本資料の説明は、「【解説】 運転の遅延時間と安全走行」に記載しています。
(https://www.soliton.co.jp/lp/rp/exposition/)

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Draft: Regulations for the latency time of communication at the remote driving system

1. Regulation for the increase of stopping distance at the braking

In the remote driving, communication latency (image latency: T_{GG}, Control latency: T_{CS}) exists and during remote driving, the driver needs a time to recognize the danger and the time to start the vehicle operation after the driver activates the braking is increased compared to the direct driving.

Therefore, stopping distance (free running distance + braking distance) that is the distance to the point of vehicle stop from the point when the direct driver recognizes the danger seems to be apparently increased at the remote driving compared to the direct driving under the same road conditions.

In addition, depending on the various driving cases and the performances of image transmission and display of remote system, the timing of danger recognition by the remote driver may be delayed (Δ) more than the image latency time (T_{GG}). In this case, such delay (Δ) is considered as an increase of driver response time.

The apparent increase of stopping distance compared to the direct driving is the subject to the regulation and it is restricted 1 m or less.

(1) General equation

(In case that Δ is not negligible or it is not possible to confirm that Δ is negligible.)

$$v * (T_{GG} + T_{CS} + \Delta) \leq 1.0 \text{ m}$$

(2) In case that Δ is almost negligible

(Under the various conditions such as daytime, very low speed, suitable camera resolutions and view angle, suitable monitor resolution and screen structure, Δ is considered to be neglected such as actual demonstration tests.)

$v * (T_{GG} + T_{CS}) \leq 1.0$ m   (Same as regulation in section 3 below)

2. [Reference regulation] Regulation for the rear-end collision prevention at the remote driving on the road with speed limit.

Instead that the increase of stopping distance for the remote operated vehicle is regulated, it is another approach that the remotely operated vehicle drives with the reduced speed which does not increase the stopping distance not to exceed the stopping distance of direct operated vehicle that drives with the speed limit of the road.

(1) Based on the communication latency ($T_{GG} + T_{CG}$) of remote driving system, the speed to be reduced from the speed limit of each road (32 km/h: LSAD, 20km/h: LSAD in Japan) for the remote driving is shown in the figure 1. (Reduction of speed is indicated with red line with two-side arrows)

ex. In case that $T_{GG} + T_{CS} = 300$ ms, the reduction of speed against speed limit of 32 km/h is approx. 4 km/h.†

† Figure 1 Addendum is a diagram when considering the increase of remote driver response time ⊿. This diagram shows that the value of reduction speed should be further increased.

