

Changes in Drivers' Heart Rates due to the Influence of Braking

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ABSTRACT

This project focused on changes in drivers' heart rates while braking, as an approach to understanding driving behavior. Using tests designed to model a variety of braking conditions, it was observed that driver psychological states while braking are displayed in the form of changes in heart rate. In a test where an obstacle darts out from the side of the road, driver heart rates were observed to increase suddenly. On the other hand, a test where the vehicle comes to a halt at a stop line showed the heart rate gradually slowing before the vehicle stopped. It was thus inferred that changes in heart rate take on a distinctive pattern in response to braking behavior. In this light, an index formula was proposed that uses the magnitude of the response in heart rate acceleration during braking to determine whether an instance of braking behavior represented panic braking.

1. Introduction

A major goal of car development is to produce safe vehicles. While effort is naturally focused on safety technology designed to minimize the damage caused by collisions, a great deal of effort is also expended on the development of safety technology that can help to effectively prevent accidents from occurring in the first place. Examples of this type of technology that has been incorporated into cars include anti-lock braking systems and power-assisted braking systems. One means by which the effectiveness of both of these systems has been verified is through panic braking tests⁽¹⁾. Such tests are set up so that the test subject is caused to panic in order to observe the braking behavior of a driver in an emergency situation. Ueno et al., presented a stress evaluation⁽²⁾ focused on the driver's physiological state, and equated a state of excessive stress with panic. However, since there has been little research on physiological and psychological states during

panic braking, it was felt that an attempt at a test that evaluates braking from the physiological standpoint of the driver would be useful in future automotive development.

This paper discusses methods for using changes in the driver's heart rate to identify panic braking when the driver is confronted with a vehicle that suddenly emerges from the side of the road.

2. Psychological State and Physiological Response

The autonomic nervous system, which is affected by emotions, consists of a sympathetic nervous system and a parasympathetic nervous system, and it is believed that psychological balance is maintained through an opposing relationship between these two systems⁽³⁾. When a person's psychological state is disturbed by stress or danger, a physiological response driven by the sympathetic nervous

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system is observed. When the sympathetic nervous system takes precedence, the blood pressure rises due to constriction of the blood vessels in the extremities. In addition, the heart rate increases and variations in the intervals between heartbeats decrease. On the other hand, when the parasympathetic nervous system (the pneumogastric nerve) takes precedence, the heart works more calmly, the heart rate drops, and the intervals between heartbeats becomes more variable.^{(4) (5)}

Therefore, this research tried to classify panic braking on the basis of differences in braking and changes in heart rate.

3. Classification of Braking Behavior

In order to compare and evaluate stress during braking, it is necessary to define braking behavior. Various types of braking behavior occur in real-world driving. Five basic modes of braking were established for this research. The first two modes are simple braking:

- (1) "Signal mode", in which the driver brakes to stop the vehicle at a specific target position, such as at a red light
 - (2) "Curve mode", in which the driver brakes to slow the vehicle down to a suitable speed, such as when entering a curve
- The remaining three modes concern more complex braking:
- (3) "Escape mode", in which the driver brakes in order to secure sufficient time for steering avoidance such as when merging onto the expressway (when, for example, the merge lane is nearing an end),
 - (4) "Hard mode", in which the driver suddenly begins to brake hard at a known "brake start" position
 - (5) "Panic mode", in which the driver brakes suddenly because of the sudden emergence of an obstacle.

The "hard mode" is a special mode that was established for the purposes of our research as a comparison for "panic mode" in order to determine the differences in physiological response, depending on whether the driver knows the position at which to start braking beforehand.

