Proposal of Non-dimensional Parameter Indices to Evaluate Safe Driving Behavior

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Abstract. Our previous study proposed Deceleration for Collision Avoidance (DCA) as an new index for use when evaluating collision risk against forward obstacles. The present manuscript proposes four non-dimensional parameter indices which are based mainly on the DCA, in order to provide quantitative assessment of safe driving behavior. Numerical simulations are performed to verify validity of the proposed indices.

Keywords: safe driving evaluation system, deceleration for collision avoidance, driving behavior.

1 Introduction

Our previous studies proposed Deceleration for Collision Avoidance (DCA) as an index to define a warning provision threshold [1,2] and examined that a Forward Obstacles Collision Warning System (FOCWS) based on the DCA was effective to enhance driver's situation awareness [3].

Meanwhile, there is a psychological theory, called "*a risk homeostasis theory*" [4], which argues that a long-term effectiveness of various kinds of driver-assistance systems will decrease because of driver's risk compensation behavior. In other words, a driver who feels the driving situation became safer tends to convert a margin gained by the driver-assistance system to improvement of his/her driving efficiency.

The driving simulator experiments of our previous study [5] suggested that a presentation of a fuel-consumption meter would improve driver's motivation for fuel-efficient driving and secondarily it would prevent the risk compensation behavior while the safer driving was derived from only the side-effect of fuel-efficient driving. Therefore, a final goal of this study is to construct a safe driving evaluation system (SDES) to encourage drivers to perform safe driving directly by a feedback of safe driving evaluation results. As the first step, the present study proposes four evaluation indices to provide quantitative assessment of safe driving, and performes numerical simulations to verify validity of the indices.

S. Yamamoto (Ed.): HIMI/HCII 2013, Part II, LNCS 8017, pp. 470–479, 2013.

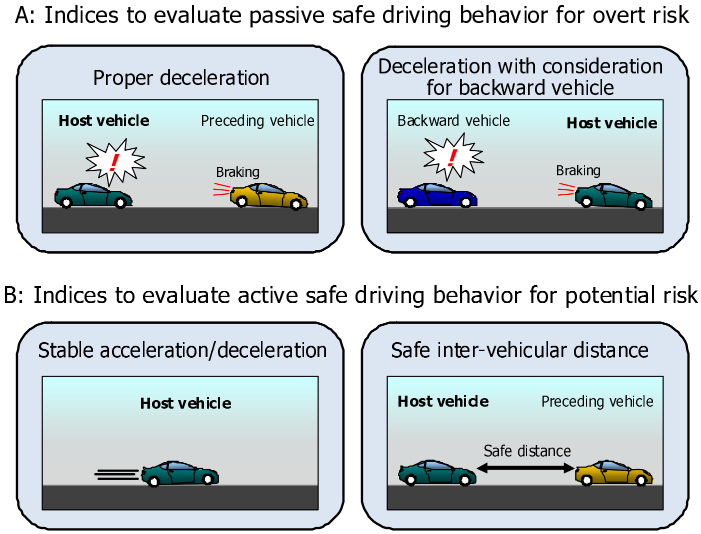

Fig. 1. Four indices to evaluate safe driving behavior. (upper) Two indicies to evaluate passive safe driving behavior for overt risk. (lower) Two indicies to evaluate active safe driving behavior for potential risk.

2 Four Types of Evaluation Indices

2.1 Deceleration for Collision Avoidance (DCA)

The DCA represents a minimum required deceleration of a host vehicle (HV) necessary to avoid a collision against a forward obstacle such as a preceding vehicle (PV) and a pedestrian [1,2]. There are two types of DCAs: a DCA in a situation where the PV maintains its current acceleration is defined as an overt DCA (ODCA), and a DCA that is based on the assumption that the PV will decelerate abruptly at any moment is defined as a potential DCA (PDCA). A driver can understand proper avoidance action to take when the DCA value is presented, because it has a strong correlation with the amount of driver's brake pedal depression.

