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An Adaptive Affective Interaction Design Framework for Smart Cockpit Human–Machine Interfaces and Ambient Lighting in Urban Traffic Congestion Scenarios

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Abstract

Urban traffic congestion can progressively accumulate driver irritation and stress and can promote attentional disengagement. Human-machine interfaces (HMIs) and ambient lighting in intelligent cockpits currently serve information feedback and spatial-atmosphere functions, respectively; however, they are rarely coordinated in terms of affective goals, intervention timing, and state transitions. This study employs a narrative literature review, comparative analysis, and design translation. It prioritizes authoritative studies and current standards published between 2016 and 2025, synthesizes research on driver affect, adaptive HMI, cognitive load, and in-vehicle dynamic lighting, and translates the findings into design requirements for stage-specific adaptation, functional differentiation, safety priority, low-stimulation feedback, and user control. On this basis, a rule-based, three-stage adaptive affective interaction framework is proposed, comprising initial congestion regulation, prolonged standstill regulation, and attention restoration with task re-engagement. The framework specifies differentiated roles for HMI and ambient lighting, finite-state transitions, safety interruption, and user-exit logic. A system architecture, low-fidelity concepts, and strategy-mapping tables are provided to support subsequent prototyping. All temporal and visual parameters are treated as conceptual reference values rather than validated optima. No user-experiment results are reported; the contribution is an implementable framework for balancing affective support and task vigilance in low-speed urban congestion.

Keywords: in-vehicle human-machine interface; context-aware adaptation; affective interaction; intelligent cockpit; ambient lighting; urban traffic congestion

1. Introduction

Automotive cockpits are evolving from collections of instruments, controls, and information displays into integrated interaction spaces that combine environmental sensing, driver-state assessment, multi-display presentation, and intelligent services. In-vehicle HMIs no longer merely present speed, navigation, and vehicle status; they increasingly participate in information orchestration, contextual feedback, and driver-state support. Previous research has argued that intelligent-cockpit interaction design must establish systematic relationships among multimodal technologies, scenario adaptation, user experience, and driving safety [1,2]. Accordingly, the development of interpretable and controllable adaptive interaction mechanisms for specific traffic contexts has become an important direction in intelligent-cockpit design.

Urban congestion is a frequent and practically significant scenario for affective interaction in intelligent cockpits. Dense traffic, repeated stop-and-go movement, travel delays, and uncertainty about waiting time can weaken a driver's perceived control. A simulated-driving study by Emo et al. [3] showed that slow-moving traffic can induce anger and stress. The negative effects of congestion may also persist after traffic clears, increasing aggressive driving behavior and reducing attention to some information sources [4]. More recent work using electroencephalography and subjective scales likewise found that congestion significantly changes drivers' emotional valence and arousal [5]. Thus, congestion-related affect influences both user experience and subsequent driving performance.

Intelligent cockpits can already provide multichannel feedback through HMI, audio, haptics, and in-cabin lighting. Existing reviews classify in-vehicle emotion regulation into visual, auditory, tactile, olfactory, and other modalities and identify multimodal regulation as an important research direction [6,7]. This study focuses on HMI and ambient lighting because both can remain continuously available while offering different information capabilities. HMI is suited to explicit semantics, information hierarchies, and operational entry points, whereas ambient lighting is better suited to low-intrusion spatial atmosphere and peripheral visual cues. Without a shared goal, however, reduced interface complexity may be offset by elaborate lighting effects, and light-based cues may be difficult to interpret without concise textual explanation.

The application scope of this study is low-speed urban congestion. A narrative literature review, comparative analysis, and design translation are used to construct a three-stage adaptive affective interaction framework for intelligent-cockpit HMI and ambient lighting. The study reviews representative research published since 2016 on driver affect, adaptive HMI, cognitive load, and in-vehicle lighting; extracts design requirements for congestion scenarios; divides the interaction process into three stages according to changing driving tasks and affective needs; and establishes functional allocation, state-transition, safety-interruption, and user-control mechanisms. This is a literature-driven conceptual-framework study; the design translation is not presented as a validated system effect.