4. Test Method

4.1 Test Overview

There were 39 test subjects (34 men, 5 women), with ages ranging from the 20s to the 50s. The test vehicle was a 1600 cc, 4-speed automatic transmission vehicle. The test subjects were instructed to drive normally, and were not informed that there would be a panic braking test. In a test such as this, controlling the vehicle speed is very important. Therefore, before commencing the tests, each subject was allowed to become comfortable with the vehicle, and was given adequate practice runs in which he or she was required to drive at a certain speed. When each subject was deemed able to control the vehicle speed adequately, the panic mode test was conducted during a practice run without warning. After the reason for the surprise test was explained to the subject, the subject's consent to proceed with the remainder of the testing was obtained. Subsequently, each braking mode was explained to the subject, and then a total of 13 braking tests were conducted: five signal mode tests, three curve mode tests, three escape mode tests, and two hard mode tests. The sequence in which the modes were tested varied from subject to subject.

4.2 Test Course Setup

Fig. 1 shows the test course for each braking mode. Fig. 2 shows the test scene for the panic mode test. In order to induce all test subjects to rapidly apply their brakes without

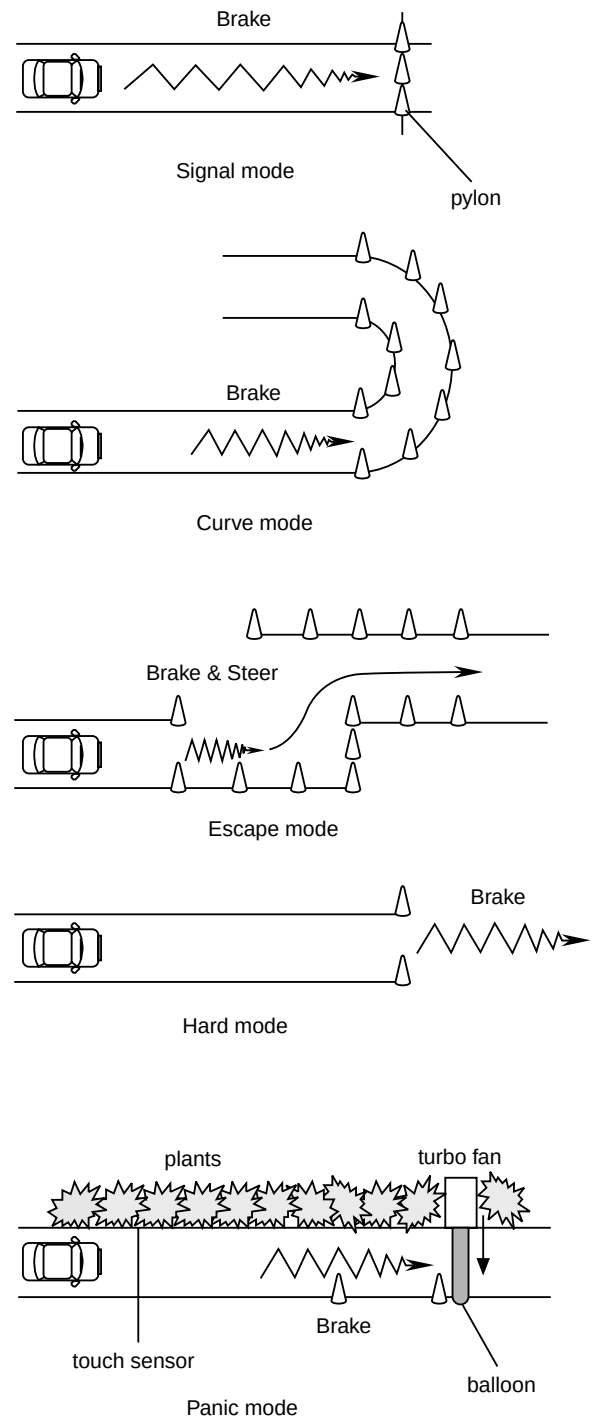


Fig. 1 Braking test modes



Fig. 2 Panic mode

steering avoidance, the test was set up so that a cylindrical balloon, inflated by a turbofan, would suddenly emerge from the left side of the road to fully block the driving lane in one second. In order to keep the timing of the balloon's emergence consistent for all of the test subjects, a touch sensor was placed on the road surface. When the front wheels of the vehicle passed over this sensor, the turbofan was activated.