Adequacy of deceleration maneuver can be evaluated by comparison of ODCA and actual deceleration of the HV. ODCA represents an overt collision risk based on a relative relationship between the HV and the PV. Moreover, application of ODCA to a relative relationship between a backward vehicle (BV) and the HV can yield estimation of a collision risk of the HV against the BV. Hence, the present study calculates a longitudinal overt collision risk from a viewpoint of acceleration (deceleration) by using the ODCA in order to evaluate adequacy of driver's maneuver against the overt risk.

2.2 Indices to Evaluate Passive Safe Driving Behavior for Overt Risk

A state where an overt collision risk from the HV to the PV exists is defined to be equivalent to a state where the HV has to decelerate at more than a constant value in order to avoid a collision against the PV. Moreover, a state where an overt risk from the HV to the BV exists is defined as a state where the BV has to decelerate at more than a constant value in order to avoid a collision against the HV. Consequently, the present study proposes two indices to evaluate passive safe driving behavior for overt risk objectively; *proper deceleration* (I_F) and *deceleration with consideration for BV* (I_B) (upper figures of Fig. 1).

Index I: Proper Deceleration (I_F). A driver of the HV has to decelerate at more than the ODCA value immediately when an overt collision risk such as abrupt deceleration of the PV appears. If a significant delay occurs in the HV driver's reaction or a deceleration in the early phase of the reaction is not enough, a large deceleration must be required after the avoidance maneuver starts. Therefore, an index I_F is defined as a ratio of the actual acceleration of the HV divided by the ODCA.

A following function $f_e(t)$ represents whether or not the overt risk appears, in other words, the current situation should be evaluated or not.

$$f_e(t) = \begin{cases} 1 \ (\alpha_{o,f} > \theta_{o,f}, \quad t > t_f + T_{r,f}(t_f)) \\ 0 \qquad\qquad\qquad \text{else} \end{cases} \tag{1}$$

where $\alpha_{o,f}(\geq 0)[\mathrm{m/s^2}]$ is an ODCA value of the HV to the PV, $\theta_{o,f}(> 0)[\mathrm{m/s^2}]$ is a constant threshold, t_f is a time when $\alpha_{o,f}$ exceeds $\theta_{o,f}$, and $T_{r,f}(t_f)[\mathrm{s}]$ is an assumed HV driver's reaction time.

Equation $f_e(t) = 1$ defines "*a state where an overt risk occurs*" as a state where $\alpha_{o,f}$ is still larger than $\theta_{o,f}$ even after the driver's reaction time $T_{r,f}$ passed from the moment when the ODCA value $\alpha_{o,f}$ exceeds the theleshold $\theta_{o,f}$.

Appropriateness $f(t)$ of deceleration behavior at time t is defined by

$$f(t) = f_e(t) \times \begin{cases} 1 \qquad (d_f > \alpha_{o,f}, \quad \alpha_{o,f} \leq d_{f,max}) \\ \dfrac{d_f}{\alpha_{o,f}} \ (\alpha_{o,f} \geq d_f \geq 0, \ \alpha_{o,f} \leq d_{f,max}) \\ 0 \qquad\qquad\qquad \text{else} \end{cases} \tag{2}$$

where $d_f[\mathrm{m/s^2}]$ denotes an actual deceleration of the HV, and $d_{f,max}$ is an assumed maximum deceleration of the HV.

Equation (2) represents that the function $f(t)$ expresses a ratio of the actual deceleration of the HV to the ODCA value in a situation where the overt risk occurs. It also denotes that the deceleration behavior is more proper when the ratio comes closer to one and conversely it is more improper when the ratio comes closer to zero. Note that $f(t)$ becomes zero in the following three cases; 1) an overt risk does not occur ($f_e(t) = 0$), 2) the HV does not decelerate ($d_f \leq 0$), or 3) an ODCA value exceeds the maximum decelertaion ($\alpha_{o,f} > d_{f,max}$).

Time integral of $f_e(\tau)$ of Eq. (1) from 0 to t describes a summation of evaluation time, and it is expressed by $T_f(t)$. Here, an index $I_F(t)$ is defined by the following equation.

$$I_F(t) = \frac{\int_0^t f(\tau)d\tau}{\int_0^t f_e(\tau)d\tau} = \frac{\int_0^t f(\tau)d\tau}{T_f(t)} \tag{3}$$

Note the index $I_F(t)$ is defined to be zero when $T_f(t)$ is zero.

