A Study in Emotion-Aware Adaptive Interaction in Intelligent Vehicle Cockpits

Sihui He[1,*], Hexuan Ying[2] and Hao Zhong[3]
[1]School of Design, Royal College of Art, London, U.K.
[2]High School Affiliated To Shanghai Jiao Tong University IB Center, Shanghai, China
[3]School of Artificial Intelligence, Zhujiang College, South China Agricultural University, Guangzhou, Guangdong, China
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Abstract: With the rapid development of intelligent cockpit technology in today's era, the emotional state of drivers has become a significant factor influencing driving safety. Among these, negative emotional behaviors such as 'road rage' pose a significant threat to traffic safety. This study focuses on analysing the integrated application of multi-modal emotion recognition and intelligent interaction. It first explores the causes of negative emotions during driving and then examines the technical pathways for emotion recognition from both single-modal and multi-modal perspectives, emphasising the advantages of multi-sensory collaboration in enhancing recognition accuracy and response sensitivity. The study explores an emotion monitoring system based on multi-modal perception and analyses adaptable human-machine interaction mechanisms. The aim is to mitigate driver emotional fluctuations through proactive intervention strategies, thereby enhancing driving safety and cabin experience. Additionally, this study identified current challenges in emotion recognition accuracy, emotion classification dimensions. Based on this, it proposed future development directions, including leveraging deep learning to enhance individual emotional personalisation and optimising the collaborative mechanisms between multi-modal sensors and driving behavior big data. This study provides a theoretical foundation and practical pathways for achieving more emotionally intelligent interaction systems, driving the evolution of intelligent cockpits toward more humanised and emotional directions.

1 INTRODUCTION

In recent years, intelligent cockpits have gradually become a hot topic of research in the automotive industry and human-machine interaction field, attracting widespread attention from all sectors of society. With the continuous development of cutting-edge technologies such as artificial intelligence, the Internet of Things, and big data analysis, a series of intelligent interaction functions such as intelligent driving, automatic parking, and voice control have emerged and are gradually being applied to mass-produced models. These features not only effectively reduce the operational burden on drivers during driving but also significantly enhance the convenience and safety of travel, driving the transformation of automobiles from traditional transportation tools to intelligent mobile terminals. Currently, an increasing number of automakers and technology companies are investing substantial resources and R&D efforts into in-depth research on intelligent driving assistance systems, striving to integrate automation technology with human-centric design to achieve a qualitative leap in driving experience (Xu & Lu, 2024).

Against this backdrop, the driver's emotional state, as a critical factor influencing driving behaviour and road safety, has garnered significant attention from researchers and the industry. In recent years, emotion recognition and intervention functions have gradually been integrated into the core design of in-vehicle systems. Research indicates that emotion recognition technology incorporating multimodal data (such as facial expressions, voice tone, and physiological signals) can significantly improve recognition accuracy, particularly in complex and dynamic driving scenarios, demonstrating strong application potential. Additionally, adaptive adjustment strategies based on real-time emotion monitoring have been proven to effectively alleviate negative emotions such as tension and anxiety in drivers, reduce their cognitive load, and thereby

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improve driving performance and road safety (Li, 2021).

Therefore, this paper will explore the application value of emotion perception in intelligent cockpits, focusing on how to achieve precise monitoring and intelligent adjustment mechanisms for driver emotional states. By analysing existing driver-centric adaptive interaction system research and exploring the complete perception-recognition-intervention process mechanism, this study will thoroughly analyse the feasibility and challenges of multimodal fusion in real-world scenarios. Additionally, by addressing the challenges faced in existing research, this study will conduct a systematic evaluation of the system's user acceptance, functional performance, and human factors adaptability, thereby providing a theoretical foundation and future outlook for more humanised and emotionally intelligent intelligent cockpit design.