A 200 m approach was set up for each mode. The braking tests were conducted from a constant vehicle speed of 50 km/h, with no other vehicles present. In addition, the road was defined by pylons, making it more difficult than it would be under actual driving conditions for the subjects to understand where the roadway was until they were in the proximity of that section of road. Therefore, it should be noted that the subjects paid more attention while driving than they normally would.

4.3 Heart Rate Measurement

To measure the heart rate, a ground electrode was attached to each subject's earlobe and an ECG (electrocardiogram) was taken from two electrodes attached to the chest. The ECG was recorded on a data recorder with a sampling frequency of 500 Hz. In addition, the level of physiological response in the autonomic nervous system is subject to cyclical fluctuation during the day, called the "circadian rhythm."⁽⁶⁾ Therefore, it would be necessary for the measurements in each test to be taken at a consistent time of day. However, if the test looked only at changes that occur when the test subject is subjected to stress, it was felt that the direction of such changes would be constant regardless of the time of day. Therefore, the test focused only on changes in heart rate during braking, without relation to the circadian rhythm.

4.4 Scope of Analysis of Heart Rate Data

Because the sudden emergence of an obstacle is unforeseeable and induces a rapid psychological change, it is likely that the heart rate would change rapidly at that instant. On the other hand, the moment at which the subject recognized the emergence of the obstacle or the instant at which the subject decided to start braking reflect internal mental processes that are difficult for an external observer to define. However, in this test, behaviors that were common to all of the subjects were releasing the accelerator pedal and depressing the brake pedal. Therefore, a laser sensor that was capable of measuring the stroke of the accelerator pedal was attached to the accelerator pedal in the test vehicle in order to pinpoint the moment at which the subject began to release the accelerator pedal. This arrangement allowed the test to focus on changes in the heart rate before and after the accelerator pedal was released, even while braking was occurring. The scope of analysis, therefore, was defined as a certain period before and after the release of the accelerator pedal.

5. Test Results

In this test, 36 of the 39 test subjects provided valid results. Some of the subjects did not provide valid results due to problems such as the seat belt rubbing against and detaching some of the electrodes.

The test results are described below.

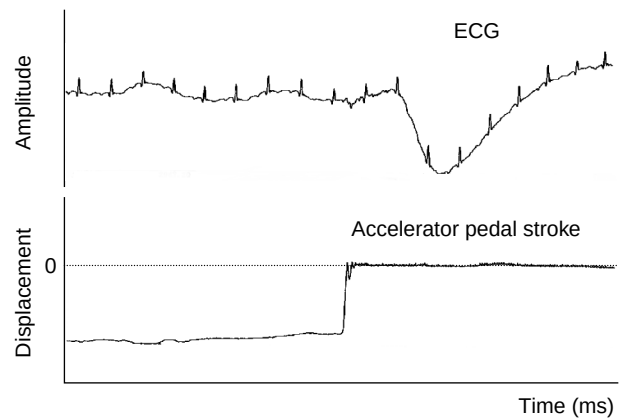


Fig. 3 Driver electrocardiogram (ECG) and accelerator pedal stroke displacement

5.1 Patterns of Change in Heart Rates for Each Mode

Fig. 3 shows an example of the data obtained from a single panic mode test. The graph shows the five second period before and after the accelerator pedal was released. (The five seconds after the pedal is released allows enough time for the vehicle to stop, whether in signal mode, hard mode or panic mode.) The upper portion of the graph shows the wave produced by the electrocardiogram; the fluctuation in the baseline is likely caused by the upper torso bending forward in response to the sudden and strong braking, or by perspiration produced in response to stress. The lower portion of the graph depicts the accelerator pedal stroke. In the graph, the negative direction represents the pedal being pressed. The graph clearly shows that the subject kept the accelerator pedal depressed by a nearly constant amount in order to maintain a constant speed up to the moment when he or she subject released the accelerator pedal. Time series data for the heart rate (Fig. 4) is obtained by calculating the instantaneous heart rate on the basis of the RRI, or the interval between peaks in the electrocardiogram. "AP-off" in the graph indicates the instant at which the accelerator pedal was released.

