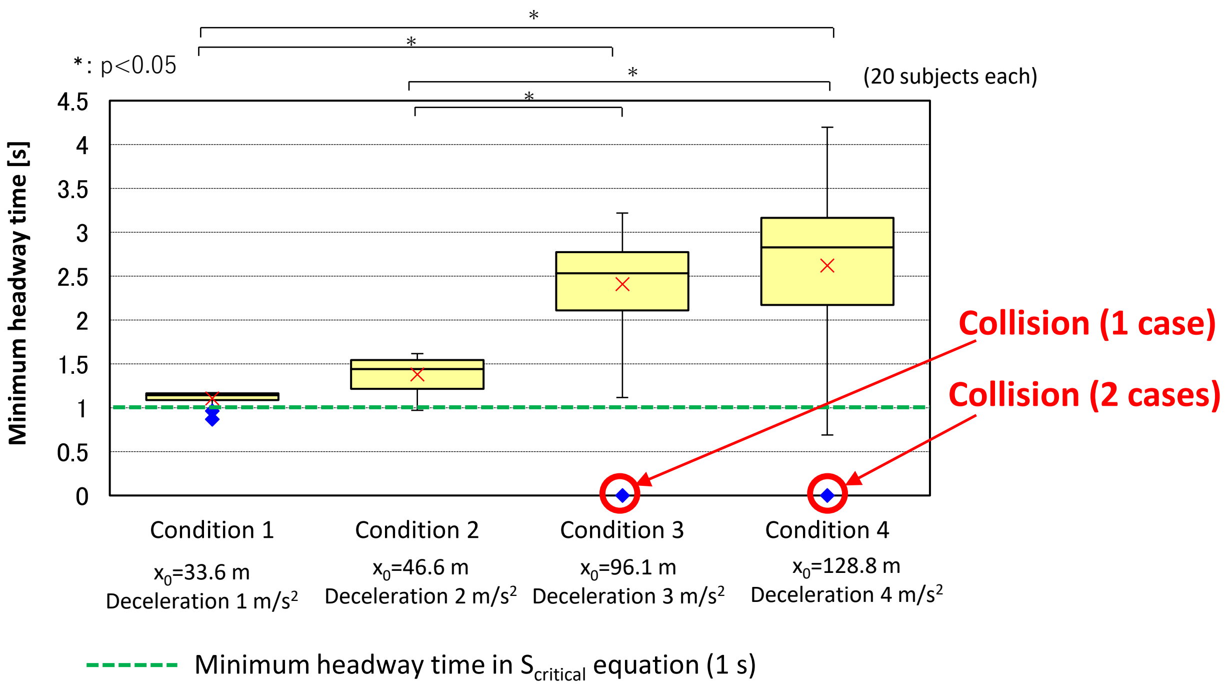
- The average deceleration of the following vehicle was equal to or lower than the deceleration of the following vehicle in the $S_{critical}$ equation (3 m/s^2) in Conditions 1 and 2 between the 25 and 50 percentiles, and was higher than 3 m/s^2 for 75 percentile. **In Condition 3 and 4, it was higher 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).



