Comfort Optimization of Adaptive Cruise Control Based on Heart Rate Variability and Fuzzy Control

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Abstract: This paper investigated the impact of braking intensity of self-driving cars at different initial speeds on straight road sections on drivers’ comfort, with a view to achieving the comfort optimization of adaptive cruise control (ACC). Specifically, the real vehicle test was conducted in an enclosed venue based on the within-subjects design of, and the data pertaining to electrocardiogram (ECG) and subjective evaluation of 9 subject drivers in 9 sub tests were collected. Besides, the impacts of different motion states on heart rate variability (HRV) parameters were analyzed using the general linear model for repeated measures, and the relationships among drivers’ comfort, decelerations, and standard deviation of NN intervals (SDNN, an index of HRV) were obtained based on subjective and objective analyses. Additionally, a control strategy based on HRV and fuzzy control was formulated to realize the comfort optimization of ACC in case of an abrupt deceleration of the preceding vehicle, the verifications were performed through joint simulation. The results exhibited that the control strategy based on HRV and fuzzy control could shorten the deceleration time in case of an abrupt deceleration of the preceding vehicle, and may improve the comfort in such scenario.

1. Introduction

Autonomous driving technologies, featuring the advantages of effective improvement of road traffic safety, relief of road congestion, emission reduction, and elevation of competitiveness of countries and enterprises in the marketplace, receive an enormous amount of attention, and are being progressively developed. With a continuous increase in levels of autopilot, autopilot is playing an increasingly vital role in undertaking driving tasks and drivers’ duties, resulting in the emergence of a brand-new human-computer interaction (HCI) mode and driving mode [¹]. In view of such innovation, the physiological adaption of drivers should be analyzed, so as to ensure that autopilot does not cause...
potentially major risks as a result of drivers’ physiological or psychological discomfort [2].

The existing studies demonstrated that some complex scenarios (e.g., short car-following distance, many traffic participants, and complicated traffic environment) led to negative impacts (e.g., decreased comfort of drivers and passengers, reduced takeover abilities, and insufficient trust) on those inside self-driving cars [3][4][5][6]. Such negative impacts may cause drivers’ improper operations, resulting in potential safety hazards. In studies on drivers’ perceptions, the subjective evaluation of drivers and passengers is usually conducted. However, a study suggested that changes in physiological indices underpinned the subjective minds and perceptions, and subjective perceptions correlated with the corresponding physiological states [7]. The physiological data, an objective index, can denote changes in drivers’ physiological and psychological states from another dimension. As accurate physiological data can be easily collected, the investigation of autopilot comfort using physiological data remains an effective approach.

A study revealed that autopilot scenarios significantly affected physiological parameters (e.g., heart rate (HR), skin conductance response (SCR), and HRV), and changes in physiological data indicated changes in subjective perceptions [8]. The driving simulator-based study conducted by Beggia et al. [3] demonstrated that significant changes in drivers’ HR and pupil diameter occurred in case of scenarios leading to discomfort during autopilot, and scenarios leading to long-term discomfort caused reduced HR and pupil diameter. The driving simulator-based study conducted by Li et al. [4] showed that remarkable changes in time domain indices of HRV occurred in case of stress scenarios, and a higher degree of stress denoted lower time domain indices of HRV. Valderas et al. [5] conducted a comparative study on the driving psychological stress of drivers on congested urban expressways and smooth highways using ECG, and the results indicated that drivers showed a higher degree of psychological stress when driving on smooth highways than congested urban expressways. The study conducted by Valderas et al. [9] revealed that noticeable changes in HRV occurred in drivers with different emotions, and the low frequency (LF) and high frequency (HF), the frequency domain indices of HRV, and the LF/HF ratio markedly characterized positive moods of subjects. Yuan et al. [10] investigated the impacts of types of urban roads on drivers’ workload, and found that there were notable changes in the root mean square of successive differences (RMSSD) and LF, the indices of HRV, effectively suggesting drivers’ psychological states. Tian [11] evaluated the mental loads of drivers through monitoring their physiological indices (e.g., HRV).

The aforementioned studies prove that objective physiological data can characterize drivers’ physiological and psychological states. On this basis, quantitative studies on drivers’ comfort can be performed. The existing studies focus on analysis of impacts of environmental scenarios where traffic participants are available on drivers, and the comfort is subject to vehicle speed and acceleration. Studies demonstrated that a high acceleration led to passengers’ physiological discomfort [12][13]. Therefore, the kinematics performances (e.g., excessive acceleration and speed) of self-driving cars under the single vehicle condition on drivers were insufficiently investigated. As a result, the comfort optimization under this condition cannot be conducted. Based on real vehicle test data, this paper explored the impacts of different braking accelerations on the drivers’ HRV at multiple initial speeds on straight road sections, the relationship between objective physiological data and subjective evaluation results was analyzed based on subjective evaluation results of the subjects, and the control strategy was formulated based on the designed fuzzy controller and relationships among comfort, deceleration, and HRV.