2. Literature Review and Theoretical Foundations

2.1 Affective Computing, Adaptive Interaction, and the Regulation Target

Research on affective automotive interfaces commonly includes affect sensing, state interpretation, feedback decisions, and regulatory output. The review by Chung et al. [8] indicates that state recognition must be coupled with an appropriate feedback mechanism to form a complete regulation process. Braun et al. [6] noted that driver-affect research and in-vehicle regulation strategies require closer methodological integration, while Li et al. [7] incorporated driving-context awareness, emotion detection, and HMI regulation into a coupled driver-vehicle-road framework. Chinese research has similarly proposed a process of affect sensing, state recognition, strategy generation, and interaction feedback for affective computing in intelligent cockpits [2]. Affect recognition is therefore only one component of the loop; recognition outcomes must be translated into interpretable and interruptible strategies before appropriate affective interaction can occur.

From an implementation perspective, affective interaction in an intelligent cockpit involves at least perceptual expression, behavioral usability, and overall experience. Huo et al. [9] converted interface visuals and functional touchpoints into analyzable design variables through affect quantification and user-experience mapping. Lai et al. [10] mapped cockpit function configurations to affective needs by jointly analyzing user behavior, text, and psychological data. These studies show that affective design does not simply mean adding decorative effects; it requires the coordinated treatment of visual stimulation, information organization, interaction burden, system explanation, and user control.

Continuous dimensions such as valence and arousal remain widely used to represent affective states in intelligent-vehicle research [7,11]. Affect during urban congestion is not always limited to high-arousal irritation. Prolonged stop-and-go traffic may reduce arousal and induce fatigue or attentional disengagement. The congestion experiment by Zhang et al. [5] suggests that restoring valence and arousal to moderate levels is more compatible with driving safety than pursuing minimum arousal alone. The target of this study is therefore defined as reducing task-irrelevant tension while maintaining or restoring the task-related vigilance needed for traffic monitoring. Continuous affective dimensions determine only the direction of regulation and do not directly prescribe color, luminance, or animation parameters.

2.2. Urban Congestion, Driver Affect, and Attention

Stress caused by traffic congestion is contextual and cumulative. Emo et al. [3] found that slow traffic can simultaneously induce anger and stress and can be associated with risky passing behavior. A simulated-driving study by Li et al. [4] further showed that post-congestion driving may involve greater aggression, reduced attention to the instrument area, and altered behavioral-response patterns. These findings indicate that negative experiences in urban congestion arise not only from waiting duration but also from interrupted progress expectations, lack of control, and the persistence of affective effects.

Driver-affect regulation should not be reduced to the production of pleasant stimuli. Congestion studies show that both valence and arousal change with the scenario and that excessively low or high arousal may conflict with task performance [5]. Reviews of affective in-vehicle interfaces likewise emphasize that regulation strategies must be considered jointly with the driving task, interaction modality, and safety evaluation [6,7]. The present framework therefore does not target "deep relaxation"; instead, it seeks to reduce intense irritation and unnecessary stimulation while actively supporting the reconstruction of attention when traffic resumes.

Waiting also has a clear temporal dimension. In a study of congested railway level crossings, Larue et al. [12] found that frustration and risky behavior increased substantially after waits exceeding 3 min, providing evidence from a related context for a prolonged-standstill stage. Questionnaire and field studies by Sieklicka et al. [13] showed that drivers may use mobile phones, send messages, or change music while waiting at signals, and that some drivers had delayed moving off because of secondary activities. These findings support the inclusion of prolonged waiting and attentional disengagement in stage-based design. Nevertheless, different road situations cannot be treated as equivalent, and time values should remain reference conditions for a conceptual framework.