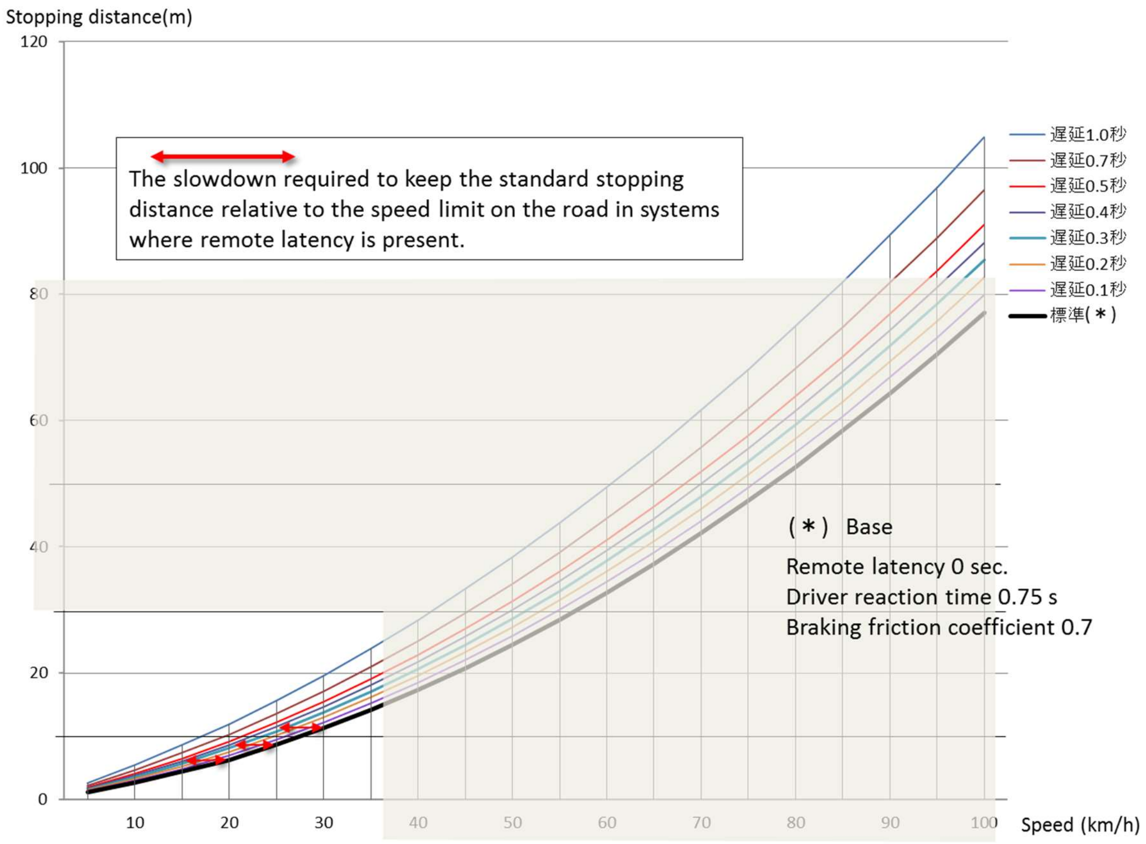


Figure 1 - Stopping distance in case of remote latency
(Latency is the RTT of uplink video latency + downlink control latency)

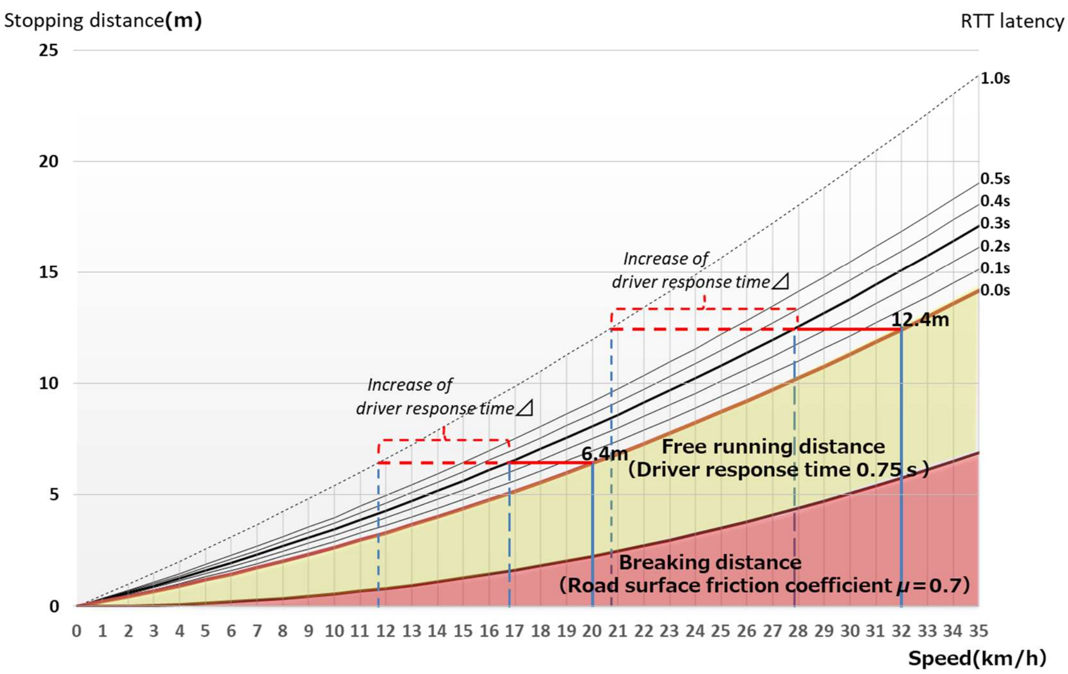


Figure 1 Addendum – Stopping distance in case of remote latency
(Considering an increase of remote driver response time)

(2) Secure the vehicle distance in-front

Secure the vehicle distance in-front that corresponds to the stopping distance (including the increase of stopping distance) specified by the driving speed and general equation in Section 1.