Experimental Results (Method 1) - Minimum Headway Time -

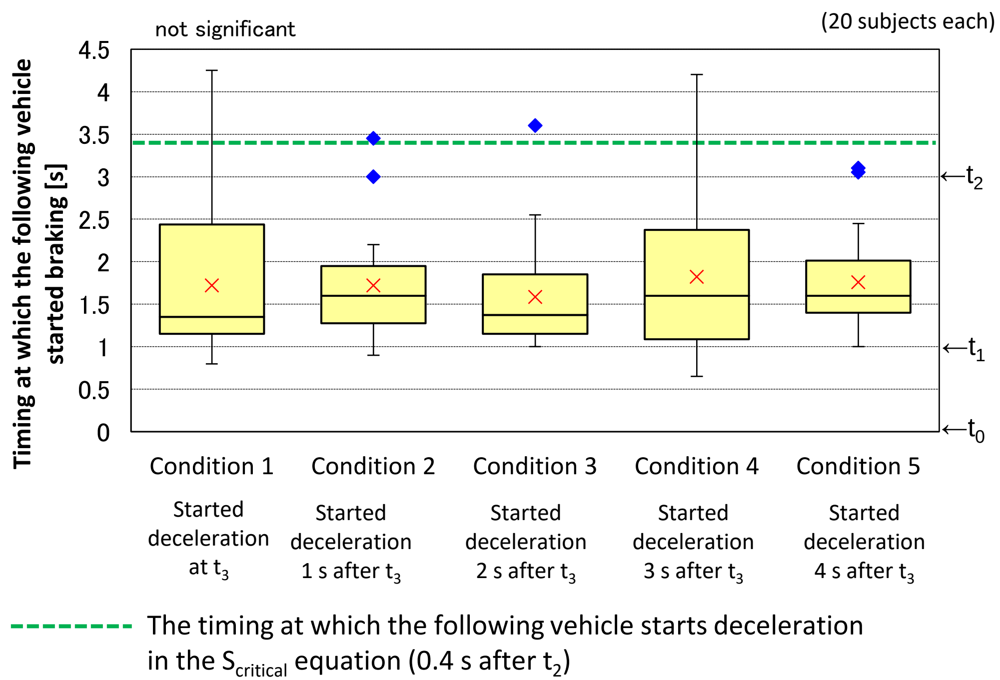
- In Conditions 3 and 4, the minimum headway time dropped to 0 s and **collisions occurred** (3 cases).
- Except for the collisions, all conditions showed that the minimum headway time (1 s) in the $S_{critical}$ equation was exceeded for values between the 25 and 75 percentiles.
- For values between 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 MRM started blinking its turn signal was longer than that of Conditions 1 and 2.



Experimental Results (Method 2) - Timing at Which the Following Vehicle Started Braking -

- 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 MRM, 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**.

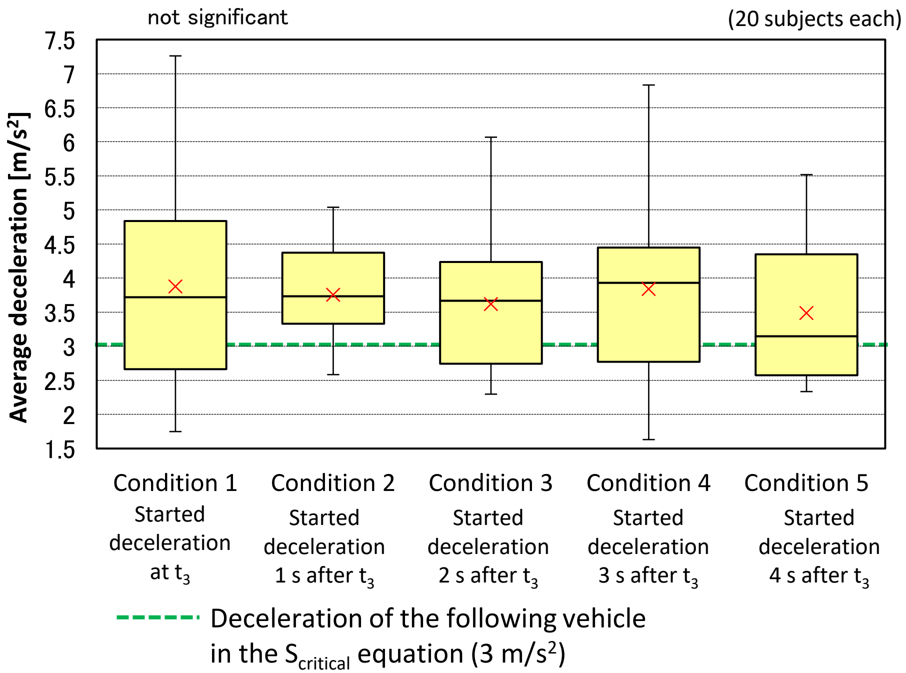
- Speed at the point in time t_0
  Vehicle under MRM: 50 km/h
  Following vehicle: 100 km/h
- Relative distance (x_0) at the point in time t_0: 94.1 m
- Deceleration of the vehicle under MRM: 4 m/s²