2.3. In-Vehicle HMI and Cognitive Load

In-vehicle HMI is characterized by multiple displays, multiple spatial positions, and multiple modalities. A Chinese review noted that intelligent-cockpit interaction has developed from single displays and controls into complex systems integrating visual, voice, gesture, and contextual services [1]. Tufano et al. [14] proposed an adaptive HMI information-management framework based on driver, vehicle, and environmental states, in which application priority, contextual state, and output-channel selection are used to orchestrate information. The design object in this study is therefore not a single screen theme but a system configuration linking contextual input, state assessment, information priority, and output medium.

Although vehicle speed is low during congestion, the driver must continue monitoring the lead vehicle, traffic signals, and navigation information. A recent systematic review found that in-vehicle infotainment systems can cause distraction, reduced situation awareness, and cognitive overload, requiring interface design to balance functional expansion with safety [15]. Xu et al. [16] further indicated that cognitive overload, cognitive underload, and task-switching costs can all impair subsequent driving performance and that the effects of attention switching may persist. Interface simplification should therefore not eliminate all information; it should reduce irrelevant competition according to task priority while retaining stable access to speed, gear position, route information, and hazard warnings.

Huo et al. [9] showed that interface color, layout, and interaction processes can be converted into evaluable affective touchpoints. Adaptive-HMI research further emphasizes that output requests should be prioritized according to driver, vehicle, and environmental states and assigned to suitable modalities, channels, and layouts [14]. Regarding safety boundaries, ISO 15005 requires in-vehicle dialogue to be consistent, predictable, and timely and not to interfere with the driver's control of the vehicle [17]. A Chinese group standard likewise emphasizes graded warnings, stable visual presentation, and restrictions on complex dynamic content [18].

2.4. In-Cabin Ambient Lighting and Affective Interaction

In-cabin ambient lighting has developed from decorative illumination into an interaction medium capable of spatial shaping, status indication, and limited information expression. Weirich et al. [19] distinguished ambience, information, and human-centric functions of in-vehicle lighting and noted that color, location, environmental conditions, and user background affect preference and interpretation. Chinese engineering research has shown that source layout, color-mixing distance, materials, structure, and output uniformity directly affect the realized quality of ambient lighting [20]. Conceptual design must therefore address not only which color to use but also illuminated-zone location, luminance stability, uniformity, and information discriminability.

The color and rhythm of dynamic lighting can affect tension responses. After comparing colors and dynamic patterns, Kim et al. [21] found that sudden, high-frequency changes received the highest tension ratings. This finding directly supports avoiding flicker, rapid transitions, and large-area high-intensity animation in intelligent cockpits. In contrast to the central visual information delivered by HMI, ambient lighting is generally positioned on the instrument panel, door panels, and other peripheral areas. It is therefore better suited to continuous, low-intrusion spatial feedback than to replacing complex text or hazard warnings.

Lighting preferences and color meanings also vary across cultures and individuals. The survey by Weirich et al. [19] found that participants from China and other regions did not fully agree in their preferences for colors, positions, and dynamic patterns. A particular warm color, green, or purple should therefore not be treated as a universally effective solution. A more robust principle is to limit luminance and dynamic intensity, maintain lighting uniformity, provide clear controls for adjustment and deactivation, and prevent ambient-light colors from being confused with vehicle hazard warnings [18,20].

2.5. Research Gaps

Three limitations directly relevant to this study can be identified from the literature.

First, existing studies often focus on detecting, recognizing, and classifying driver affect, whereas a unified method is still lacking for regulating recognized states in a restrained, continuous, and user-exitable manner. Emotion-recognition accuracy does not automatically translate into a satisfactory interaction experience. The system must still determine when to intervene, how strongly to intervene, and when to exit [6,7].

Second, HMI and ambient lighting are commonly designed as separate functional modules. HMI research focuses more on information efficiency, usability, and task load, whereas ambient-lighting research focuses more on color, position, and spatial experience. Functional allocation, rhythmic coordination, and state transitions are rarely discussed under a shared affective goal. Research on intelligent cockpits has begun to emphasize affective-computing processes and scenario-based interaction, but the coordination rules between screens and spatial lighting require further specification [1,2].