The index $I_F(t)$ is a non-dimensional parameter varied from 0 to 1, and it denotes an average value of adequacy of deceleration behavior in a time range from 0 to t. Accordingly, when $T_f(t) > 0$ and $I_F(t)$ comes closer to one, the driver's deceleration behavior is evaluated to be more proper against the overt risk occurred in front of the HV.

Index II: Deceleration with Consideration for Backward Vehicle (I_B). When the HV decelerates abruptly, a driver of the BV has to decelerate at more than a minimum required deceleration in order to avoid a collision. It means that the deceleration of the HV might cause an overt collision risk of the BV. If the inter-vehicular distance is short or the avoidance action of the BV is delayed because of the driver's distraction and so on, the collision risk will be increased. In other words, the BV cannot decelerate properly when the HV decelerates without consideration for the BV. Consequently, an index I_B is defined as a ratio of the actual acceleration of the BV divided by its ODCA.

By substitutions of PV to HV and HV to BV in a relationship mentioned in "Index I: Proper deceleration (I_F)", adequacy of the BV's deceleration behavior against the HV in a time range from 0 to t can be expressed by

$$I_B(t) = \frac{\int_0^t b(\tau)d\tau}{\int_0^t b_e(\tau)d\tau} = \frac{\int_0^t b(\tau)d\tau}{T_b(t)}. \tag{4}$$

Functions $b_e(t)$ and $b(t)$ are defined by

$$b_e(t) = \begin{cases} 1 \ (\alpha_{o,b} > \theta_{o,b}, \quad t > t_b + T_{r,b}(t_b)) \\ 0 \qquad\qquad\qquad \text{else} \end{cases} \tag{5}$$

$$b(t) = b_e(t) \times \begin{cases} 1 & (d_b > \alpha_{o,b}, \quad \alpha_{o,b} \leq d_{b,max}) \\ \dfrac{d_b}{\alpha_{o,b}} & (\alpha_{o,b} \geq d_b \geq 0, \ \alpha_{o,b} \leq d_{b,max}) \\ 0 & \text{else} \end{cases} \tag{6}$$

where $\alpha_{o,b}(\geq 0)$ is an ODCA value from the BV to the HV, t_b is a time when $\alpha_{o,b}$ exceeds a constant threshold $\theta_{o,b}$, $T_{r,b}(t_b)$ is an assumed the BV driver's reaction time, d_b is an actual deceleration of the BV, and $d_{b,max}$ is an assumed maximum deceleration of the BV.

3 Indices to Evaluate Active Safe Driving Behavior for Potential Risk

We define a state where the risk is potential as a state where an overt risk does not occur in a longitudinal direction of the HV (e.g., there is no obstacle, or the HV follows the PV which runs at a constant velocity). In order to respond adequately to the overt risk, it is desirable to take safer driving behavior in a preventive manner from a stage when a collision risk is still potential. The present study, therefore, proposed two indices to evaluate passive safe driving behavior for overt risk objectively; *stable acceleration/deceleration* (I_A) based on the actual acceleration of the HV, and *safe inter-vehicular distance* (I_D) based on the PDCA (lower figures of Fig. 1).

Index III: Stable Acceleration/Deceleration (I_A). Stability of the HV must be ensured in order to perform proper avoidance maneuver when the overt risk occurs. For example, if the driver accelerates or decelerates roughly on a slippery road such as packed snow road, it is difficult to respond to the overt risk because a sideslip will happen. Accordingly, it is valid to employ the index which can represent whether the driver performed reasonable maneuver. That is to say, an index I_A is defined by a ratio of the actual acceleration to the order acceleration and it can evaluate an adequacy of the acceleration maneuver.