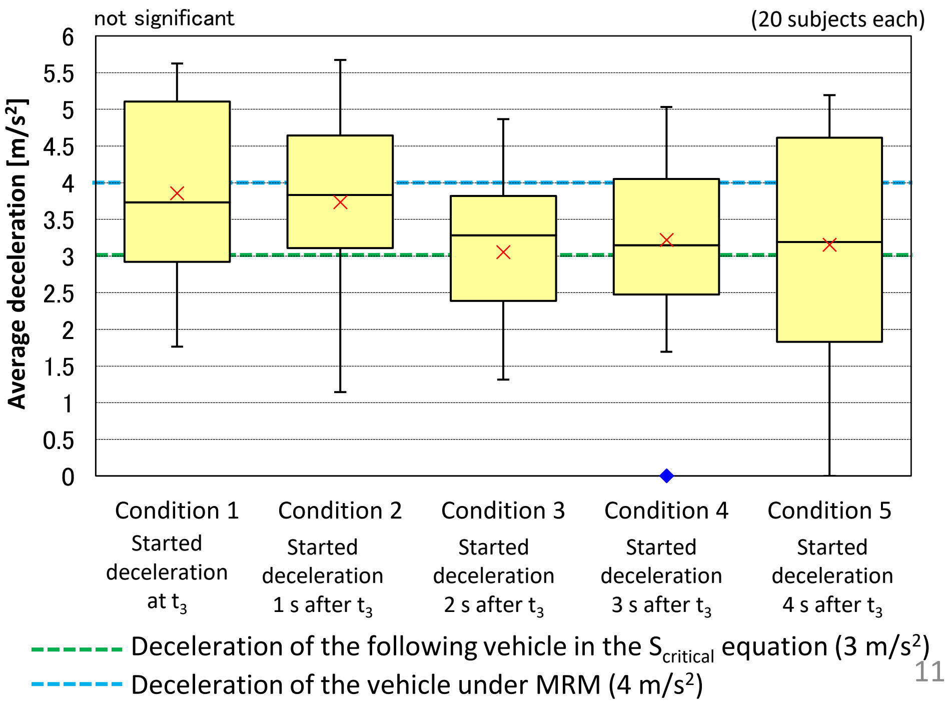
Experimental Results (Method 2) - Average Deceleration of the Following Vehicle -

- In the section before the vehicle under MRM 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 MRM 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 MRM started deceleration**.

Before the vehicle under MRM started deceleration



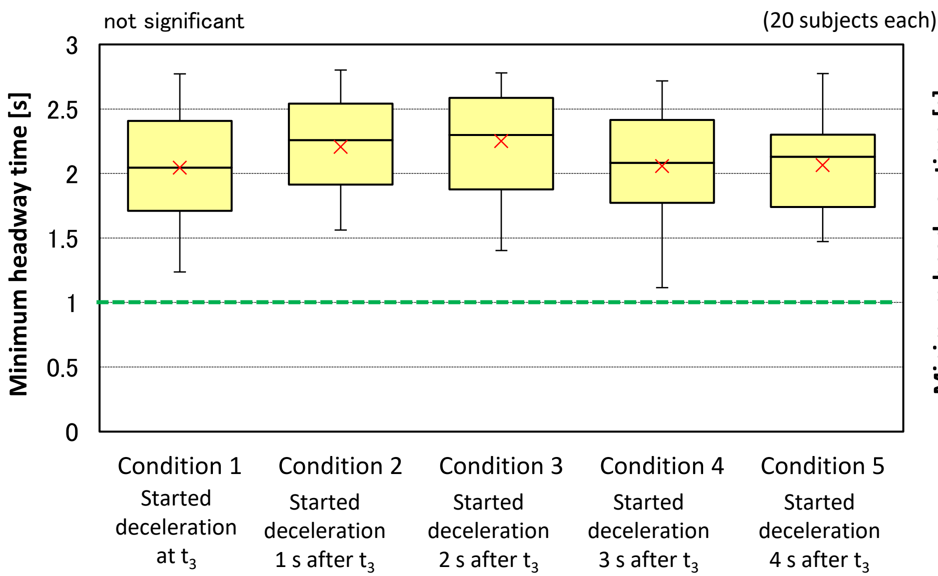
After the vehicle under MRM started deceleration



