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Influence of driver's reaction time and gain on driver–vehicle system performance with rear wheel steering control systems: part of a study on vehicle control suitable for the aged driver

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Abstract

1. Introduction

Older people are the most rapidly growing segment of the population in the developed countries. In Japan, the ratio of the population over 65 years old exceeded those of all other listed countries after 2000, as shown in Fig. 1 [16]. According to the prediction, the population over 65 will be about 27% after 2020. Eby [1] refered to Carp's [14] research results in his paper. An important component to well-being is the ability of a person to satisfy those needs that give life an "acceptable and positive quality." In these needs, the "higher-order" ones include social interaction, usefulness, recreation and religion. The higher-order needs typically cannot be satisfied within the elderly person's home. Because of the undesirability and impracticality of public transportation, walking and family dependence for elderly people, driving remains the primary mode of transportation for satisfying higher-order needs. Thus, when driving ability is reduced, mobility in elderly people is also reduced, which leads to a potential decline in emotional well-being. From this viewpoint, it is very important to maintain the driving ability of elderly people. Thus it is important to develop vehicles that can adapt to aged drivers' properties and satisfy their needs. Recently more and more electronic control systems are being used for the vehicle control. These both improve the performance of the vehicle and provides great flexibility to make the vehicle adapt to variation of the environment in which it is used.

In the driver–vehicle system, driver's abilities have direct effect on the system performance. For aged drivers, their abilities of vision, perception, cognition and decision-making decline. Reaction time and reflex time increase. In the case of multi-task decision-making, as the number of tasks increases, the reaction time of the aged people becomes increasingly longer than that of young people. Kondo [2] and Yoshimoto [3] proposed the first and the second order preview models, respectively, McRuer [4], Allen [5] established a multi-loop model with preview, integral and driver's high frequency compensation. Hess [6] also proposed a driver model with preview and compensatory element. There is some research on driver-vehicle closed loop system. Abe [7] studied vehicle handling evaluation and Harada [8] researched the handling stability when driver's preview time and gain change with the first order preview driver model. Modjtahedzadeh and Hess [6] utilized their model to study the vehicle handling quality. Horiuchi and Yuhara [15] analyzed and gave their results on handling quality with a multi-loop driver model.

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Nomenclature

m	mass (1310 kg)
L	wheelbase (2.582 m)
l	distance from the C.G. to front axle (0.986 m)
l_r	distance from the C.G. to rear axle (1.596 m)
I	yaw moment inertia (2352 kg*m^2)
V	speed of vehicle
D_{T}	tread ($D_f = 1.525$ m, $D_r = 1.515$ m)
W_{T}	tire vertical load ($W_f = 3938$ N, $W_r = 2451$ N)
K_{T}	front or rear tires cornering stiffness ($K_f = 77350$ N/rad, $K_r = 51600$ N/rad)
F_{T}	tire lateral force
X_{T}	tire longitudinal force
T	(f, r) front and rear
r	Yaw rate of vehicle
ϕ	Yaw angle (heading angle)
u, μ	friction coefficient
β	vehicle side-slip angle
β_{T}	tire side-slip angle
δ_{T}	wheel steering angle

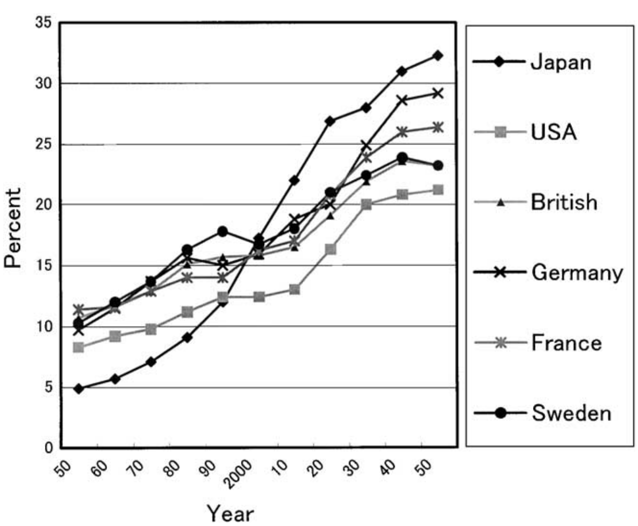

Fig. 1. Ratio of population over 65 yr old.