Based on the concept, the adequacy $I_A(t)$ of the acceleration maneuver in a time range from 0 to t is expressed as follows.

$$I_A(t) = \frac{\int_0^t a(\tau)d\tau}{\int_0^t a_e(\tau)d\tau} = \frac{\int_0^t a(\tau)d\tau}{T_a(t)} \tag{7}$$

The functions $a_e(t)$ and $a(t)$ are defined by

$$a_e(t) = \begin{cases} 1 \ (v_f > 0, \quad |a_i| > \theta_a) \\ 0 \qquad\qquad \text{else} \end{cases} \tag{8}$$

$$a(t) = a_e(t) \times \begin{cases} 1 & \left(1 < \frac{a_f}{a_i}\right) \\ \dfrac{a_f}{a_i} & \left(0 \leq \frac{a_f}{a_i} \leq 1\right) \\ 0 & \left(\frac{a_f}{a_i} < 0\right) \end{cases} \tag{9}$$

where v_f[m/s] and a_f[m/s^2] represent the HV's velocity and acceleration, $\theta_a (> 0)$ [m/s^2] is a constant threshold, and a_i[m/s^2] is acceleration order value input by a gas pedal and a brake pedal.

The index I_A has a similarity with the above-mentioned two indices I_F and I_B in the point where all of them are non-dimensional parameters based on acceleration to evaluate adequacy of driving behavior although I_A does not employ the the DCA unlike with other two indices.

Index IV: Safe Inter-vehicular Distance (I_D). If the PV decelerates abruptly in a case of short inter-vehicular distance, the HV has to perform a hard braking because of the driver's response lag. Conversely, in a case of long inter-vehicular distance, a possibility to take proper avoidance action against the forward overt risk will be increased. The present paper proposes an index I_B to evaluate adequacy of the inter-vehicular distance by using score from 0 to 1 which is calculated based on the PDCA value.

PDCA is a minimum required deceleration of the HV to avoid a collision on the assumption that the PV will decelerate at 0.6[G] at any moment. The PDCA value becomes smaller according to wider inter-vehicular distance [1,2], and then the present study propses an index to evaluate adequacy of the inter-vehicular dinstance by using the PDCA.

Similarly with other three indices, an adequacy $I_D(t)$ of the inter-vehicular distance in a time range from 0 to t is expressed as the following ratio.

$$I_D(t) = \frac{\int_0^t d(\tau)d\tau}{\int_0^t d_e(\tau)d\tau} = \frac{\int_0^t d(\tau)d\tau}{T_d(t)} \tag{10}$$

A function $d_e(t)$ is defined by

$$d_e(t) = \begin{cases} 1 \ (\alpha_{p,f} > \theta_{p,f},\ \alpha_{o,f} \le \theta_{o,f},\ v_p > 0) \\ 0 \qquad \text{else} \end{cases} \tag{11}$$

where v_p is the PV's velocity, $\alpha_{p,f}(\ge 0)[\text{m/s}^2]$ is a PDCA value from the HV to the PV, and $\theta_{p,f}(> 0)[\text{m/s}^2]$ is a constant thresholdDInequality $\alpha_{p,f} > \theta_{p,f}$ represents a situation where the HV follows the PV, and inequality $\alpha_{o,f} > \theta_{o,f}$ represents a situation where a collision risk becomes overt. Note that the index I_D is not evaluated in the latter case.

This manuscript defines a function $d(t)$ with respect to the PDCA as follows.

$$d(t) = d_e(t) \times \begin{cases} 1 & (\alpha_{p,f} < \theta^-_{p,f}) \\ \dfrac{\theta^+_{p,f} - \alpha_{p,f}}{\theta^+_{p,f} - \theta^-_{p,f}} & (\theta^-_{p,f} \le \alpha_{p,f} \le \theta^+_{p,f}) \\ 0 & (\theta^+_{p,f} < \alpha_{p,f}) \end{cases} \tag{12}$$

where $\theta^+_{p,f} > \theta^-_{p,f}(> \theta_{p,f})[\text{m/s}^2]$ are upper and lower constant thresholds. As shown in Eq. (12), the function $d(t)$ becomes one when the PDCA value $\alpha_{p,f}$ is smaller than $\theta^-_{p,f}$, it becomes zero when $\alpha_{p,f}$ is larger than $\theta^+_{p,f}$, and it changes linearly in a range $\theta^-_{p,f} \le \alpha_{p,f} \le \theta^+_{p,f}$.