Third, urban congestion is often treated as a single traffic state, even though the driving tasks differ among initial low-speed movement, prolonged standstill, and traffic recovery. When entering congestion, the driver must continue monitoring the road. During a longer standstill, irritation, boredom, and attentional disengagement accumulate. When traffic resumes, task-related vigilance must be re-established. Research on adaptive HMI and task switching indicates that contextual state and task transitions should affect information priority and feedback method [14,16].

2.6. Design Requirements Derived from the Literature

To translate theoretical and empirical findings into an operational design framework, seven design requirements were formulated, as summarized in Table 1. They constrain stage segmentation, channel functions, safety boundaries, feedback rhythm, and user control and provide a common basis for the three-stage framework.

Table 1. Design Requirements Derived from the Literature

ID	Design requirement	Main rationale
DR1	The interaction strategy should vary with the congestion stage and driving task.	Affective and attentional needs change over the waiting process.
DR2	HMI should deliver semantic information, state explanation, and information hierarchy.	HMI provides high information precision and is suited to organizing critical driving information.
DR3	Ambient lighting should provide spatial atmosphere, peripheral visual feedback, and supplementary cues.	Ambient lighting supports continuous, low-intrusion spatial feedback.

ID	Design requirement	Main rationale
DR4	Speed, gear position, navigation, and hazard warnings should always have the highest priority.	In-vehicle dialogue should be consistent and predictable and should not impede safe control.
DR5	Dynamic feedback should be low-frequency and continuous and should avoid flicker or sudden high luminance.	High-frequency and abrupt lighting changes may increase tension and distraction.
DR6	Users should be able to adjust intensity, select a theme, or disable automatic intervention.	Acceptance of affective functions and color preferences varies across users.
DR7	The system should include attention-restoration and safety-interruption mechanisms.	Reducing irrelevant arousal must not impede task re-engagement when traffic resumes.

3. Research Method

3.1. Narrative Literature Review

A narrative literature review was conducted around urban congestion and driver affect, affective computing and adaptive interaction, in-vehicle HMI and cognitive load, in-cabin ambient lighting, and driving-safety principles. To improve timeliness and verifiability, the final corpus comprised 21 sources, prioritizing publications from 2016 onward while retaining Russell's foundational circumplex model of affect [11]. The corpus included peer-reviewed international journal articles, Chinese core-journal articles, an international standard, and a Chinese group standard. The purpose was not to calculate a unified effect size but to identify stable findings, evidence from related scenarios, and design boundaries.

International sources were used mainly to support claims concerning congestion-related affect, driving behavior, adaptive information management, task switching, dynamic lighting, and cross-cultural preferences. Chinese sources supplemented reviews of intelligent-cockpit interaction, affective-computing processes, user-data-driven design, ambient-lighting engineering quality, and local HMI evaluation requirements. The review is not presented as an exhaustive systematic assessment of all databases; instead, it integrates multiple disciplines according to topical relevance, publication quality, source traceability, and value for design translation.

3.2. Comparative Analysis

The literature was compared across four dimensions. First, the driving tasks and affective and attentional needs of different traffic stages were compared. Second, HMI information density, color, layout, motion, and prompting methods were compared. Third, ambient-lighting color, luminance, position, coverage, and dynamic rhythm were compared. Fourth, safety constraints, user-control mechanisms, and exit mechanisms proposed in different studies were compared. The results were translated into the design requirements in Section 2.6.

3.3. Framework-Construction Process

Framework construction followed a literature-to-design translation path. First, research on congestion-related affect and waiting behavior was used to identify changes in tasks and affect across stages. Second, findings from affective computing, adaptive information management, cognitive load, and lighting research were converted into design requirements. Third, the traffic process was divided into three stages, and different functions were allocated to HMI and ambient lighting. Finally, state transitions, safety interruption, and user-control logic were established to form a conceptual framework for subsequent prototype implementation. This path combines the computational logic of context awareness and information orchestration [14] with the design translation of affective needs into interaction solutions [2,9].