In this paper, we utilize the research results on the aged driver's abilities and driver model. By means of the method of vehicle handling quality evaluation, the vehicle performance with several chassis controls (2WS, 4WS) are simulated under different road friction coefficients different speeds and different derivative time constants of the driver. The results are analyzed. How the chassis controls contribute to the vehicle performance suitable for the aged driver was investigated.

2. Driver–vehicle system

Fig. 2 is a general driver-vehicle-system model [17]. The driver collects information, processes the information, makes operational decision and performs the operation based on target function and related information. In general, the process of decision-making is a very complex mental activity. However, in a basic driving process, the driver's target is to drive the vehicle to trace a specified path. Therefore, a control theoretic model can present the driver's driving process in this case.

2.1. Driver's model

Some kinds of control models are proposed to describe the basic driving process of the human driver as mentioned in the last section. All of these models can describe the basic driving process well. The multi-loop models, proposed by McRuer, Allen and Hess et al., include not only preview, derivative and feedback properties but also human operational and integral properties. They can express the driving operation more suitably in a basic driving process. Now the multi-loop models were widely used for handling quality evaluation. Allen's [5] model is used in this paper. This is shown in the dashed line box in Fig. 3. It includes the driver's preview property (τ_{p}), delay time (τ), integral (K_i/S) and high frequency dynamics ($D(S)$). K_y is the gain of lane position error and K_{fi} is the gain of head angle error. In this driver model, the delay time represents driver's decision time plus the time required to transmit decision to limbs by the neural system. The preview, integral and derivative (T_l) properties depend on the driver's driving ability. Both gains, K_y and K_{fi}, are adjusted by the human driver according to the vehicle properties and driving states.

2.2. Properties of aged drivers

Since the 80 s, many researchers have investigated the properties of the aged driver, especially their driving abilities. Sivak et al. [9] and Eby [10] summarized the research results. It is clear that the abilities of vision, perception, information processing, cognition and human biomechanics tend to decline with age. All of them affect the ability of elderly persons to access and operate motor vehicle safely.

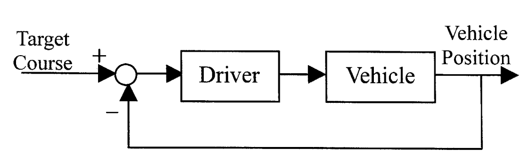

Fig. 2. Driver–vehicle system.

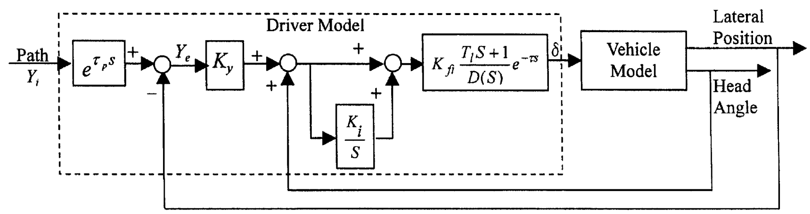

Fig. 3. Simulation model of driver–vehicle system.

From the research results, it is found that feedback information about lane position becomes worse because the aged driver's vision and perception abilities decline. Since his (or her) muscular strength and flexibility decline, control ability and adjustability become weak. In particular, the reaction time of the aged driver becomes long with his (or her) age in the case of a single task and becomes even longer in a multi-task environment. Since driving is a multi-task environment, the reaction time of the aged driver becomes much longer compared with the young driver.