Once this conversion is made for all subjects and all tests, qualitative trends in changes in heart rate such as those indicated below can be determined. Fig. 5 shows the

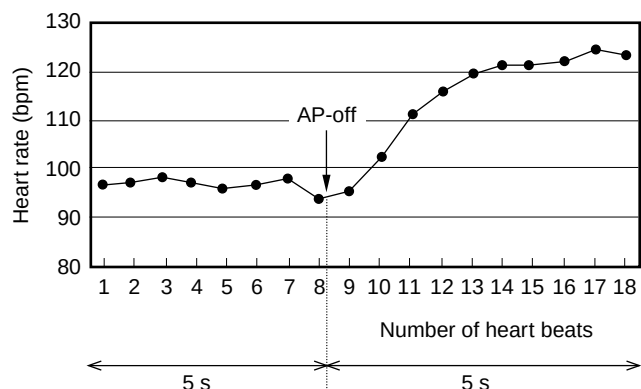


Fig. 4 Change in heart rate between 5 s before and after accelerator pedal release (AP-off)

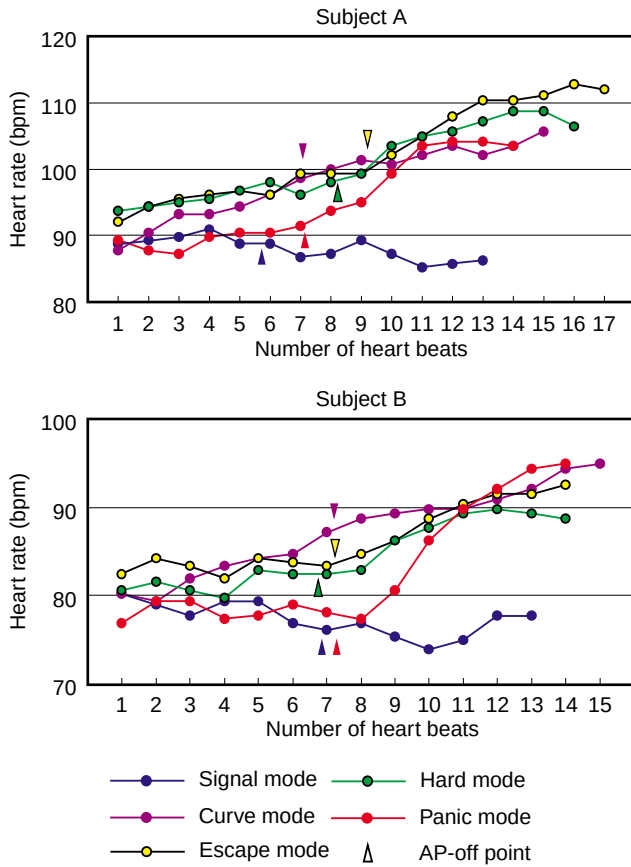


Fig. 5 Heart rate change pattern in each mode

data for two subjects.

In short, when braking in the signal mode, the heart rate begins to decline before the driver begins braking, and as the vehicle slows down the heart rate also slows down gradually with some fluctuation.

When braking in the curve mode, the heart rate increases as the vehicle approaches the curve, and continues to increase even as the subject enters the curve.

When braking in the escape mode, the heart rate increases as the vehicle approaches the point where braking begins. The heart rate increases further while the driver is performing steering avoidance maneuvers.