[Remarks] in case that the regulation in Section 2 (1) is satisfied, in principle, increase of stopping distance is eliminated and the regulation in section 1 is no more necessary. However, in case of normal driving situation (not at the braking), other regulations described in section 2 (2), 3, 4 and 5 are still necessary.

3. (Normal) Regulation for straight driving

Normal straight driving of remote driven vehicle should be 1 m or less total error distance caused by subject vehicle forward image latency and control latency. This value corresponds to the allowable regulation of the stopping distance increase in case that Δ is negligible as described in section 1.

$v * (T_{GG} + T_{CS}) \leq 1.0$ m (straight)

4. (Normal) Regulation for curve driving

In case of normal curve driving with remote driven vehicle, the overrun width from the normal path of the direct driving vehicle with consideration of the minimum rotation radius should be kept in 0.5 m or less.†

In case the curvature angle is more than 90 deg, regardless the curvature radius, this overruns width shall not exceed the total error distance with image latency and control latency.

Consequently,

$v * (T_{GG} + T_{CS}) \leq 0.5$ m (curve)

This regulation means that in case of remote driving, speed of curve driving should be 50% or less than that of straight driving.†

† If the curvature radius of the curve is sufficiently larger than the vehicle minimum turn radius, the overrun width will not exceed 0.5m.

According to analysis, in case that the curvature radius is greater than the sum of the vehicle minimum turn radius and the delay error distance, the overrun width does not exceed at most 42% of the delay error distance. Also, as the curvature radius increases further, it asymptotically approaches zero.

In other words, if the curvature radius of the curve on which the vehicle is running is greater than the sum of the above values, and the delay error distance is about 1 m, the overrun width is "automatically" guaranteed not to exceed 0.5m.

Therefore, the above inequality is meaningful only for sharp curve where the curvature radius is less than the sum of the vehicle minimum turn radius and the delay error distance, or less than twice the vehicle minimum turn radius.

Consequently,

$v \cdot (T_{GG} + T_{CS}) \leq 0.5m$

(Curve radius: less than vehicle minimum turn radius + delay error distance < less than twice the vehicle minimum turn radius)

5. Regulation of vehicle control stability during the curve driving

$T_{GG} \leq 300$ ms (temporary regulation)

This is caused mainly by the excess continuous maneuver control from the remote driver because the remote driver can not recognize the start of operation immediately after the activation of control at the vehicle by the remote driving control with control latency due to the image latency.

This phenomenon is obviously affected by the absolute time of image latency exclusively, but it will be immediately settled if speed is reduced during the driving.

Currently detailed analysis of this phenomenon and the countermeasures are under development.

Furthermore, this phenomenon can be settled by the training and mastering of remote driver.

Descriptions of regulations (Draft)

1. Increase of apparent stopping distance (free running distance + braking distance) of remote driving system at the braking

(a) Remotely operated driving has the communication latency (image latency and control latency) and increases stopping distance from the point of danger recognition to the stop point compare to the direct driving which has no latency when the vehicles are same speed (Figure 2).

Explanation of Figure 2

Direct driving vehicle <0>

Initial speed: v_0

Driver response time: T_H

Road surface friction coefficient: μ (= 0.7) (same for 3 vehicles)

Free running distance: $L_{F0} = v_0 * T_H$

Braking distance: $L_{B0} = (v_0^2 / 254\mu)$: L_{B0} [m] , v_0 [km/h].