Many researchers reported their research results on reaction time of aged drivers as well as young drivers. Table 1 shows the results of Stelmach and Nahom [11] as well as Uno and Hiramatsu [12]. As the ability of information processing declines, the derivative control ability of the aged driver declines. Sawada et al. [13] presented their research result on the derivative property of the aged driver. According to their result, the derivative ability of the aged driver is lower than that of the young driver.

Table 1
Simple reaction time (T_e, simple task)

Researchers	Young driver	Aged driver
H. Uno; K. Hiramatsu	0.33 s	0.47 s
G.E. Stelmach; A. Nahom	0.28 s	0.45 s

3. Evaluation method of system performance

For a driver–vehicle system, the most widely used evaluation function is based on the sum of integral of weighted square of variables, such as path error, steering wheel angle and steering torque. Abe [7] described this kind of man–machine system evaluation method in detail and verified the result through experiments. Because the square integral represents the power of the signal, it is a good evaluation method from the viewpoint of reducing driver's load. Generally, the steering torque is used as a feedback signal to the driver. However, with a mechanical steering system, this torque becomes an additional workload for the driver when the tire side slip angle becomes large. This disadvantage is more serious for the aged driver. Recently more and more electronic control systems are being introduced to the car. The steering-by-wire technique is rapidly being developed. Utilizing this kind of system, the steering torque can be reduced and adjusted easily. In particular, the torque can be adjusted or adapted to the driver. So the effect on the workload of the driver is greatly reduced when if this kind of system is used. Based on this consideration, we only consider the path error and the steering wheel angle in this evaluation function. The evaluation function is expressed by the Eq. (1).

$$J = K_p \int Y_e^2 \, dt + K_s \int \delta^2 \, dt. \tag{1}$$

We first analyzed the simulation results and compare the value of evaluation function to determine the weighted constant of evaluation function. We set the weighted constants in this evaluation function as follows:

$$K_p = 0.25; \quad K_s = 1.$$

When a driver drives his car, the driver makes decision in a multi-task environment. For example, when the driver makes a lane change, he must observe the road, confirm position and operate the steering wheel according to the speed, vehicle properties, etc. The latter is the main load on the driver when he drives a car. So if we can design a vehicle control system that can reduce the tasks while driving, then we can reduce the load on the driver and the driver's reaction time can be reduced as well. In consequence, the safety is increased.

We set the following as the criteria for choosing and designing a vehicle chassis control algorithm suitable for the aged driver.

- To keep the vehicle handling stable even when the reaction time becomes longer.
- To make the vehicle have high robustness, especially when the driver's abilities decline.
- The aged drivers require little or no change in their properties in order to adapt to the variation of the vehicle speed.

4. Simulation and analysis of vehicle chassis control techniques

An outline of the vehicle model used in this simulation is shown in Fig. 4. The vehicle model is a two degrees of freedom plane model with nonlinear tire, under the assumptions that the vehicle side-slip angle, heading angle and tire side-slip angles are very small. No suspension system is considered. The steering mechanism is a simple one in which the front wheel steer angle is proportional to the steering wheel angle and the steering ratio is supposed to be equal to 16.0.

The tire model of Fig. 4 is expressed by Eq. (2).

$$F_T = -\left[K_T\beta_T - \mathrm{sign}(\beta_T)\frac{K_T^2}{4\mu W_T}\beta_T^2\right]\sqrt{1-\left(\frac{X_T}{\mu W_T}\right)^2}, \quad \text{when } |\beta_T| < \frac{2\mu W_T}{K_T}, \tag{2}$$

$$F_T = -\,\mathrm{sign}(\beta_T)\mu W_T\sqrt{1-\left(\frac{X_T}{\mu W_T}\right)^2}, \quad \text{when } |\beta_T| \geqslant \frac{2\mu W_T}{K_T}.$$

It is a non-linear model. Though the 4WS control algorithms are derived from a linear model, the real tire property is non-linear when tire side-slip angle is larger. We can compare the control effects of 4WS in a more realistic way with the non-linear tire model. Some 4WS-control algorithms are feedback and feed-forward control and others are only feed-forward control. We can check the effects of the feedback term under the non-linear tire model.