In the hard mode, the heart rate increases as the vehicle approaches the point at which the subject is supposed to begin braking. Subsequently, the heart rate continues to increase, but then it begins to decrease right before the vehicle stops.

In the panic mode, no change in heart rate is observed until immediately before braking. Once braking begins, the heart rate increases dramatically.

These results made it clear that there is a pattern to the change in heart rate in response to each mode. Next, an attempt was made to identify panic braking through a quantitative approach.

5.2 Quantification of Heart Rate Acceleration

Response

First, a comment about terminology. “Heart rate acceleration response” in this text refers to a physiological condition in which the heart rate increases. This is

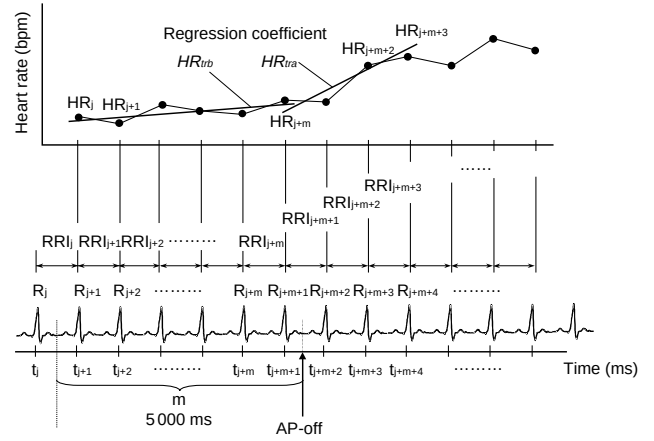


Fig. 6 Explanation for Eq.1

mathematically defined by Equation (1). V_{tr} is the difference between HR_{tra} , which is the slope of the regression line defined by one heart rate data point immediately preceding the release of the accelerator pedal and the next three subsequent heart rate data points, and HR_{trb} , which is the slope of the regression line defined by the heart rate data over the five second period immediately preceding the release of the accelerator pedal. This value represents the curve in the slope of the heart rate series arranged as a time series (Fig. 6), and it allows the consideration of the effects of both the gradual increase in heart rate before the pedal is released as well as the increase in heart rate that occurs subsequently while the subject is steering around the curve.⁽⁷⁾

$$V_{tr} = HR_{tra} - HR_{trb} \quad (1)$$

here,

$$HR_{trb} = \frac{\sum_{i=j}^{j+m} (t_{i+1} - \frac{\sum_{i=j}^{j+m} t_{i+1}}{m}) (HR_i - \frac{\sum_{i=j}^{j+m} HR_i}{m})}{\sum_{i=j}^{j+m} (t_{i+1} - \frac{\sum_{i=j}^{j+m} t_{i+1}}{m})^2}$$

$$HR_{tra} = \frac{\sum_{i=j+m}^{j+m+3} (t_{i+1} - \frac{\sum_{i=j+m}^{j+m+3} t_{i+1}}{4}) (HR_i - \frac{\sum_{i=j+m}^{j+m+3} HR_i}{4})}{\sum_{i=j+m}^{j+m+3} (t_{i+1} - \frac{\sum_{i=j+m}^{j+m+3} t_{i+1}}{4})^2}$$

V_{tr} : difference between HR_{trb} and HR_{tra} (beats/min/s)

HR_i : heart rate (beats/min)

HR_{trb} : regression coefficient calculated from heart rate data before AP-off (beats/min/s)

HR_{tra} : regression coefficient calculated from heart rate data after AP-off (beats/min/s)