Stopping distance: $L_{S0} = L_{F0} + L_{B0}$

Remote driving vehicle <1>

Image latency: T_{GG}

Control latency: T_{CS}

Initial speed: $v_1 = v_0$

Driver response time: $\Delta + T_H$ (assume to increase Δ)

Road surface friction coefficient: μ (same)

Free running distance: (Starting point is the danger recognition point of <0>)

$L_{F1} = v_0 * (T_{GG} + [\Delta + T_H] + T_{CS})$: apparent increase

Braking distance: $L_{B1} = L_{B0}$

Stopping distance: (Starting point is the danger recognition point of <0>)

$L_{S1} = L_{F1} + L_{B1}$

$= L_{S0} + v_0 * (T_{GG} + T_{CS} + \Delta)$

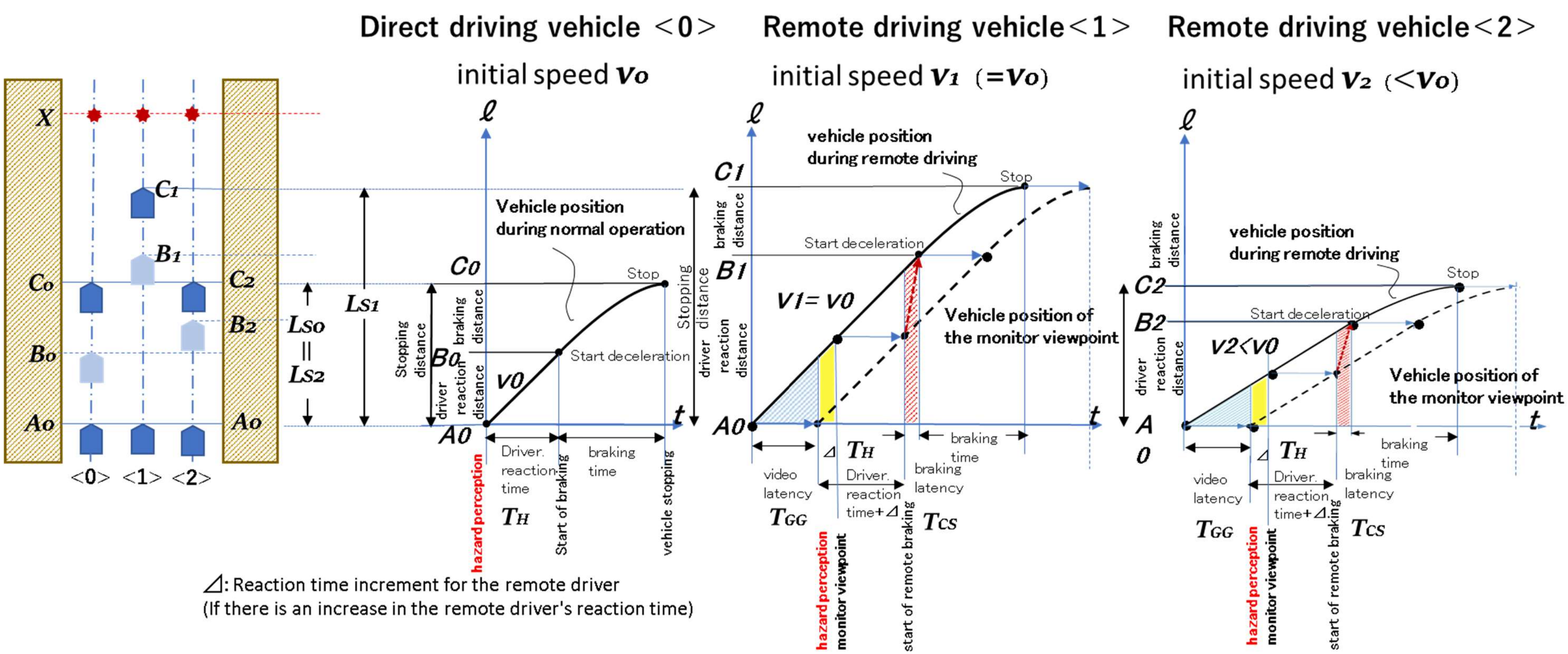


Figure 2 - Stopping distance during braking diagram

Vehicle stopping distance L_{S1} driven by remote driving system against initial speed v_0 are shown in Figure 1, using the latency time (T_{GG} + T_{CG}) as a parameter. Starting point is the danger recognition point by direct driver.) †

† The stopping distance when considering the value of ⊿ within a certain range is shown in Figure 1 Addendum.

(b) Estimation of Δ through the demonstration tests

From the previous equations, when the initial speed is same, increase of stopping distance of remote vehicle is;

$LS_1 - LS_0 = v_0 * (T_{GG} + T_{CS} + \Delta)$.