The vehicle state space equation is as shown Fig. 4. The state vector (X) includes following four variables:

- Vehicle body sideslip angle (β).
- Yaw rate (γ).
- Yaw angle (heading angle) (ϕ).
- Lateral position (y).

The output vector (Y) is the same as the state vector. The arrays A, B and C are given as the following under the above assumptions:

$$A = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ V & 0 & V & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 1/mV & 1/mV & 1/mV & 1/mV \\ l_f/I & l_f/I & -l_r/I & -l_r/I \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The values of parameters are shown in the nomenclature.

A target path for this simulation is shown in Fig. 5. It is based on the standard of the single lane change. The path is composed of the line of three segments.

4.1. Simulation and results

In this paper, the following simulations are executed with different chassis controls and the results are analyzed:

- $J(\tau)$: In different vehicle speeds and road friction coefficients.
- $J(K_{fi})$: For the young driver and the aged driver when derivative time (T_1) is equal to 0.3 and 0.2 s.

The parameter τ of the driver model is set to be equal to the driver's reaction time T_e (see Table 1). This is due to the following: First, in general, the (common) driver's delay time (τ) is about 0.2–0.3 s. From the reported results, a young driver's reaction time is nearly this value. Secondly, even though reaction time is a little larger than τ, the researchers always try to design their experiment to reduce the error. Thirdly, because driving is in a multi-task environment, the delay time is longer than that of single task. In our simulation, we select 0.28 s as a younger driver's delay time and 0.45 s as an aged driver's time.

Depending on the results of other researchers and our simulation, we determine

$$\tau_p = 1.0,$$

$$K_y = 1/V. \tag{3}$$

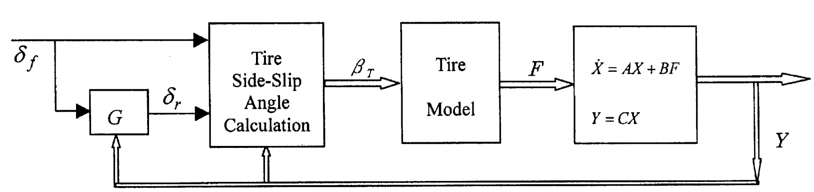

Fig. 4. Vehicle control structure of simulation.

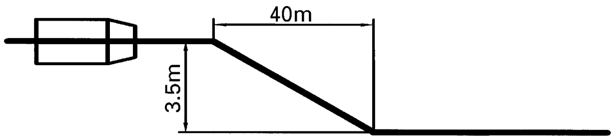

Fig. 5. Input path for the simulation.

This means that driver's preview time is about 1.0 s. We also set

$K_i = 0.01,$

$$D(S) = 0.2S + 1. \tag{4}$$

Here, we mainly consider 2WS and three types of 4WS control systems. The control law of 4WS-1 is described by Eq. (5). The rear wheel steering angle is only determined by the front wheel steering angle. This control algorithm makes the steady state vehicle side-slip angle (β) equal to zero. $\{\beta(s=0)=0\}$.

$\delta_r = K_1 * \delta_f,$

$$K_1 = -\frac{l_r - \left(\dfrac{ml_f}{2LK_r}\right)V^2}{l_f + \left(\dfrac{ml_r}{2LK_f}\right)V^2}. \tag{5}$$

The control law of 4WS-2 is presented by Eq. (6), which is also a feed-forward control. However, the vehicle side–slip angle is equal to zero, not only at the steady state but also at the transient state of vehicle motion $\{\beta(s) = 0)\}$.

$\delta_r = K_1(S) * \delta_f,$

$$K_1(S) = -\frac{l_r - \left(\dfrac{ml_f}{2LK_r}\right)V^2 + \left(\dfrac{IV}{2LK_r}\right)S}{l_f + \left(\dfrac{ml_r}{2LK_f}\right)V^2 + \left(\dfrac{IV}{2LK_f}\right)S}. \tag{6}$$

The control algorithm of 4WS-3 is expressed by Eq. (7).