2. Materials and methods

2.1 Participants
A total of 12 participants (including 2 female participants) were selected as the subjects, and participated in the real vehicle test in an enclosed venue. All subjects hold a valid Chinese driver’s license, with an average age of 30 ± 3 years, a driving experience of more than 3 years, and no past history of heart diseases. Additionally, the subjects were required to avoid heavy exercise and intake of
foods and drinks that excite the heart (e.g., caffeine, alcohol, and functional drinks) within 24 h before the study was initiated. During the study, the physiological data of three subjects were ruled out. Specifically, the physiological data of two subjects could not be collected effectively because of their excessive sweating, and the ECG data of one subject were significantly abnormal because of underlying health problems compared with those of others.

2.2 Apparatus
In this study, the real vehicle test was conducted in an enclosed venue, so as to provide the subjects with a practical experience of autopilot and vehicle dynamics. Additionally, we used a conventional vehicle equipped with driverless robots to achieve L4 autonomous driving, so as to easily obtain different speeds and accelerations during autopilot. The Toyota Highlander equipped with CBAR and SR60 driverless robots (AB Dynamics) was selected as the test vehicle, and the driverless robots could accurately control the accelerator pedal, brake pedal, and steering wheel after calibration, and accurately control and record the position, speed, and acceleration of the vehicle based on the RT3000 inertial navigation system.

The physiological data of the subjects were collected and analyzed using PhysioLAB system and equipment (Ergoneers GmbH), ECG signals were collected through Lead I electrode placement, and the sampling frequency was 100 Hz.

Figure 1 Schematic diagram of ECG acquisition and driverless robots

2.3 Study design and procedure

2.3.1 Experiment design
In this study, the test was conducted based on the within-subjects design of \( 3 \times 3 \times 2 \), with Factor 1 of three driving speeds (20, 60, and 100 Km/h), Factor 2 of three braking accelerations (-2, -4, and -6 m/s\(^2\)), and Factor 3 of two measured time points (before and during the test). Each subject successively completed 9 sub-tests, and there were a driving speed and a braking speed in each sub-test. The brake action occurred randomly within 10 s after the vehicle speed stabilized for 1 min, the sequences for 9 sub-tests were randomly assigned among all subjects to avoid learning effect, all sub-tests were conducted on the same road section in an enclosed venue where traffic participants were not available, and the weather was fine during the test.

2.3.2 Procedure
Upon arrival at the venue, the subjects signed the risk informed consent form after fully understanding the test details on the spot. Subsequently, the subjects were briefed of the basic situations of the test and equipment, including the test contents, working principles of driverless robots, emergency stop operations in case of dangers, and meanings of the subjective perception evaluation table (Table 1).
Next, the subjects entered the vehicle for adaption test, including familiarization with the test process and emergency stop operations. The adaption test was conducted at the test point (-4 m/s²-60 km/h), and then the subjects with electrode placement started the formal test. Specifically, at 2 min before each sub-test, ECG data were collected, and after a sub test started and the vehicle speed stabilized, ECG data were collected until 1 min after occurrence of the braking. After each sub-test, the subjects took a 10-min break, and subjectively scored the test based on their subjective perceptions.

### Table 1 Subjective scoring criteria

| Scores | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Evaluation | Very poor | Poor | OK | General | Fairly good | Good | Excellent | Perfect |
| Comfort | Very dissatisfied | Dissatisfied | Little dissatisfied | Acceptable | Fairly satisfied | Satisfied | Very satisfied |

### 2.3.3 Data

In this study, HR and HRV indices were selected as physiological parameters of the subjects, and the physiological and psychological characteristics were investigated under different motion conditions. HR measures the number of times the heart beats per minute, and HRV is the physiological phenomenon of variation in the time interval between heartbeats, both of which can objectively reflect the emotional changes of subjects. SDNN and RMSSD, the time domain indices of HRV, were selected as the study parameters. Table 2 shows the description of parameters.