Δ is an important factor to evaluate the safety performance except for the latency time of visual and audio transmission and indication factors in the remote driving system, and from the various system performances and functions of many different driving situations, it should be evaluated and measured comprehensively.

In the future, multiple evaluation tests under the various conditions should be conducted and improvements of Δ should be investigated.

In case of demonstration test of remote driving with less than certain speed, it has already been experienced that Δ can be kept at remarkably low under the proper condition.

Based on Figure 1, stopping distance L_{S0} against initial speed v_0 of direct driving (no latency) LSAD vehicle is shown as below. L_{SO} is less than 13 m as maximum and less than 10 m when v_0 is 25 km/h.

Initial speed V_0 (km/h)	Stopping distance L_{SO} (m)
32	12.42
30	11.31
25	8.72
20	6.42
15	4.40
10	2.26

In case that the forward view distance to be monitored from remote driven vehicle is less than 40 m, it is observed through the experiments that Δ can be significantly small with optimization of applied camera field of view, resolution, monitoring conditions etc. at the remote driving system demonstration tests.

(Remarks) Summary of conditions at the demonstration tests: 3 cameras (2K standard HTV, 30 fps) are horizontally set to generate the image with view angle of 200 degree (horizontal) and 66 deg (vertical). Proper monitor resolution and 2 stage (upper and lower) screen structure of monitor. Remote driving speed is approx. 10 km/h.

(1) During daytime, recognition time of incandescent type signal red lamp at a distance of approximately 40 m by the operator are confirmed and there is no remarkable difference between direct view and image through camera and screen.

(2) In fine day, during the driving at the backlight with 10 deg solar altitude, forward environmental visibility of remote driving is rather higher than that of direct view driving.

Under these remote driving systems with such driving conditions, it is estimated that

$v_0 * (T_{GG}+T_{CS})$

is possible to be considered.

This regulation value is as below in consideration of consistency with section 3 below.

$\underline{v_0 * (T_{GG}+T_{CS}) \leq 1\ \text{m}}$

(In the range of under 25 km/h, it is within the range of 10 m visibility even at the stopping distance added this allowable increase.)

2. Speed reduction value from the direct driving speed by remote driving not to exceed the stopping distance of direct driving

(a) In case the remote driven vehicle run on the road with speed limit, in order not to run into the following direct driven vehicle, the measure as described in the police guideline in Japan that speed of remote driven vehicle is reduced from the limit speed not to exceed the stopping distance of direct driven vehicle, is considerable.

Speed reduction value is calculated as following.

In Figure 2,

<u>Remote driving vehicle <2></u>

Image latency: T_{GG}

Control latency: T_{CS}

Initial speed: $v_2 < v_0$

Driver response time: T_H (assume Δ is negligible within the considering range)

Road surface friction coefficient: μ (=0.7, common in all case)

Free running distance: $L_{F2} = v_2 * (T_{GG} + T_H + T_{CS})$

Braking distance: $L_{B2} = v_2^2/254\mu$: L_{B2} [m] , v_2 [km/h] .

Stopping distance: $L_{S2} = L_{F2} + L_{B2}$

Now $L_{S2} = L_{S0}$, therefore

$$v_2 * (T_{GG} + T_H + T_{CS}) + v_2^2/254\mu$$
$$= v_0 * T_H + v_0^2/254\mu$$

Calculate v_2 against v_0 at $L_{S2} = L_{S0}$ with latency time ($T_{GG} + T_{CG}$) of remote driving system as parameter.

Based on Figure 1, for example, in case that latency time ($T_{GG} + T_{CG}$) is 0.3 s, approx. 4 km/h speed reduction from the road speed limit is necessary when the road speed limit is less than 30 km/h.

(b) Security of in-vehicle distance

Stopping distance with consideration of system latency corresponding to the speed of the remote driving should be secured.