Experimental Results (Method 2) - Minimum Headway Time -

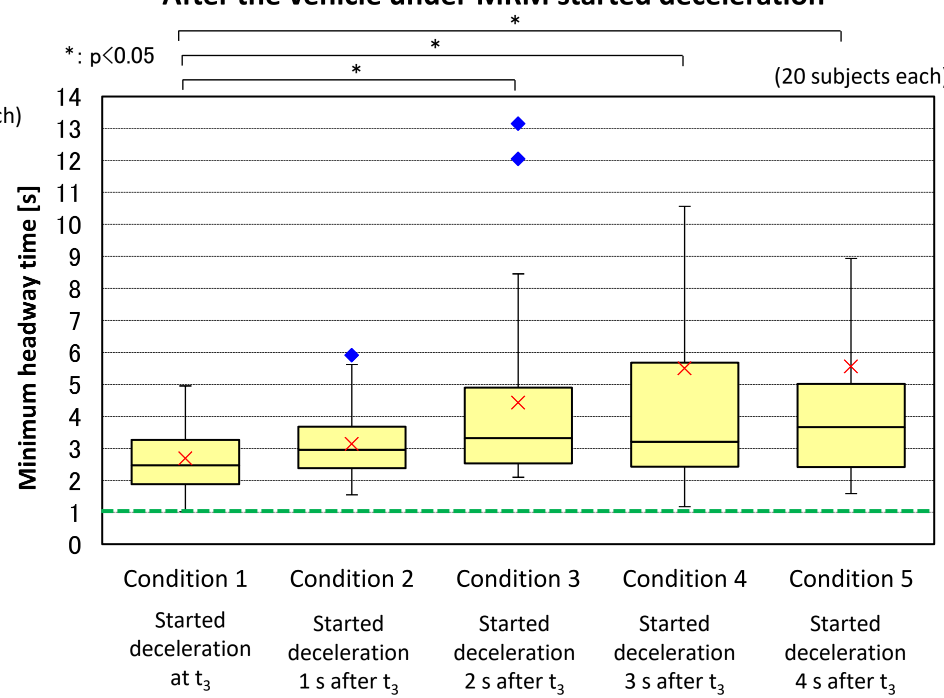
- In the section before the vehicle under MRM started deceleration, **the minimum headway time was longer than that in the $S_{critical}$ equation (1 s)** between the 25 and 75 percentiles in all conditions.
- In the section after the vehicle under MRM started deceleration, too, the minimum headway time 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 MRM started deceleration



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

After the vehicle under MRM started deceleration

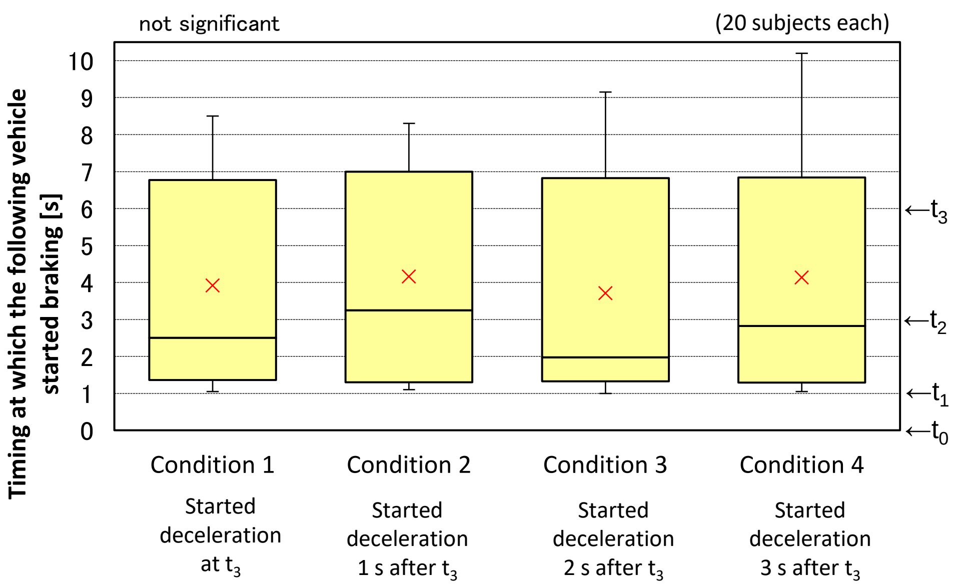


Minimum headway time (1 s) in the $S_{critical}$ equation (Conditions 3 to 5)