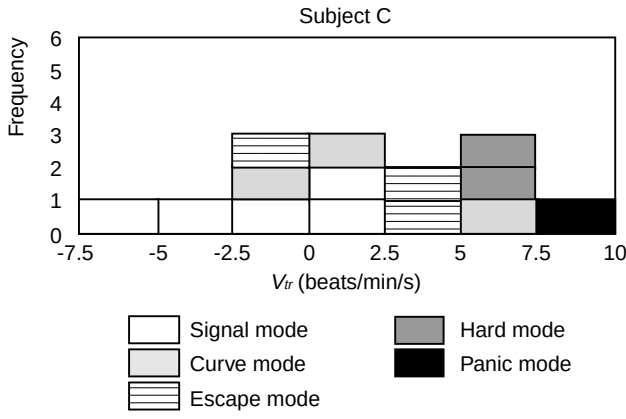


Fig. 7 V_{tr} frequency distribution (subject C) in each mode

The V_{tr} frequency distribution shown in Fig. 7 is an example showing the results produced by processing the data for a given subject.

5.3 V_{tr} Standardization

Although this analysis focused on heart rate acceleration response, throughout all the tests some of the subjects demonstrated a small response while others demonstrated a large response. As a result, a simple comparison of the V_{tr} values among all of the subjects would not be useful. In order to compare the data among all subjects, an attempt was made to standardize the V_{tr} values for each subject. The standardization equation is defined in equation (2) below.

$$V_{trst} = \frac{V_{tr} - AVV_{tr}}{\sigma} \quad (2)$$

V_{trst} : standardized V_{tr}
 σ : standard deviation of V_{tr} without panic mode
 AVV_{tr} : average value of V_{tr} without panic mode

Based on this equation, it becomes clear where V_{tr} in each mode for each subject falls in the frequency distribution graph for that subject. Because panic mode is not a phenomena that occurs frequently in normal braking behavior, the panic mode value cannot be included in calculations of σ and AVV_{tr} both of which presume normal driving. Fig. 8 shows the frequency distribution diagram that is obtained when V_{trst} is plotted for all subjects.

5.4 Subject Reaction

Immediately after the panic mode test, each subject was asked to fill out a questionnaire. Each subject was given four choices concerning their reaction to the panic mode test: “Did not notice”, “Was not surprised”, “Was surprised”, and “Was very surprised”. Of the 36 subjects, 34 indicated that they were surprised. (Fig. 9)

The subjects were also asked to select one of four choices that described their response during the test: “Could not do anything”, “Braked instinctively”, “Considered various factors and was barely able to brake in time”, “Considered various factors, judged braking to be the optimal response and applied the brake”. Fig. 10 shows the distribution of these results. According to these results, two of the 36 subjects answered that they “Could not do anything”.