3. (Normal) Regulation of straight driving

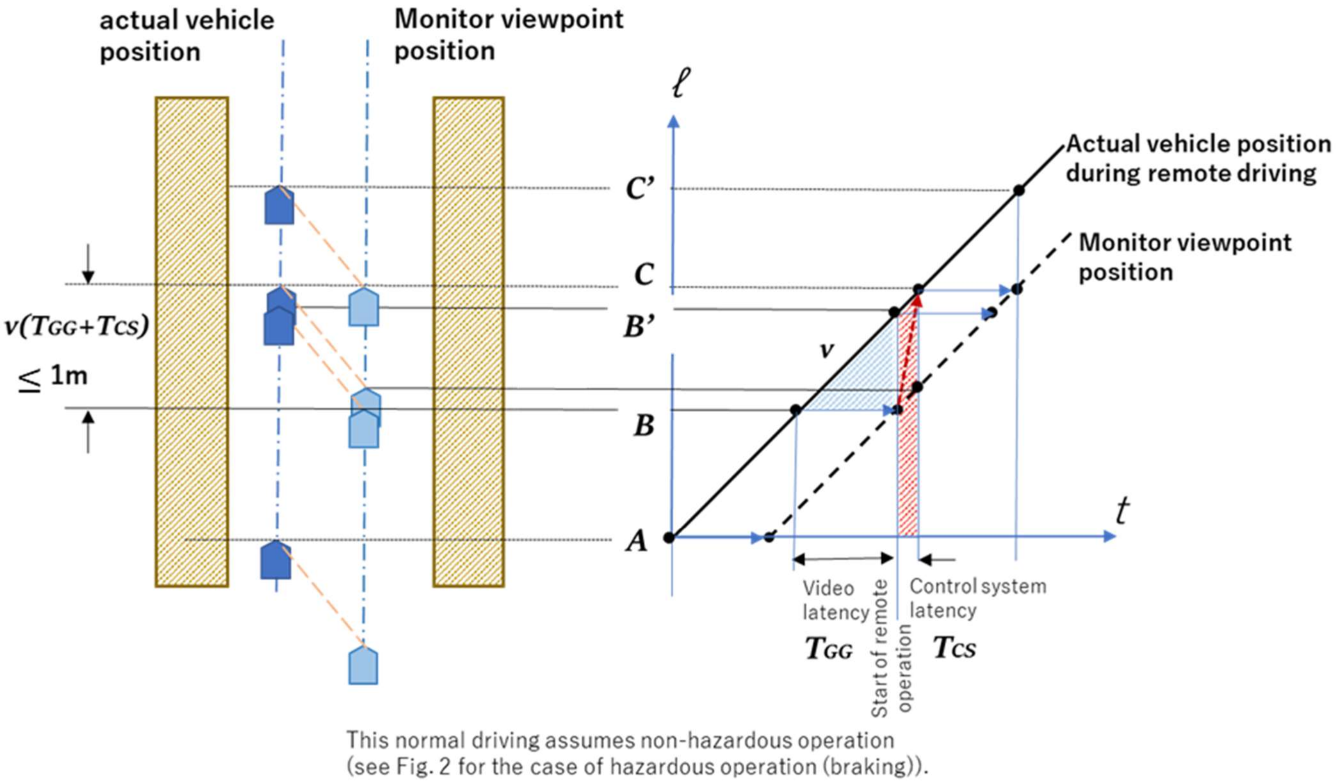


Figure 3 - Straight line driving normal and remote driving diagram

In this normal driving, normal operation is supposed, and emergency operation is not supposed, so driver response time itself is not considered. (Emergency operation is shown in Figure 2.)

Regulation is settled to limit the total error distance of image latency and control latency of remote forward driving in 1 m or less compare to the normal straight driving. This value is corresponding to the allowable regulation of stopping distance increase as described in section 1.

$v * (T_{GG} + T_{CS}) \leq 1.0$ m (straight)

４．(Normal) Regulation of curvature driving

See Figure4.

In this normal driving, normal operation is supposed, and emergency operation is not supposed, so driver response time itself is not considered. (Emergency operation is shown in Figure 2.)

In case of normal curve driving of remotely driven vehicle, overrun width δ from the normal driving path of direct driving with consideration of vehicle minimum turn radius is settled in 0.5 m or less.

Maximum gap δ between the normal path by direct driving vehicle and the path by remote driving vehicle is considered in case that the vehicle with minimum turn radius r_{min} drives curve road at the right angle with radius R.