The evaluation index I_D of Eq. (10), therefore, becomes higher when the PDCA value $\alpha_{p,f}$ is smaller (e.g., the inter-vehicular distance is longer).

4 Numerical Simulations

The positions, velocities, and accelerations of HV, PV, BV are defined as x_f, v_f, a_f, x_p, v_p, a_p, x_b, v_b, a_b, respectively, and the relative positions between PV

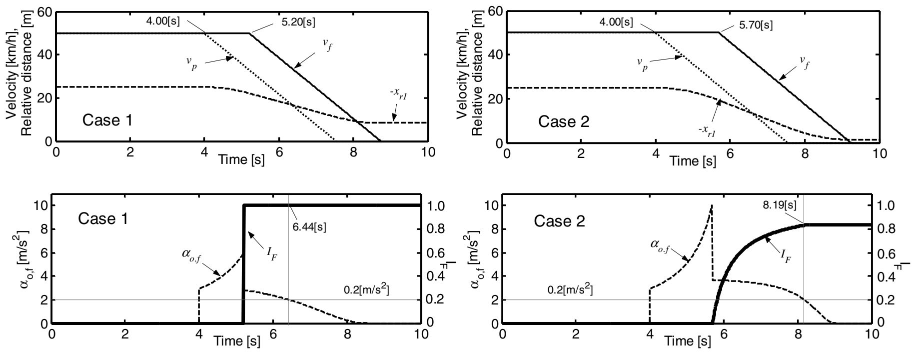

Fig. 2. Simulation results of Index I: Proper deceleration: (upper) Velocities of HV and PV, and inter-vehicular distance (left: Case 1, right: Case 2), (lower) Time series data of ODCA value $\alpha_{o,f}$ and Index value I_F (left: Case 1, right: Case 2).

and HV, HV and BV are defined as x_{r1} and x_{r2}. Note that the relative poisions $x_{r1}(= x_f - x_p)$, $x_{r2}(= x_b - x_f)$ become negative when the HV (BV) follows the PV (HV) from behind. The inter-vehicular distance can be calculated by multiplying the relative distances x_{r1}, x_{r2} by minus [6].

In this simulation, the constant variables necessary to calculate the four indicies are defined as follows; $\theta_{o,f} = \theta_{p,f} = 2.0[\text{m/s}^2]\text{C}\theta_a = 0.5[\text{m/s}^2]\text{C}\theta^-_{p,f} = 4.0[\text{m/s}^2]$, $\theta^+_{p,f} = 8.0[\text{m/s}^2]$, and $d_{f,max} = d_{b,max} = 6.0[\text{m/s}^2]$.

4.1 Proper Deceleration (I_F)

Here, assume a situation where the PV performs abrupt deceleration when the HV follows the PV. Upper figures of Fig. 2 illustrate velocities v_p, v_f and the inter-vehicular distance $-x_r$. The PV decelerates at 3.92[m/s^2] (=0.4[G]) after a following state where $v_p = v_f = 50$[km/h] and $-x_{r1} = 25$[m], and then, the HV starts to decelerate 1.2[s] (Case 1) or 1.7[s] (Case 2) after the PV's deceleration.

Lower figures of Fig. 2 show the time series data of ODCA value $\alpha_{o,f}$ and the index I_F which evaluates adequacy of the deceleration behavior. The ODCA value exceeds the threshold $\theta_{o,f} = 2.0[\text{m/s}^2]$ at 4.0[s] when the PV starts to decelerate, and therefore, the index I_F is evaluated from 5.2[s], which is a moment the assumed driver's reaction time (=1.2[s]) passes. In the Case 1 where the HV decelerates in the assumed reaction time, the ODCA value is decreased at a moment when the HV starts to decelerate and it falls below $\theta_{o,f} = 2.0[\text{m/s}^2]$ at 6.44[s]. Namely, the overt risk occurs from 5.2[s] to 6.44[s], and the lower-left figure of Fig. 2 shows that the ODCA value is smaller than the HV's actual deceleration 0.4[G] during that time. Therefore, the index I_F which is the average value of $f(t)$ during the evaluation time maintains a perfect score.