### Table 2 Description of study parameters

| NAME | UNIT | DESCRIPTION |
|------|------|-------------|
| HR   | Beat/min | Number of times the heart beats per minute |
| SDNN | ms   | Standard deviation of intervals between two R waves in ECG |
| RMSSD | ms | Root mean square of the successive differences between adjacent RR intervals |

### 3. Result

After the outliers with the stud residual exceeding ±3 were rejected, the normality test was conducted for all data, and the results exhibited that all data conformed to normal distribution. Therefore, the paired T test and variance analysis were performed.

#### 3.1 General remark

The paired t-tests were performed for all data before and during the test. Table 3 shows the results. Specifically, HR during test (76.09 ± 7.79 bpm) was 0.68 bpm greater than HR before test (75.41 ± 7.38 bpm) (95% CI: 0.27-1.33 bpm), t (70)=-2.078, P<0.05. SDNN before test (32.46 ± 18.39 ms) was 11.32 ms lower than SDNN during test (43.79 ± 20.46 ms) (95% CI: 8.42-14.23 ms), t (70)=7.777, P<0.001. RMSSD during test (26.71 ± 13.82 ms) was 6.19 ms lower than RMSSD before test (32.90 ± 16.65 ms) (95% CI: 3.18-9.19 ms), t (70)=4.112, P<0.001. The aforementioned results suggested that the braking at different initial speeds during autopilot led to marginally increased drivers’ HR and markedly reduced SDNN and RMSSD, and such reduction indicated drivers’ significant discomfort [4][14].

The impacts of different speeds and accelerations on drivers’ comfort were further investigated. Since marginal changes in HR was not conducive to measurement of HR, the analysis of variance was carried out for the time domain data of HRV only. As physiological indices were significantly subject to individual differences, there were differences in the baseline values of subjects’ physiological indices under the same circumstances, and it was challenging to maintain the same outdoor weather conditions (e.g., temperature and lighting), resulting in differences in baseline values. Therefore, the data differences ΔSDNN, ΔRMSSD of each subject between two time points were selected as the
indices, so as to investigate the impacts of different speeds and accelerations on drivers’ physiological and psychological states.

Table 3 Paired T test

| Before and during the test | Description of paired samples | Paired differences | T      | Degrees of freedom | Significance (Two-tailed) |
|----------------------------|--------------------------------|--------------------|--------|--------------------|--------------------------|
|                            | Mean          | Standard deviation | Mean      | Lower limit | Upper limit |                           |                      |
| Before the test            | During the test | Before the test    | During the test |            |            |                           |                      |
| HR - hr                    | 75.41         | 76.09              | 7.38      | 7.79        | -0.68      | -1.33                   | -0.27               | -2.078               | 70                     | 0.041                  |
| SDNN - sdnn                | 43.79         | 32.46              | 20.46     | 18.39       | 11.32      | 8.42                  | 14.23               | 7.777               | 70                     | 0.000                  |
| RMSSD - rmssd              | 32.90         | 26.71              | 16.65     | 13.82       | 6.19       | 3.19                  | 9.20                | 4.112               | 70                     | 0.000                  |

3.2 SDNN
The two-way repeated-measures analysis of variance (ANOVA) was performed for ΔSDNN meeting the mauchly’s test of sphericity. The results revealed that the interaction between speed and acceleration was not significant (F (4,24) = 0.872, P=0.495). Therefore, the main effects of each factor were analyzed separately, and the results indicated that the main effects of different horizontal accelerations (F (2, 12) = 4.517, P=0.034) on ΔSDNN were significant, while the main effects of speed (F (2,12) =0.880, P=0.440) were not significant. This demonstrated that there were remarkable differences in the reduction of SDNN as a result of different braking accelerations, and such reduction was not subject to speed changes.

The comparisons between main effects of accelerations showed that there were marked differences in ΔSDNN between at -6 m/s² and -2 m/s² (P=0.012) and at -4 m/s² (P=0.092) at the 90% confidence level, yet the differences between at -2 m/s² and at -4 m/s² were not remarkable (P=0.853). Figure 2 shows that ΔSDNN shows a reduction of -18.45 ms (95% CI: -24.95—11.95 ms) at -6 m/s², which is significantly greater than the reductions at -2 m/s² (-7.55 ms (95% CI: -15.41—-0.32 ms)) and -4 m/s² (-8.21 ms (95% CI: -12.60—-3.82 ms)). This reveals that the reduction of SDNN increases with an increase in braking intensity, and the aggravated physiological discomfort induced by excessive deceleration can be quantitatively characterized based on changes in SDNN. In addition, such great changes occur when -4 m/s² is exceeded, which may indicate that such acceleration is the critical point for drivers’ significantly enhanced physiological discomfort.