Remotely driven vehicle driving direction (tangential direction of curve) overrun width is defined as L,

$\delta = L$ (in case $r_{min} \geq R$)

$\delta < L$ (in case $r_{min} < R$)

At this point, $L = v * (T_{GG} + T_{CS})$ (total error distance of image latency and control latency)

Therefore δ =< 0.5 m can be satisfied when the total error distance of image latency and control latency is 0.5m or less.

$v * (T_{GG} + T_{CS}) \leq 0.5$ m (curve)

This regulation means that every remotely driven vehicle run curvature road 50% or less speed of straight driving speed.†

† Figure 4 Addendum shows a related formula for obtaining the ratio δ/L between the overrun width δ and the overrun length L.

If the parameter $(R - r_{min})/L > 1.0$, then always $\delta/L < 0.42 < 0.5$.

Under this condition, $\delta \leq 0.5$m is automatically satisfied whenever $L \leq 1.0$m, even if the remote driving vehicle does not reduce speed.

Therefore, when $(R - r_{min})/L \leq 1.0$ is satisfied, that is, when driving on a sharp curve such as

$R \leq r_{min} + L$, the above regulation is validly applied.

Consequently,

$v \cdot (T_{GG} + T_{CS}) \leq 0.5m$ (curve radius : $r_{min} + L$ or less $< 2 \cdot r_{min}$ or less)