2 ANALYSIS OF THE CAUSES OF ROAD RAGE

Road rage refers to angry or aggressive behaviour exhibited by drivers while driving. The causes of road rage can generally be categorised into: age, driving experience, driving frequency, road conditions, and personal circumstances (Ren et al., 2021; Fan, 2024). A study (Fan, 2024) using a binary logistic regression model found that age and driving experience have an inverse relationship with road rage. Among those aged 36–48, the proportion of road rage incidents caused by cutting in line was 55.1% of that among those aged 18–24. while among driving frequency, the proportion of road rage among infrequent drivers was 66.4% of that among frequent drivers (Fan, 2024). Road conditions include traffic obstacles such as congestion, rude behaviour such as cutting in line, uncivil language, sudden appearances of pedestrians or non-motorised vehicles, and dangerous behaviour. Among these, rude behaviour is more likely to trigger road rage than the other two. Personal circumstances include gender, personality, family situation, and education level. Male drivers are more prone to road rage than female drivers; among family circumstances, married but childless and married with children have lower road rage probabilities than unmarried individuals, and married with children have lower probabilities than married but childless individuals; among educational backgrounds, postgraduate and undergraduate degrees are more likely to trigger road rage (Ren et al., 2021; Fan, 2024). When driving an SUV, road rage caused by frequent lane changes and U-turns is 56.6% higher than in sedans, indicating that open spaces help alleviate road rage (Fan, 2024).

Based on the theoretical framework of the Momentary Experience Model (as shown in Figure 1), it can be concluded that a driver's momentary emotional state is composed of transient factors (Cannon, 1927; Ningjian, 2024), situational factors (Behnke & Beatty, 1981), and subjective experiences. Therefore, by regulating a driver's momentary emotional state, their emotional responses can be intervened, thereby effectively alleviating the potential risks associated with negative emotions and enhancing overall driving safety and user experience.

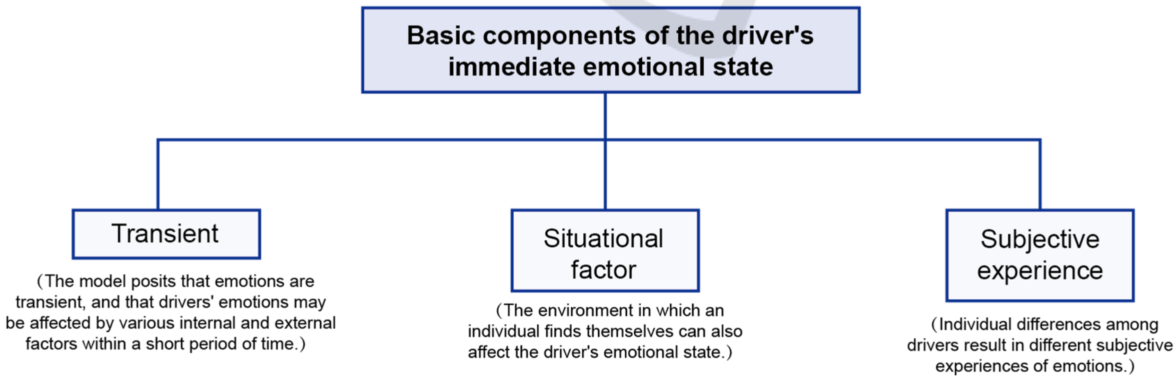

Figure 1: Basic components of the driver's immediate emotional state. (Picture credit: Original)

Additionally, research has utilised the Kubler-Ross Change Curve model (Kübler-Ross, 1973) to simulate the detailed emotional changes associated with road rage in traffic congestion scenarios (as shown in Figure 2). By identifying the psychological state at each stage, it is possible to analyse potential behavioural characteristics, further inferring the risk behaviours that may be triggered, thereby identifying the highest-risk emotional stages and providing a foundation for subsequent measures to mitigate these risks. This also helps us clearly identify at which stage most need to intervene in the driver's emotions, providing theoretical support for subsequent experimental testing.