It is a feed-forward and feedback control, by which vehicle sideslip angle is always equal to zero at the steady state was well as at the transient state. $\{\beta(s) = 0\}$.

$\delta_r = K_1 * \delta_f + K_2 * r,$

$$K_1 = -\frac{K_f}{K_r}, \quad K_2 = \frac{mV^2 + 2(l_f K_f - l_r K_r)}{2K_r V}. \tag{7}$$

The effects of driver's delay time on driver–vehicle system performance are shown in Figs. 6–9. This can be regarded as one of the effects of the driver's age. In the four figures, the derivative time (T_1) is 0.3 s. Figs. 6 and 8 are the simulation results under road friction coefficient 1.0, and Figs. 7 and 9 are the results under the road friction coefficient 0.3. Also the vehicle speed is 25 m/s in Figs. 6 and 7, and is 17 m/s in Figs. 8 and 9. No information about the variation of road friction is considered in any rear wheel steering control algorithm. Figs. 10 and 11 show the effects of driver's gain variation for typical young and aged drivers. The simulation conditions are a speed of 30 m/s and a road friction coefficient 1.0. The only difference is that the derivative time is 0.3 s in Fig. 10 and 0.2 s in Fig. 11. Smaller derivative time as well as longer delay time are regarded as the typical properties of the aged driver.

4.2. Analysis of the simulation results

In Figs. 6–9, the gray areas show the typical time ranges of the young driver and the aged driver, which are taken from Table 1. According to the research results of some researchers [12], it is necessary to mention that the distribution variance of reaction time of the young driver is smaller than that of the aged driver.

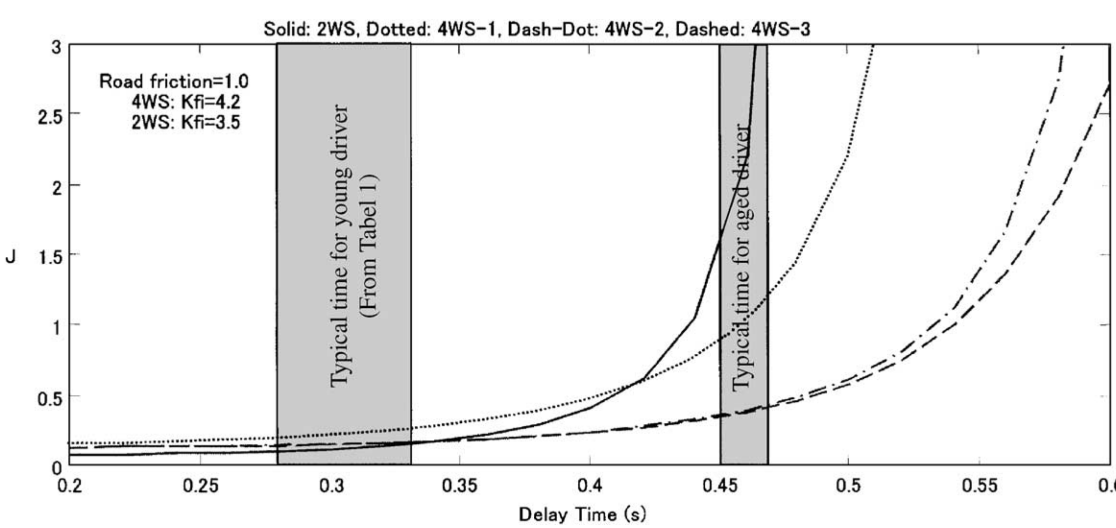

Fig. 6. Effects of delay time at speed 90 km/h and $T_l = 0.3$ s.