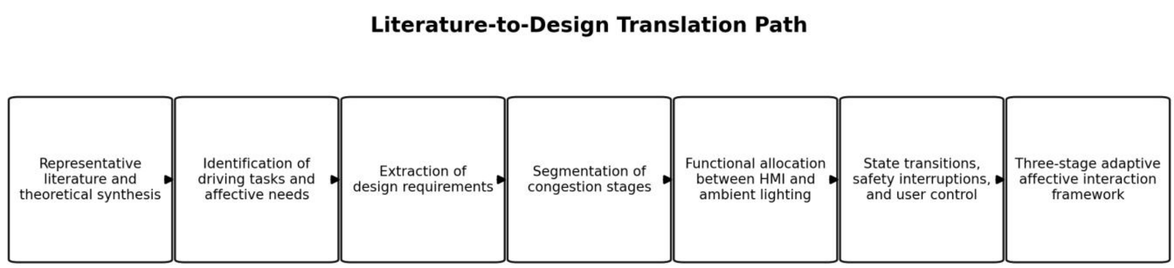

Figure 1. Literature-to-Design Translation Path

3.4. Formal Definition of the Framework

To rigorously describe the adaptive affect-regulation mechanism for an intelligent cockpit in congestion, this section presents the core formal definitions, objective function, and stage-transition completeness theorem supporting the interaction-system design.

Definition 1 (Congestion Context Space):

Any urban-congestion driving scenario can be fully represented by the tuple

$$\mathbf{C=(v,t_p,d_f,\tau)},$$

where:

- v is the real-time speed of the ego vehicle, in m/s;
- t_p is the accumulated continuous standstill duration, in s;
- d_f is the following distance between the ego vehicle and the lead vehicle, in m; and
- τ is an estimate of macroscopic traffic-flow state, which may be discretized as free flow, slow flow, or congestion, or represented by a continuous value.

All valid congestion conditions jointly constitute the congestion context space C . Any moment during congested driving can be mapped to a unique coordinate in this space, providing a unified quantitative input for subsequent affect-regulation strategies.

Definition 2 (Affect-Regulation Objective Function):

For interaction state s, define

$$\mathbf{G(s)=\alpha\ arousal_{task}(s)+\beta(1-|valence_{irrelevant}(s)|)},$$

subject to

$$\mathbf{\alpha+\beta=1, \qquad \alpha>\beta.}$$

Here, $arousal_{task}(s)$ denotes task-related arousal, representing the vigilance required to maintain driving surveillance; $valence_{irrelevant}(s)$ denotes task-irrelevant affective valence, including negative states such as irritation and anxiety that interfere with driving. The constraint $\alpha+\beta=1$ normalizes the weights, whereas $\alpha>\beta$ implements the safety-first principle by assigning greater weight to maintaining driving vigilance than to affective soothing alone.

Theorem 1 (Stage-Transition Completeness):

Given the threshold set $\Theta=\{T_1,T_2,T_3\}$, the system transition satisfies

$$\mathbf{\forall c\in C,\ \exists!\, s\in S:\delta(s_0,c)=s},$$

where ∀ denotes every congestion condition c in the context space; ∃! denotes the existence of one and only one matching interaction stage s; S is the set of all interaction stages (initial congestion, prolonged standstill, and attention restoration); s_0 is the initial normal-driving state; and $\delta(\cdot)$ is the context-to-state mapping function that takes a congestion condition and initial state as input and outputs a unique regulation stage.

This theorem is adopted as a foundational assumption of the finite-state interaction framework and is not accompanied by a strict mathematical proof. It ensures that any congestion condition triggers only one interaction stage, avoiding logical conflicts caused by parallel modes or ambiguous state transitions.