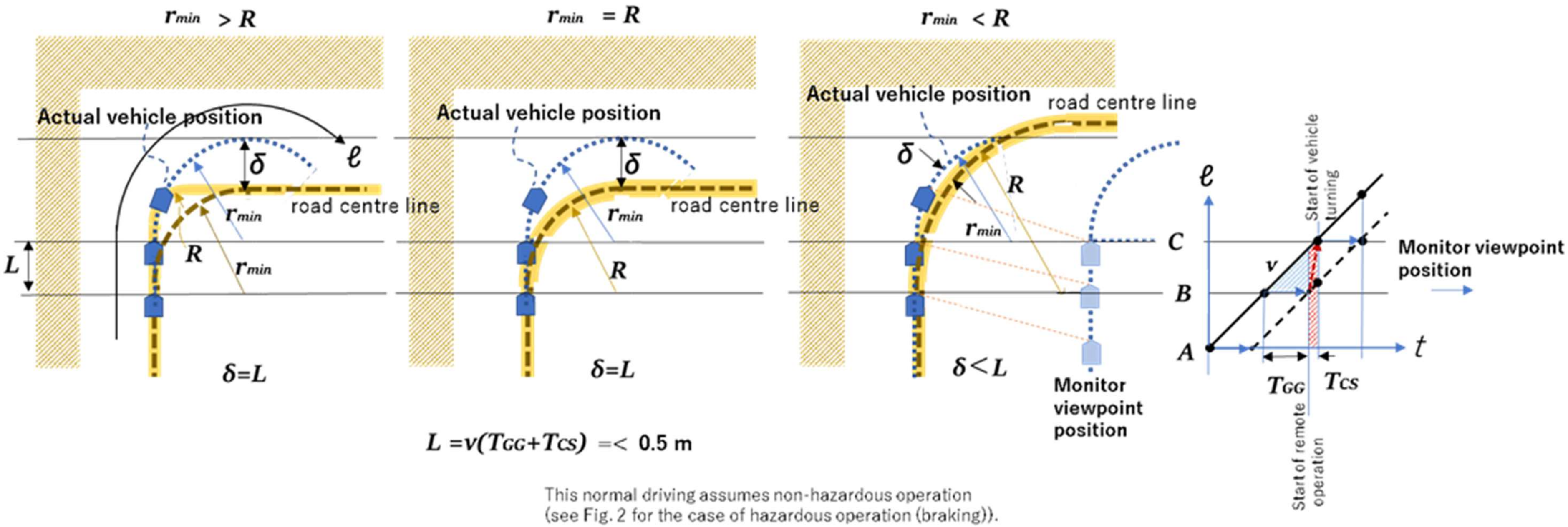
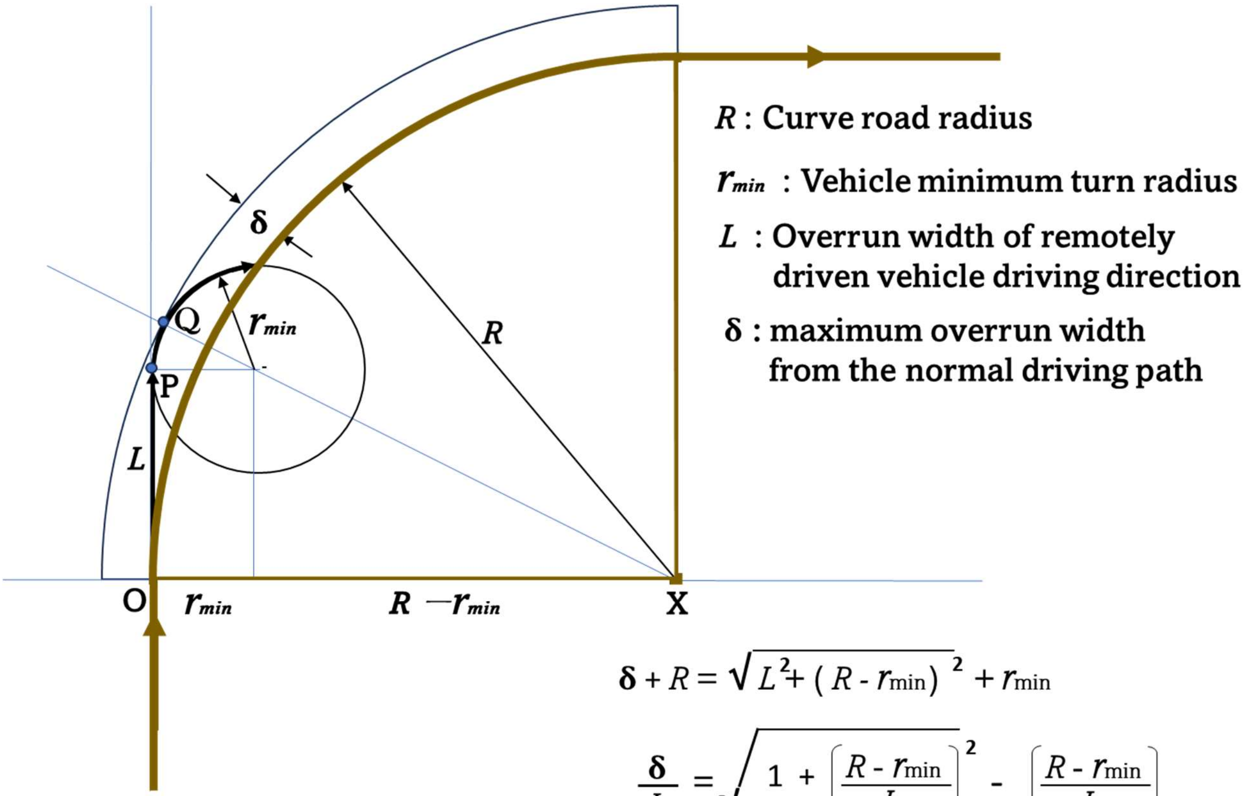


Figure 4 - Curved line driving normal and remote driving diagram



$$\delta + R = \sqrt{L^2 + (R - r_{\min})^2} + r_{\min}$$

$$\frac{\delta}{L} = \sqrt{1 + \left(\frac{R - r_{\min}}{L}\right)^2} - \left(\frac{R - r_{\min}}{L}\right)$$

Figure 4 Addendum - Overrun width δ from rhe normal driving path

５． Regulation of driving control stability during curve driving

$T_{GG} \leq 300$ ｍs **(temporary regulation)**

This is caused by the continuation of excess control by inexperienced driver of remote driving that remote driving control is already applied and implemented in the vehicle after the control latency, but because of image latency, its implementation is not immediately recognized by the remote driver, and it seems the delay of control is expanded. Inexperienced driver sometimes applies excess braking when braking is applied, and also slight meandering happens at the end of curve driving.

This phenomenon is obviously affected by the absolute time of image latency, but it is closed as soon as the driving speed is reduced.

Currently more detailed analysis and the countermeasures are under development.

This phenomenon can also be avoided with the training and experiences by the remote driver.