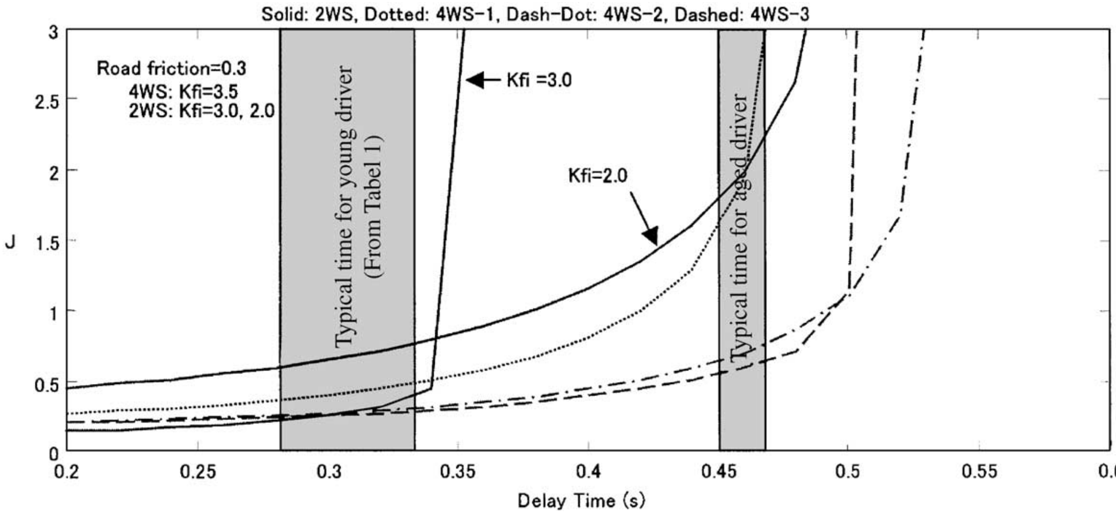

Fig. 7. Effects of delay time at speed 90 km/h and $T_l = 0.3$ s.

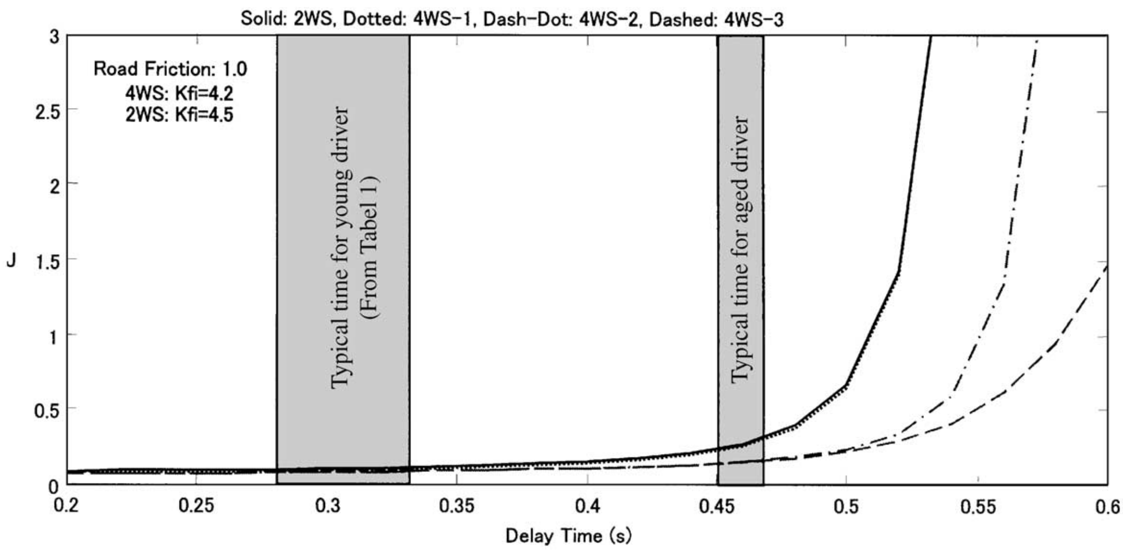

Fig. 8. Effects of delay time at speed 61.2 km/h and $T_l = 0.3$ s.