Experimental Results (Method 3) - Timing at Which the Following Vehicle Started Braking -

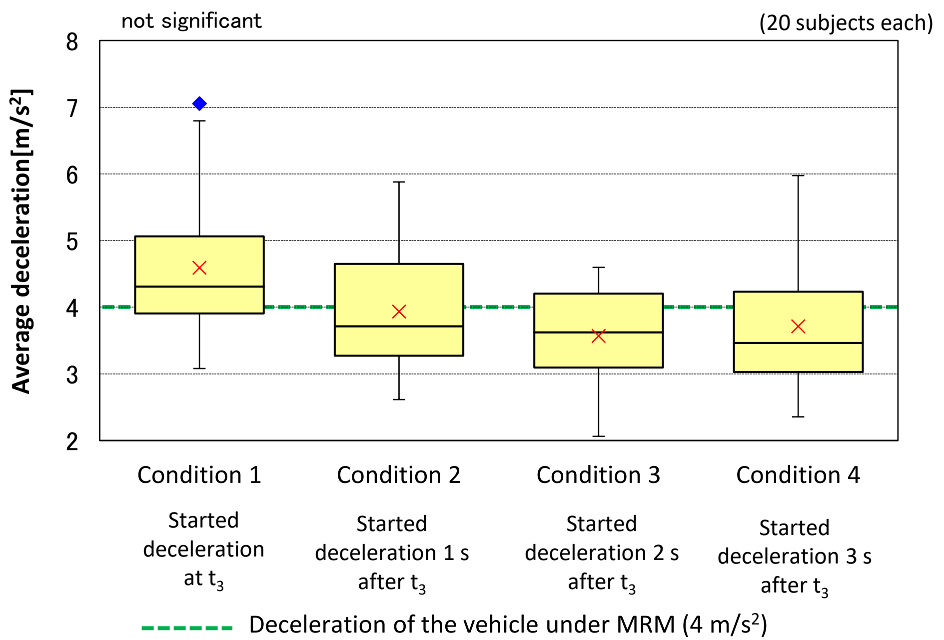
- **The timing at which the following vehicle started braking was more widely distributed than in Methods 1 and 2**, ranging roughly from 1.3 s to 7 s between the 25 and 75 percentiles in all conditions.
  →This was presumably because there was no speed difference at t_0 and the relative distance was 27.8 m (equivalent to 1 s of headway time), which, after the vehicle under MRM 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 MRM started deceleration**.

- Speed at the point in time t_0
  Vehicle under MRM: 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 MRM: 4 m/s²



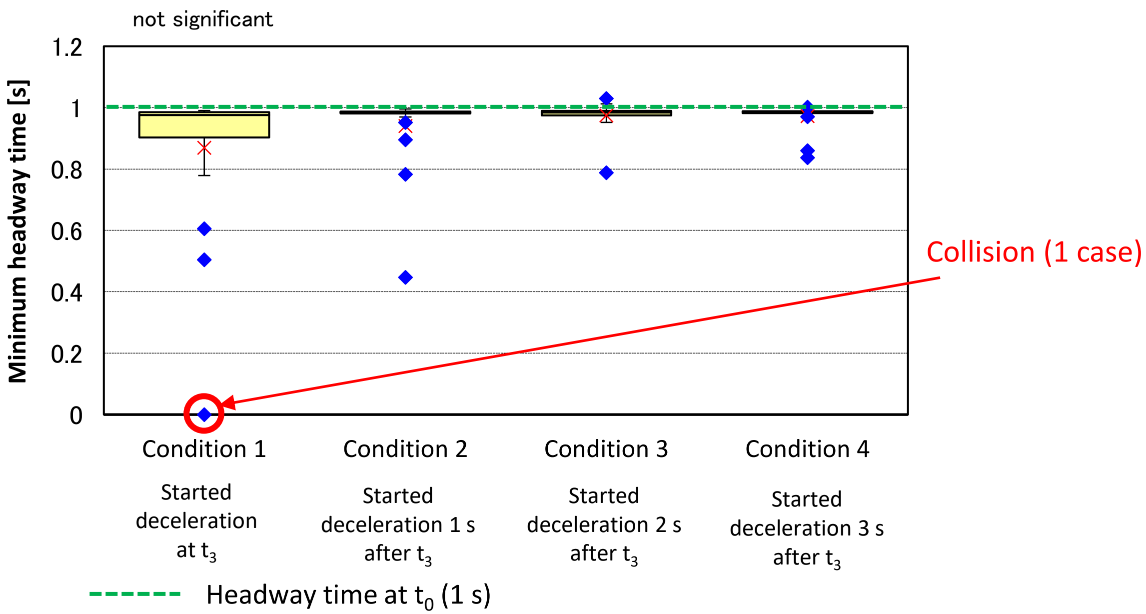
Experimental Results (Method 3) - Average Deceleration of the Following Vehicle -