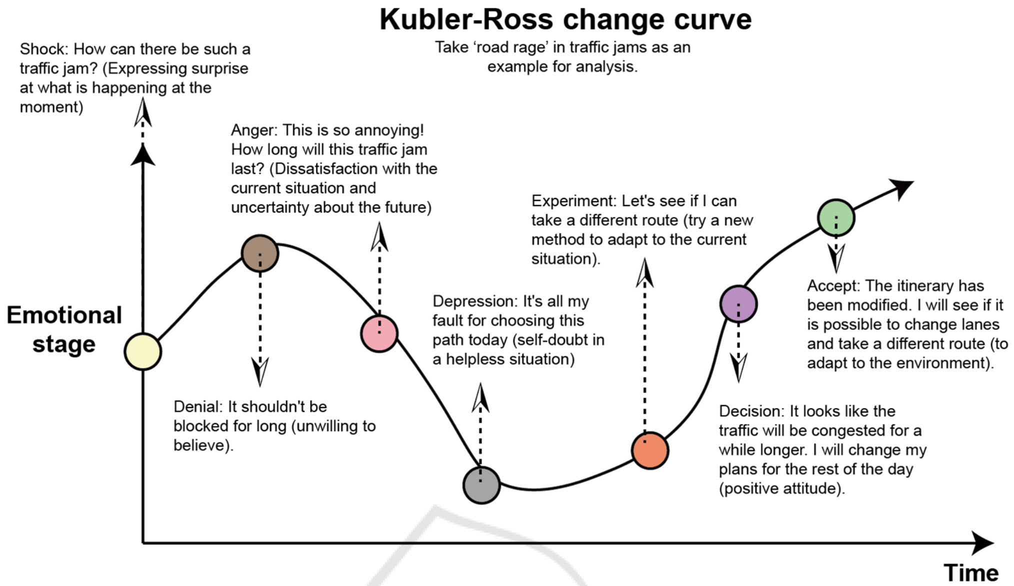

Figure 2: Kuber-Ross change curve. (Picture credit: Original).

3 ROAD RAGE EMOTION MONITORING METHOD

A driver's emotional state directly affects their attention, judgment, and reaction speed while driving, making it an important factor in traffic safety. Emotion detection technology analyses data such as facial expressions, physiological signals, and voice characteristics to detect changes in a driver's emotions in real time, providing a basis for risk warning and emotional intervention. Applying emotion detection to driving scenarios helps prevent dangerous behaviour caused by negative emotions, improving the overall driving experience and road safety.

3.1 Emotion Detection based on Single Modality

The in-vehicle system is based on the Android operating system and includes features such as communication, apps, and podcasts. The voice recognition module currently has errors in identifying dialects and Mandarin, requiring improved accuracy. The dynamic visual monitoring system uses real-time monitoring of the eyes to assess focus on the road surface and confirm whether the interaction module may have a negative impact on the user. The eye-tracking system Super Cruise enters autonomous driving mode after the user fails to respond to warnings, reducing the risk of fatigued driving (Operator, 2016). The in-vehicle system can monitor vehicle status in real time when connected to the internet. Gesture interaction has been proven through experiments to be more efficient than touch interaction (Wu, 2016). Currently, emotional detection in automotive applications lacks data on multi-sensory interaction, particularly olfactory interaction. Eye-tracking is relatively more mature compared to other modules, with abundant experimental data available. The voice module has diversified voice tones, but there are still issues with dialect recognition. Currently, monitoring and prevention of road rage are based on Spatial-Temporal Attention Neural Networks (STANN), which combine electroencephalography (EEG) signals and eye movement signals, and are validated using the public dataset SEED IV to ensure accuracy. Additionally, by improving techniques such as CenterFace, StarGAN, and KMU-FED, it is possible to capture more facial information from drivers and more accurately detect expressions of anger (Li, 2024).

3.2 Emotion Detection Based on Multimodal Data

In the study of road rage detection mechanisms, the method of integrating facial expressions with driving behavior has demonstrated significant advantages. This method uses in-vehicle devices to capture the driver's facial expressions in real time, combining them with driving behavior data such as steering wheel angle change rate, acceleration, and braking pedal operation to construct a Fisher linear discriminant model for comprehensive judgment (Huang et al., 2022). Experiments have shown that compared to using facial expressions or driving behavior features alone, the fusion method significantly improves recognition accuracy, providing an effective means for online monitoring of road rage. Key technological research on intelligent vehicle occupant monitoring systems (OMS) has also provided new insights into road rage detection. The passenger-side child monitoring and warning scheme achieved through technologies such as OpenPose demonstrates the potential of multimodal information fusion in enhancing vehicle safety monitoring (Fu, 2022).