Figure 2 SDNN differences at different accelerations
3.3 RMSSD
After Greenhouse–Geisser correction, the two-way repeated-measures ANOVA was conducted for \( \Delta \text{RMSSD} \) that did not meet mauchly’s test of sphericity. The results revealed that the interaction between speed and acceleration was not significant (F (4,24) = 1.121, P=0.359). Therefore, the main effects of each factor were analyzed separately, and the results exhibited that different accelerations (F (2,12) = 0.382, P=0.691) and speed (F (2,12) = 0.414, P=0.670) did not significantly affect the main effects of \( \Delta \text{RMSSD} \). Figure 3 shows that there are no marked differences in \( \Delta \text{RMSSD} \) between at different speeds and at accelerations. This demonstrates that although the braking at different speeds leads to markedly reduced RMSSD, the reduction of RMSSD is not subject to different horizontal speeds and braking accelerations, and the discomfort at different motions cannot be characterized using variations.

![Figure 3 RMSSD differences at different speeds and accelerations](image)

3.4 Relationship between subjective and objective evaluations
The correlations between subjective evaluation scores and speed as well as acceleration were analyzed using Spearman’s model. Table 4 shows that the subjective evaluation scores significantly correlate with acceleration (Rho=0.9, P<0.001) and \( \Delta \text{SDNN} \) (Rho=0.287, P=0.015). This suggests that \( \Delta \text{SDNN} \) can quantitatively characterize the discomfort induced by different braking accelerations in the study scenarios (Figure 4).

![Table 4 Correlation analysis of subjective evaluation](image)
3.5 Fuzzy control for comfort optimization

Since the absolute values of physiological indices vary greatly and are easily subject to the environment, and there are marked differences among individual physiological indices, it is challenging to establish an accurate mathematical model. Fuzzy control, an intelligent algorithm, is applicable to nonlinear and time-varying systems and systems for which the mathematical model can be hardly established, and has a good robustness. In addition, the system features a good adaptability, because fuzzy rules can be easily modified and adjusted whenever necessary. Therefore, the comfort optimization of ACC based on HRV was conducted using fuzzy control in this paper.

In this paper, \( \Delta SDNN \) and the expected deceleration of ACC were taken as the input parameters, and deceleration was taken as the output parameter. According to previous studies, degrees of comfort can be divided into comfortable, general, and uncomfortable. Based on general experience, the collision risks are divided into three types: severe, general, and none according to calculated acceleration. Figure 5 shows the relationship between collision risks, SDNN and the expected deceleration of ACC. Figure 6 shows the established simulation model.
The scenario where the preceding vehicle decelerated abruptly at -6 m/s² when ACC was used was designed. The simulation results demonstrated that the deceleration of the vehicle could be appropriately reduced when the preceding vehicle decelerated abruptly after the fuzzy control system was employed, and such deceleration could be increased to avoid collision in case of a collision risk (Figure 7).

4. Discussion and conclusion
The analysis of HRV data exhibits that RMSSD and SDNN are significantly reduced during the braking process, which is consistent with the prior knowledge. This indicates that the braking leads to drivers’ discomfort, which is primarily induced by braking deceleration rather than driving speed.
Additionally, this study reveals that the main effects of changes in accelerations on the reduction of SDNN are remarkable, and such changes are the most significant when the braking acceleration exceeds $-4 \text{ m/s}^2$, which are similar to the study results obtained by Bossetti[13]. After collecting and analyzing the natural driving data of 24 drivers, Bossetti found that the braking acceleration of drivers did not exceed $-2 \text{ m/s}^2$ in 99.99% of the duration for data collection, and their braking accelerations exceeded $-4 \text{ m/s}^2$ in very few cases. Therefore, changes in SDNN objectively indicate that $-4 \text{ m/s}^2$ is a critical point for drivers’ physiological discomfort. The subjective evaluation scores demonstrate that the subjective perceptions of drivers are highly consistent with the results based on objective physiological data, namely, drivers’ subjective comfort decreases with an increase in braking intensity, and the subjective scores do not correlate with the speed. In addition, subjective evaluation scores significantly correlate with $\Delta$SDNN, exhibiting that $\Delta$SDNN can be used as the objective data to directly characterize drivers’ discomfort.

Based on the aforementioned results, the fuzzy control strategy is designed, and the controller model is established using the fuzzy controller. Additionally, the joint simulation is performed using Matlab/Simulink and Carmaker, and the results demonstrate that the deceleration can be reduced while ensuring safety, suggesting that drivers’ comfort can be improved.

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