4. Three-Stage Affective Interaction Design for Urban Congestion

4.1. Overall Framework and Functional Allocation between HMI and Ambient Lighting

A rule-based, three-stage conceptual solution is proposed for prototyping. The interaction process in urban congestion is divided into initial congestion regulation, prolonged standstill regulation, and attention restoration with task re-engagement. Stage segmentation is based primarily on driving tasks and affective needs rather than time alone. In the first stage, traffic monitoring remains the primary task, and the system should reduce tension caused by sudden obstruction. In the second stage, the vehicle remains stationary for a relatively long period, and the system should mitigate sustained irritation and the perceived burden of waiting. In the third stage, traffic flow resumes, and the system should help the driver move from a relatively low-activity state back into the driving task. This structure is consistent with adaptive-HMI approaches in which information priority and output methods are selected according to driver, vehicle, and environmental conditions [14].

The two visual channels share stage goals and state-transition logic but do not duplicate the same expression. HMI delivers explicit semantics, critical data, information hierarchy, and mode explanation. Ambient lighting delivers spatial atmosphere, peripheral visible cues, and rhythmic continuity. When the interface reduces secondary content, the lighting should not reintroduce stimulation through elaborate motion. When lighting provides peripheral cues, the interface should still provide a concise and comprehensible state explanation. This functional complementarity responds to discussions of multimodal affect regulation and output-channel selection [7,14]. Table 2 summarizes the functional allocation.

Table 2. Functional Allocation between HMI and Ambient Lighting

Interaction channel	Primary functions	Functions that should not be assigned
In-vehicle HMI	Display speed, gear position, navigation, and warnings; adjust information hierarchy; provide textual prompts and control entry points.	Replace driving information with large decorative animations; use complex interaction that attracts prolonged visual attention.
In-cabin ambient lighting	Establish spatial atmosphere and peripheral visual cues; maintain rhythmic continuity; supplement the expression of state changes.	Replace explicit text or hazard warnings; use persistent flicker, sudden high luminance, or colors that are difficult to interpret.

From the perspective of computer applications and intelligent interaction systems, the solution comprises five components: context input, state assessment, strategy decision, coordinated output, and safety/user control. Vehicle state and traffic changes are used to identify the congestion stage. The strategy layer selects intervention, maintenance, transition, or exit according to the current task. HMI and ambient lighting then output semantic information and spatial cues, respectively. This is a conceptual adaptive mechanism based on predefined states and priority rules rather than an implemented emotion-recognition algorithm. Figure 2 presents the system architecture.