Figs. 6 and 7 shows the simulation results at the speed of 25 m/s. The performance of the 2WS vehicle becomes very bad with the increase of delay time. Under the normal road friction (Fig. 6), it is difficult to control this type of vehicle as the driver's delay time increases to near 0.45 s. The performance of 2WS vehicle is sensitive to the gain (K_{fi}) when the road friction coefficient becomes small (Fig. 7). Even when a driver reduces the steering gain (K_{fi}) in order to keep the vehicle stable, the performance of the vehicle with 2WS is the worst among the four types for not only the aged driver but also the young driver. If the gain (K_{fi}) is bigger, i.e. $K_{fi} = 3.0$, the vehicle cannot be controlled when delay time is over 0.34 s (Fig. 7). The four-wheel steering controls, 4WS-2 and 4WS-3, give better performance, especially for the aged driver. In the case of the speed of 17 m/s, as shown in Figs. 8 and 9, the aged driver can control 2WS vehicle on the road of normal friction (Fig. 8). The performance difference is small between the vehicle with 2WS and the vehicle with 4WS-2 or 4WS-3, but it is near to the dangerous area for the aged driver with 2WS. This is to say that a small increment of τ can cause the vehicle to become uncontrollable. When the road friction coefficient decreases to 0.3 (Fig. 9), the vehicle performance with 2WS becomes much worse and those with 4WS-2 and 4WS-3 are nearly the same for the aged driver. In order to achieve the best performance, the driver must adjust the gain (K_{fi}) at different speeds. The required variation of K_{fi} is much bigger for the vehicle with 2WS than that with 4WS-2 or 4WS-3 [18].

Figs. 10 and 11 show that 2WS can achieve and bring us the same performance as 4WS-2 and 4WS-3 for the

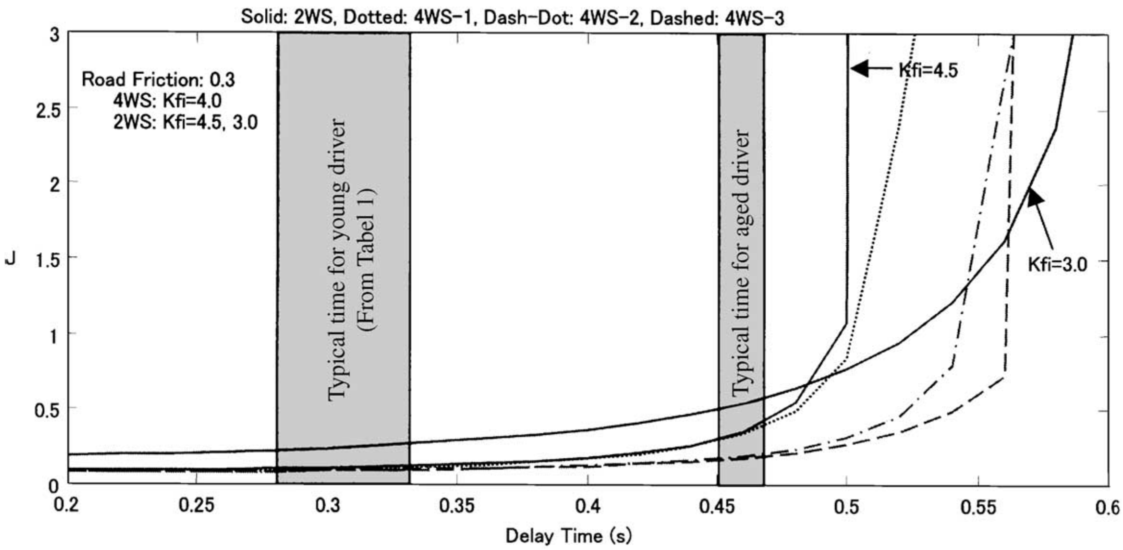

Fig. 9. Effects of delay time at speed 61.2 km/h and $T_l = 0.3$ s.