Next, let us consider the Case 2 where the HV decelerates in 1.7[s] which is behind the assumed reaction time. The index I_F maintains zero from 5.2[s] to 5.7[s] because $f(t)$ becomes zero. After the HV decelerates, I_F is increased

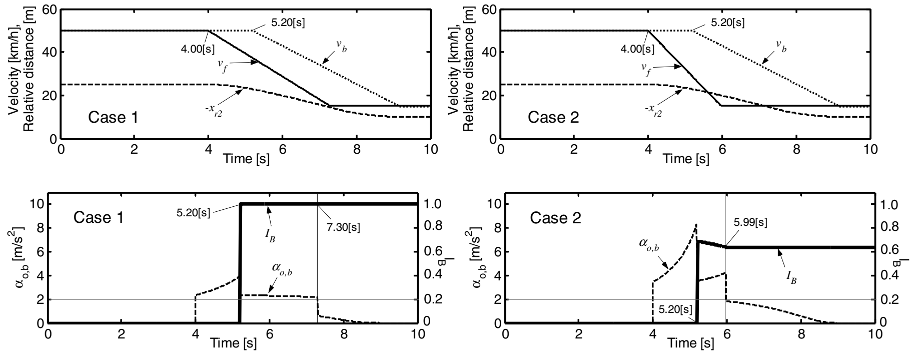

Fig. 3. Simulation results of Index II: Deceleration with consideration for BV: (upper) Velocities of BV, HV, and inter-vehicular distance (left: Case 1, right: Case 2), (lower) Time series data of ODCA value $\alpha_{o,b}$ and Index value I_B (left: Case 1, right: Case 2).

because $f(t)$ becomes one. The evaluation is terminated at 8.19[s] when the ODCA value becomes smaller than 2.0[m/s^2], and finally the index I_F becomes 0.83.

In the Case 1 where the HV performs necessary deceleration to avoid collision against the PV immediately, the evaluation score becomes higher than that in the Case 2. Consequently, the simulation results suggest that the index I_F can evaluate the adequacy of the deceleration behavior.

4.2 Deceleration with Consideration for Backward Vehicle (I_B)

Assume that the BV follows the FV from behind as shown in upper figures of Fig. 3. The FV decelerates at two types of deceleration at 4.0[s]; Case 1: 2.94[m/s^2] (=0.3[G]) and Case 2: 4.9[m/s^2] (=0.5[G]), and the BV decelerates at 2.45[m/s^2] (=0.25[G]) 1.2[s] after the FV's deceleration.

The lower figures of Fig. 3 illustrate the transitions of the BV's ODCA value ($\alpha_{o,b}$) and the index I_B. Similarly with the index I_F of the Case 1 as mentioned in 4.1, the index I_B of the Case 1 becomes one because $b(t) = 1$ is satisfied for all evaluation time. In the Case 2, the index I_B finally becomes 0.64 because the BV's actual deceleration (=0.25[G]) is lower than $\alpha_{o,b}$ for evaluation time between 5.2[s] and 5.99[s].

The evaluation index I_B in the Case 1 where the HV decelerates gently becomes higher than that in the Case 2 where the HV performs abrupt deceleration. Therefore the simulation results represents the validity of I_B.

4.3 Stable Acceleration/Deceleration (I_A)

Let us consider a situation where the HV decelerates on a slippery road whose road surface friction coefficient is 0.2 (upper figures of Fig. 4).

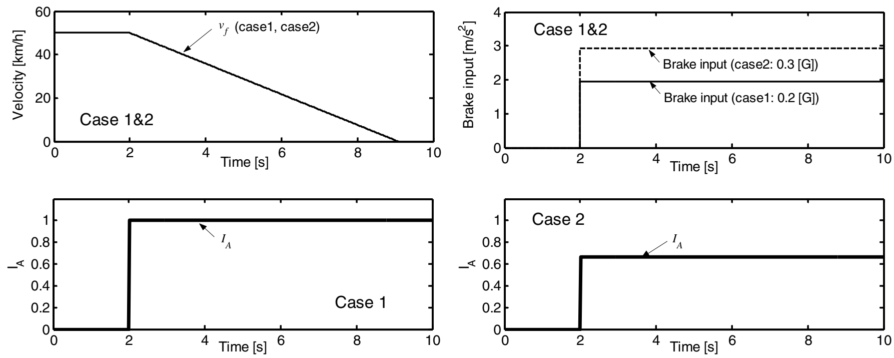

Fig. 4. Simulation results of Index III: Stable acceleration/deceleration: (upper-left) Velocities of HV (Cases 1&2), (upper-right) Brake inputs of HV (Cases 1&2). (lower) Time series data of Index value I_A (left: Case 1, right: Case 2).