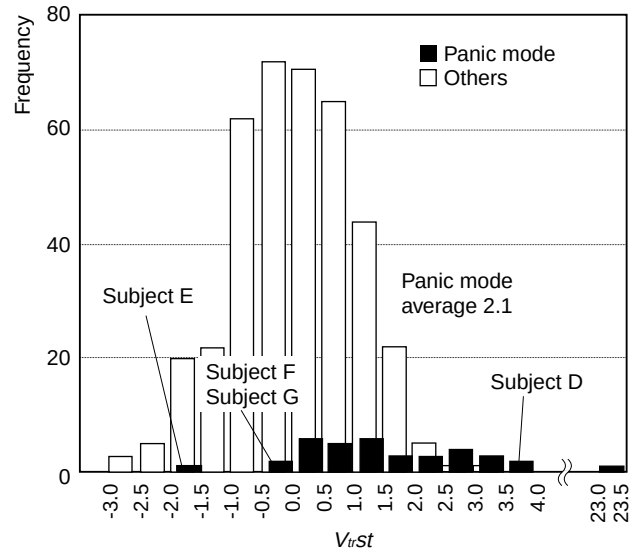


Fig. 8 V_{trst} frequency distribution

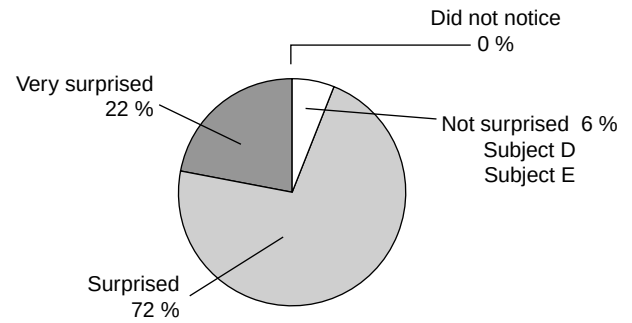


Fig. 9 Self-evaluation of feelings toward panic mode

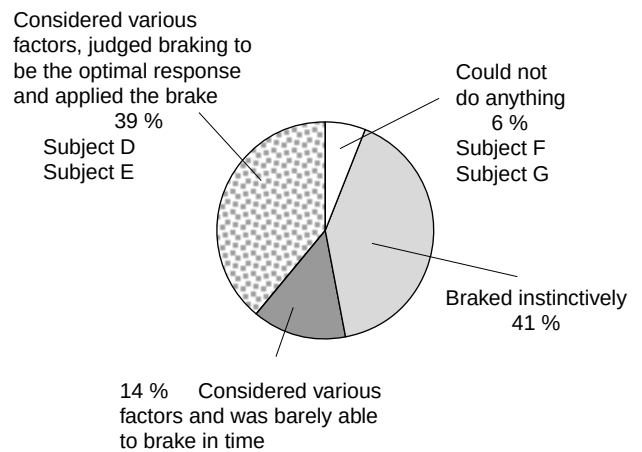


Fig. 10 Self-evaluation of behavior in panic mode

6. Observations and Conclusions

6.1 Patterns of Change in Heart Rate

Patterns of change in heart rate had certain special characteristics that corresponded to the braking behavior. In the case of the curve mode, escape mode and hard mode, it is likely that the increase in heart rate prior to removing the foot from the accelerator pedal was due to an increase in stress accompanying the vehicle's increasing proximity to the point where braking should start. In contrast to the prediction made by Ueno et al.,⁽⁸⁾ it is likely that the increase was the result of stress produced by the mind preparing for an action, in the same manner as occurs when people get their heart rates checked. Each subject's mind, in these tests, was preparing for steering through a lane change, and rapid deceleration, respectively. In the case of the panic mode, however, the absence of an increase in the heart rate immediately prior to the release of the accelerator pedal confirms that the subjects were unaware of the impending need to brake suddenly and therefore did not undergo mental preparation prior to braking. Furthermore, the subsequent increase in heart rate in the curve mode and the escape mode indicates the continuation of stress due to the driving tasks of steering and lane changes, respectively, in addition to braking. On the other hand, the gradual decline in the heart rate in the signal mode and the decrease in the heart rate as braking ends in the hard mode likely reflect an easing of stress due to the decrease in vehicle speed caused by braking and the end of the driving task when the vehicle comes to a stop. Therefore, the gradual decrease in heart rate that occurs before the accelerator pedal is released in signal mode likely reflects that stress has begun to ease even before braking.

6.2 Relationship between Heart Rate Acceleration

Response and Subject Reactions

Of the two subjects who were not surprised, subject D commented in regards to the emergence of the obstacle, "I was able to calmly react right away", and thus responded "Not surprised" on the questionnaire. When the obstacle emerged, subject D immediately "considered various factors", decided that applying the brake was optimal, and began braking. The standardized value $V_{r,st}$ for the heart rate acceleration differential in this case is high, indicating that the heart rate increased instantaneously. (Fig. 8) In the case of subject E, a mistake by the tester allowed the subject to gain prior knowledge of the obstacle, resulting in subject E being "Not surprised", as this subject knew beforehand approximately where to brake for the suddenly emerging obstacle. In this case, $V_{r,st}$ does not reflect a sudden increase in the heart rate. Subjects F and G, however, answered on the questionnaire that they "Could not do anything," because they were so surprised, and the $V_{r,st}$ for the panic mode for both of these subjects was lower than the others even though they fell right in the middle of the distribution for the other modes. On the other hand, in terms of their actual behavior, both subjects stepped on the brake in panic mode, just like the other subjects.