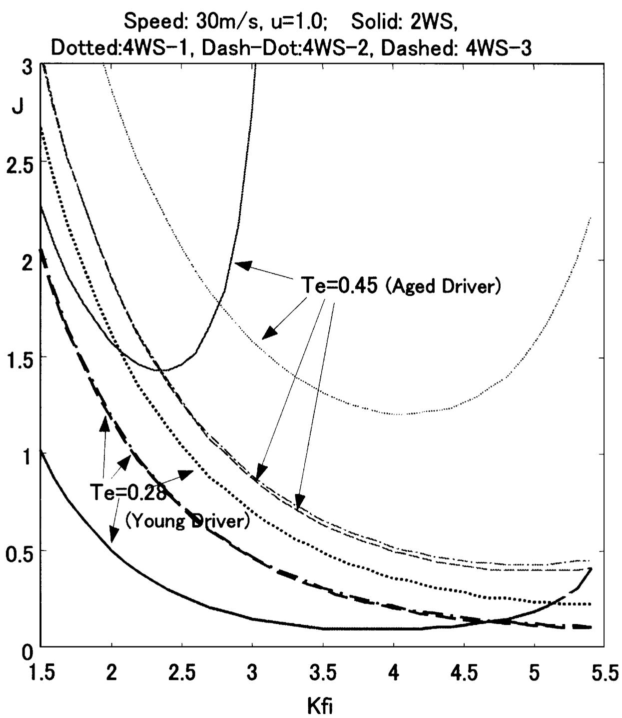

Fig. 10. Effects of driver's gain variation at $T_l = 0.3$ s.

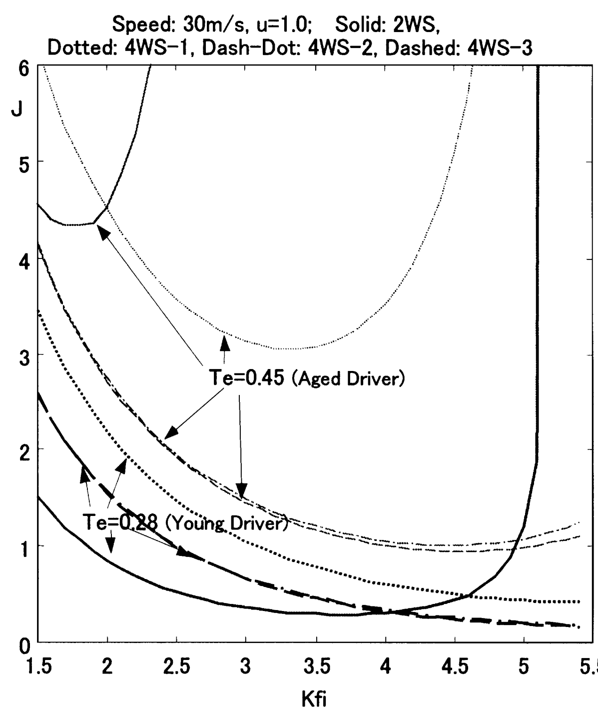

Fig. 11. Effects of driver's gain variation at $T_l = 0.2$ s.

young driver. However, the vehicle performance with 2WS becomes very bad and those of 4WS-2 and 4WS-3 are much better for the aged driver. The acceptable range of K_{fi} is much wider with 4WS-2 and 4WS-3. In case of 2WS, not only does the performance become worse, but the performance is also very sensitive to the variation of the gain (K_{fi}). This means that the vehicle with 2WS is not good, especially for the aged driver from the viewpoint of the system robustness to the variation of K_{fi}. Comparing Fig. 10 with Fig. 11, the vehicle performance with 2WS becomes very bad and the value of optimum K_{fi} becomes small when T_l is changed to 0.2 s from 0.3 s, which means that a very precise control is required.

5. Conclusion

According to the analysis of the last section, the following conclusions are given.

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