Emotion perception technology plays a critical role in driving safety within intelligent cockpits, especially in high-risk emotional scenarios such as road rage. A driver monitoring system (DMS) based on a 940 nm wavelength infrared light source combined with facial micro-expression analysis can real-time capture physiological features of anger in drivers (such as tense brow muscles and drooping corners of the mouth) (Shaobi, 2021). When road rage symptoms are detected, the system can collaborate with the cockpit environment control module for proactive intervention: for example, dynamically adjusting the lighting to a cooler tone via environmental light sensors to reduce visual stimulation; simultaneously activating the fragrance system to release calming scents to alleviate emotional escalation (Shaobi, 2021). This real-time response mechanism effectively suppresses aggressive driving behavior and reduces the risk of traffic accidents caused by emotional outbursts. However, precise perception of road rage still faces significant challenges. While existing algorithms perform well in laboratory settings, they are easily influenced by individual differences in real-world driving scenarios (e.g., variations in facial expressions due to cultural backgrounds or dialectal intonation changes) (Guo et al., 2023). Additionally, intervention strategies for road rage are currently limited to environmental regulation functions and have not yet achieved deep synergy with vehicle control layers (e.g., adjusting adaptive cruise control following distance or steering sensitivity). Future research should establish a dedicated road rage dataset covering multiple driving scenarios and design a layered response logic: primary interventions use environmental adjustments to alleviate emotions, and if emotions continue to deteriorate, the level of autonomous driving intervention is automatically increased, with cognitive guidance provided by a voice assistant when necessary (Guo et al., 2023). This tiered response system can achieve a closed-loop safety protection mechanism from emotion recognition to behavior correction.

Existing multimodal emotion recognition systems have achieved a certain level of accuracy, collecting data from multiple sensors to identify and analyses the driver's state and provide emotion regulation measures (Zhang & Chang, 2025). Building on this, the relationship between emotional changes and driving state is a critical step that requires experimental validation. Monitoring driving behaviour styles under different emotional states, testing and analysing factual data, and constructing a reasonable logical structure will lay the foundation for subsequent integrated mechanisms.

Research indicates that a driver's emotional state (primarily negative emotions) can spontaneously influence driving behaviour without cognitive control (Eherenfreund Hager et al., 2017). Additionally, drivers cannot clearly articulate the specific triggers for these emotions (Hu et al., 2013). Based on this, previous studies have shown that experimental tests using driving simulators with emotionally charged vocabulary can induce emotional responses in drivers (Steinhauser et al., 2018). Some tests have used video presentations to induce fluctuations in drivers' emotions (Gu, 2021), while others have employed emotionally charged music and evocative recollections to induce emotional responses (Kwallek et al., 1988).

In summary, it can be seen that drivers' emotions can be influenced by external factors, and different methods can cause varying degrees of emotional changes. Therefore, based on the identified emotional states, we need to design an integrated mechanism for the overall cabin environment to achieve positive intervention and interaction with drivers, thereby regulating users' psychological states, enhancing driving safety and experience, and achieving personalised interaction optimisation—this is the core challenge of our research.

3.3 Analysis of the Advantages of Multi-Sensory Coordination and Regulation

A multi-sensory coordination strategy integrates multiple stimuli from hearing, touch, smell, and even sight to provide a new solution for alleviating road rage. Research shows that this strategy can effectively improve drivers' reaction speed and warning effectiveness when fatigued (Li et al., 2014). At the same time, it can change drivers' perception of speed through multi-sensory stimulation, thereby adjusting driving behaviour and reducing the risk of traffic accidents (Liu et al., 2013). In terms of emotional regulation, multi-sensory coordination can comprehensively intervene in drivers' emotions. For example, using stimuli such as soft music, warm lighting, and mild vibrations, creates a soothing driving atmosphere, helping drivers detach from tense or angry emotions and regain composure. This strategy not only demonstrates the universality of multi-sensory stimulation principles but also offers a new perspective on addressing driving-related mental health issues.

Multisensory coordination demonstrates multiple advantages in road rage intervention. From a physiological perspective, multisensory stimulation can more quickly capture the driver's attention and interrupt negative emotional cycles. From a psychological perspective, multisensory coordination may trigger positive emotional responses in drivers, alleviating tension. From a behavioural perspective, multisensory coordination can also indirectly reduce road rage triggers by regulating driving behaviour.

With the widespread adoption of autonomous driving technology and the continuous development of intelligent cockpits, multi-sensory coordination strategies are poised to become a new paradigm in emotional management, enhancing road safety and comfort more comprehensively by integrating different sensory stimuli.

4 CURRENT LIMITATIONS AND FUTURE PROSPECTS

4.1 Current Limitations

To reduce the safety risks posed by road rage drivers and help them calm down more quickly, an interactive system design has been adopted that adjusts angry emotions through multi-channel sensory stimulation. When the emotion sensing system detects that the driver is in an angry state, the adaptive system will address the issue based on the following detailed principles. First, visual sensory adjustment: the interior lights are switched to a cool colour tone to help the driver transition to a calm state, reducing stress and relaxing the mind, creating a cool-toned environment throughout the vehicle. Second is auditory sensory adjustment, where the in-vehicle system automatically plays soothing music to promote the relaxation of tense emotions, enhances voice support, and provides positive feedback to the driver to help restore their state. Third is olfactory sensory adjustment, where the air conditioning system releases mint-scented or plant-based essential oils to alleviate physical fatigue, awaken the brain's senses, and soothe the driver's anxious emotions.