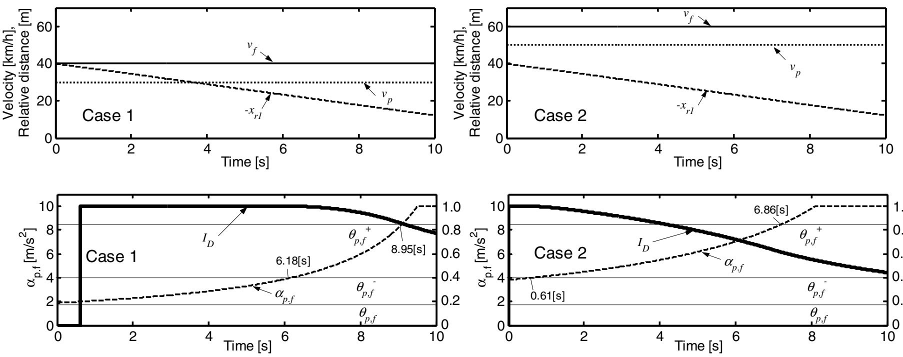

Fig. 5. Simulation results of Index IV: Safe inter-vehicular distance: (upper) Velocities of HV and PV, and inter-vehicular distance (left: Case 1, right: Case 2), (lower) Time series data of PDCA value $\alpha_{p,f}$ and Index value I_D (left: Case 1, right: Case 2).

The index value I_A keeps a perfect score in the Case 1 where the driver of the HV inputs a proper deceleration order (a_i=0.2[G]) in consideration of the road condition. On the other hand, the index value I_A becomes lower (0.67) in the Case 2 where the driver inputs a danger deceleration order (a_i=0.3[G]) which exceeds the road surface friction coefficient.

4.4 Safe Inter-Vehicular Distance (I_D)

This subsection assumes two types of following situations; an initial inter-vehicular distance is 40[m] and a relative velocity is 10[km/h] where initial velocities of the Case 1 are (v_p, v_f)=(30, 40) and those of Case 2 are (v_p, v_f)=(50, 60), as shown in upper figures of Fig. 5.

The lower figures of Fig. 5 show transitions of the FV's PDCA value ($\alpha_{p,f}$) for the PV and the index I_D. In both cases, evaluation is started at a moment when $\alpha_{p,f}$ exceeds the threshold $\theta_{p,f} = 2.0[\mathrm{m/s^2}]$, and the score of I_D begins to decrease when $\alpha_{p,f}$ exceeds $\theta^-_{p,f} = 4.0[\mathrm{m/s^2}]$. The value of $d(t)$ becomes smaller as increasing $\alpha_{p,f}$, and it becomes zero when $\alpha_{p,f}$ exceeds $\theta^+_{p,f} = 8.0[\mathrm{m/s^2}]$. Comparison of lower figures of Fig. 5 shows that the I_D becomes higher in the case of lower velocity even if the relative inter-vehicular distance and the relative velocity are same. In other words, the simulation results indicate that the index I_D can evaluate safe driving behavior properly according to the difference of velocity.

5 Conclusions

The present manuscript proposed four indices to evaluate longitudinal driving behavior; *proper deceleration* (I_F) and *deceleration with consideration for backward vehicle* (I_B) in the situation when the overt collision risks occur, and *stable acceleration/deceleration* (I_A) and *safe inter-vehiclular distance* (I_D) in the situation when the overt risks do not occur. The four indices are non-dimensional parameter based on acceleration (deceleration). Moreover, numerical simulations indicated that these indices could evaluatesafe driving behavior properly.

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