- The average deceleration of the following vehicle was equal to or higher than that of the vehicle under MRM (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 MRM started deceleration reacting to the flashing hazard lights after t_3**, which distributed the average deceleration in lower areas.



Experimental Results (Method 3) - Minimum Headway Time -

- 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 MRM 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 MRM 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 MRM started deceleration, and **the minimum headway time after the vehicle under MRM 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 MRM decelerated upon the completion of LCP, a collision occurred** (1 out of 20 cases).
  - When the vehicle under MRM 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 MRM started decelerating**, resulting in a slightly lower deceleration after starting braking.

Proposal

Based on the results of the study, Japan proposes adding the following requirements* :

*This study is mainly for MRM-LC, but this result can be applied to Regular LC as well.

5.2.6.7.7. **In case the ALKS decelerates the vehicle during a ~~lane change procedure~~RLCP, this deceleration shall be factored in when assessing the distance to a vehicle approaching from the rear, and the deceleration shall [not exceed 2m/s^2, except for the purpose of avoiding or mitigating the risk of an imminent collision / be manageable for the vehicle approaching from the rear].**
How the provisions of this paragraph are implemented in the system design shall be demonstrated to the Technical Service during type approval.

5.2.6.7.8. **Where there is not sufficient headway time for the vehicle behind at the end of the ~~lane change procedure~~RLCP, the ALKS shall not increase the rate of deceleration for [at least 2 seconds / a certain period of time] after the completion of the ~~lane change procedure~~RLCP except for the purpose of avoiding or mitigating the risk of an imminent collision.**
How the provisions of this paragraph are implemented in the system design shall be demonstrated to the Technical Service during type approval.

Proposal

5.5.7.12.8.~~.2.6.7.7.~~ In case the ALKS decelerates the vehicle during a ~~lane change procedure~~MRMLCP, this deceleration shall be factored in when assessing the distance to a vehicle approaching from the rear, and the deceleration shall [not exceed 2m/s^2, except for the purpose of avoiding or mitigating the risk of an imminent collision / be manageable for the vehicle approaching from the rear].
How the provisions of this paragraph are implemented in the system design shall be demonstrated to the Technical Service during type approval.

5.5.7.12.9.~~2.6.7.8.~~ Where there is not sufficient headway time for the vehicle behind at the end of the ~~lane change procedure~~MRMLCP, the ALKS shall not increase the rate of deceleration for [at least 2 seconds / a certain period of time] after the completion of the ~~lane change procedure~~MRMLCP except for the purpose of avoiding or mitigating the risk of an imminent collision.
How the provisions of this paragraph are implemented in the system design shall be demonstrated to the Technical Service during type approval.

Appendix

Experimental Method (Experimental Setups)

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 MRM (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 MRM 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 under MRM [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 MRM reached 0 km/h, but then resumed slowing down at a deceleration of 3 m/s^2 0.4 s after the vehicle under MRM started slowing down. In this case, in Conditions 1 and 2, the vehicle under MRM started to decelerate before the speed difference reaches 0 km/h, and the minimum headway time was 0 s (collision).