Although this system has established a foundation and feasible strategies for positive emotional regulation, it still has certain limitations. First, the accuracy and timeliness of emotional recognition are easily affected. Multi-modal emotional recognition algorithms are still susceptible to interference from factors such as lighting, obstructions, and driving behavior in real driving environments, leading to reduced recognition accuracy. Especially when dealing with drivers whose emotional expressions vary greatly, errors in judgment and inappropriate adjustments are more likely to occur. Secondly, the multi-sensory intervention mechanism lacks personalisation. Different drivers have individual differences in their acceptance of colours, smells, and sounds, and the current system has not implemented personalised adaptive intervention schemes, which may cause some users to feel uneasy or affect their driving experience.

Therefore, future technical improvements and personalised multi-modal sensory mechanisms are also key areas that require attention. However, existing research still faces numerous limitations. On one hand, the algorithm complexity is high, and the process of integrating multiple information streams may affect real-time performance, making it difficult to meet the rapid response requirements of complex traffic scenarios. On the other hand, environmental adaptability needs to be enhanced, as factors such as varying lighting conditions and changes in driver posture may affect detection accuracy. Additionally, current research primarily focuses on group characteristics and lacks in-depth consideration of individual driver differences.

4.2 Future Prospects

Looking ahead, research into road rage detection and intervention systems can be explored from multiple dimensions, with the ultimate goal of developing an intelligent emotional driving cockpit system. First, explore the deep integration of multimodal data, combining physiological signals such as heart rate variability and skin conductance response, as well as behavioral data such as voice features and gesture recognition, to build more refined emotion detection models, enhancing the comprehensiveness and accuracy of identification. This will facilitate the incorporation of deep learning and personalized big data, further optimising the multimodal driver emotion recognition system to improve identification accuracy and generalisation capabilities. Second, optimise algorithm structures by adopting lightweight neural networks or improved algorithm workflows to reduce computational complexity, ensuring the system's real-time response capability in complex traffic scenarios. Additionally, integrate machine learning and AIGC technology to provide personalised intervention strategies based on drivers' historical behaviour and emotional responses, achieving strategy optimisation. Additionally, environmental adaptability testing should be strengthened to ensure algorithm stability under various lighting conditions and road conditions in real-world driving scenarios. During system design, human factors engineering and driving safety assessments should be integrated to prevent sensory interventions from causing new attention burdens. Through continuous simulation and testing, intervention intensity and frequency should be optimised. Finally, personalised recognition research is conducted, fully considering factors such as the driver's age, gender, and driving habits to enhance the targeting of recognition and the effectiveness of interventions. This enables the system to accurately identify emotions while adapting to individual differences, providing drivers with customised emotional management solutions. Through these improvements, it is anticipated that more reliable and efficient road rage detection and intervention solutions will be provided for intelligent vehicle safety driving, further reducing driving risks and enhancing road safety standards.

5 CONCLUSIONS

This paper focuses on the identification of driver emotional states and adaptive interaction mechanisms in intelligent cockpits. It proposes an emotion monitoring system that integrates multi-modal sensory information from vision, hearing, and smell, and designs a coordinated adjustment strategy based on emotion recognition results. When the system detects negative emotions such as ‘road rage’ in the driver, it can employ proactive intervention measures (such as in-cabin atmosphere adjustment, soothing voice prompts, and aromatic scent release) to create a calm cabin environment, thereby effectively alleviating emotional fluctuations and enhancing driving safety and user experience. This study highlights the advantages of multi-modal collaboration in improving emotion recognition accuracy and human-machine interaction sensitivity, and preliminarily validates its feasibility and practical value in real-world application scenarios. Future research, will further explore more refined emotional modelling algorithms to enhance the system's personalised response capabilities. Simultaneously, by optimising edge computing performance and sensor collaboration mechanisms, aim to drive the transformation of intelligent cockpits from traditional ‘feature aggregation’ to ‘emotion-driven’ deep-level human-machine collaboration, ultimately achieving a more human-centric intelligent interaction system and providing theoretical support for human-centred intelligent cockpit design.

AUTHORS CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

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