Based on the above, it is possible that the heart rate acceleration response in the panic mode indicates whether stress emerged suddenly while the subject was braking in order to avoid the sudden obstacle, instead of merely being a response to the surprise caused by the sudden emergence of the obstacle. As indicated by the response, subject D calmly and quickly reacted to the sudden emergence of the

obstacle, but the high $V_{r,st}$ value is likely to have been caused by stress that arose immediately after, while braking. Because subject E knew beforehand that braking would be necessary, it seems there was no sudden stress, resulting in a low $V_{r,st}$ value. The low $V_{r,st}$ values for subjects F and G is interpreted to be due to no stress developing while braking as a result of feeling that braking was hopeless and that they could not take any action in response to the sudden emergence of the obstacle. Therefore, the fluctuation in the heart rate of both of the subjects who answered "Could not do anything," even though they both applied the brakes was the result of physiological changes caused by subconscious behavior that is thought to be an automatic process⁽⁹⁾.

The reason for the sudden increase in heart rate in the panic mode is likely to be the sudden stress caused by trying to brake in response to the sudden emergence of the obstacle. However, because this research focused only on heart rate as a physiological measure, it is not possible to clearly determine if a heart rate acceleration response occurred in subjects while braking because they gasped in surprise or because they held their breath for an extended period. Another possibility is that the subjects tensed their torsos when braking, which along with the seatbelt caused an increase of pressure on the heart and lungs, resulting in a heart rate acceleration response. In any case, the results of this experiment clearly indicate the occurrence of a major heart rate acceleration response when braking in conjunction with the stress of having to somehow stop the vehicle.

6.3 Detection of Panic Braking

It is possible to use a quantitative index to identify panic braking by focusing on differences in heart rate acceleration. The nature of the panic mode differs from the other modes in that braking occurs under unanticipated conditions. When a U-test was performed in order to determine whether there is a difference in the population of $V_{r,st}$ values between the panic mode and the other modes (excluding the results from subjects E, F, and G), it was found that the other modes are likely to have a distribution that is independent of that of population ($p = 1.18E-0.5 < 0.025$). When the panic mode results from this test are excluded, the distribution of $V_{r,st}$ is deemed to be a normal distribution ($p = 0.44 > 0.05$); therefore, assuming that the $V_{r,st}$ produced by braking has a normal distribution, and based on the 95% confidence interval of the $V_{r,st}$ distribution, the threshold value at which panic braking can be identified is believed to be around $V_{r,st} = 2$. However, because the test that was used for standardization was set up to be more difficult than normal driving conditions, it is believed that the distribution itself is formed by values that are high. Accordingly, given normal driving conditions, the distribution would move to a relatively lower position, which should result in making the distinction between panic braking and other types of braking even clearer. Furthermore, because the heart rate rapidly increases to around 100 to 120 beats per minute while braking after the sudden emergence of the obstacle, then using the definition proposed here makes it possible to identify the panic state within two seconds from the start of braking that induces a rapid change in heart rate in the driver.

7. Summary

This research focused on driver reactions, behavior, and physiological response while braking, and the following results were obtained from tests (conducted in actual automobiles) on the relationships among these elements.

- (1) Patterns in the changes in heart rate were observed in relation to various braking modes. For example, as a vehicle approaches a curve, the heart rate increases, and the mental preparation made for entering the curve is reflected in a change in the heart rate. Research also clearly indicated that a large heart rate acceleration response occurs during panic braking.
- (2) Next, a method of quantifying these trends was proposed. A relationship was established between non-ordinary braking behavior (such as panic braking) and physiological responses, suggesting that it may be possible to use the heart rate acceleration response to determine when panic braking is occurring.

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