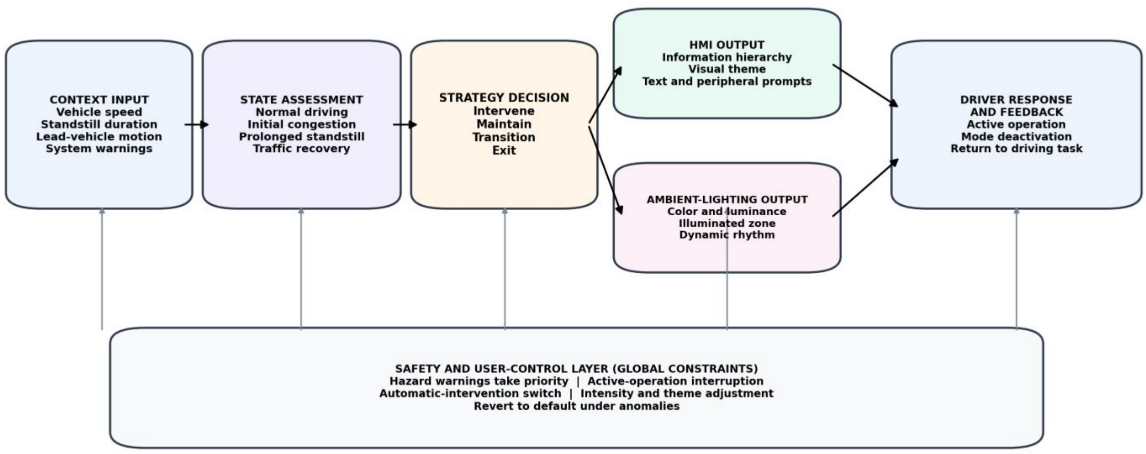

Figure 2. Context-Driven Coordinated Architecture for HMI and Ambient Lighting

4.2. Stage 1: Initial Congestion Regulation

The initial-congestion stage is characterized by reduced speed, short stops, and frequent stop-and-go movement. In a congestion experiment, Zhang et al. [5] used a speed below 5 km/h as the activation condition for congestion intervention, indicating that low speed can serve as a context-recognition input. Tufano et al. [14] likewise support rule-based information orchestration according to vehicle and environmental states. On this basis, the present framework uses "low speed or standstill for approximately 30 s" as a prototype reference to prevent brief pauses from causing frequent state changes. The included literature published since 2016 does not directly validate 30 s as a universal psychological threshold; the value only illustrates state-machine debounce logic.

The HMI strategy in this stage is to keep critical data stably visible while reducing competition from secondary content. Speed, gear position, navigation, and hazard warnings do not change location. Entertainment notifications, detailed energy-consumption data, and nonessential cards are deprioritized or temporarily collapsed. The background transitions smoothly from the normal high-contrast theme to a low-saturation theme, while core numerals remain clear and secondary text receives less visual emphasis. This design follows priority-based orchestration in adaptive HMI and avoids distraction and cognitive overload commonly associated with in-vehicle information systems [14,15].

Ambient lighting remains localized and restrained during this stage. It primarily affects the instrument panel and front-door panels and uses a medium-to-low luminance, low-saturation candidate theme. The lighting may employ slow and continuous luminance variation but should not expand into large-scale cabin animation or use abrupt, high-frequency changes. This strategy is supported by evidence that abrupt high-frequency dynamic lighting increases tension [21], while specific luminance and cycle values remain prototype parameters.

4.3. Stage 2: Prolonged Standstill Regulation

After the vehicle has remained stationary for a longer period, the primary problem changes from sudden tension to sustained irritation, boredom, and an amplified sense of waiting. Larue et al. [12] found that frustration and risky behavior increased substantially after waits longer than 3 min at congested railway level crossings. Although railway-crossing waits and urban-road congestion are not equivalent, this finding provides recent evidence from a related situation for entering prolonged-standstill regulation after approximately 180 s. The value distinguishes a brief stop from a longer wait and is not interpreted as a universal stress threshold.

During this stage, the HMI further reduces nonessential information while keeping zero speed, time, critical warnings, and necessary route status visible. The background may use a slow

low-saturation gradient, and very slow non-chasing abstract lines or sparse particles may appear. Motion should not cover critical content or form a visual target that requires continuous tracking. This treatment reduces information competition while avoiding cognitive underload and difficulty with task switching [15,16]. The system does not enter a full-screen entertainment mode.

Ambient lighting may moderately expand to the door armrests and the front-passenger area, creating a more complete but still low-stimulation spatial enclosure. The dynamic rhythm is slower than in Stage 1, luminance and saturation remain low, and the light-strip structure should maintain basic uniformity of color and luminance [20]. Users can adjust lighting intensity, select an alternative theme, or disable automatic changes. The goal is to ease the waiting process, not to induce deep immersion from which the driver cannot rapidly disengage.

4.4. Stage 3: Attention Restoration and Task Re-Engagement

When congestion eases or the lead vehicle begins to move, the design goal shifts from reducing irrelevant tension to restoring task-related vigilance. Questionnaire and field research by Sieklicka et al. [13] showed that drivers may use mobile phones or perform other secondary activities while waiting and that some drivers have delayed moving off for this reason. Xu et al. [16] further showed that switching back to the driving task can produce reaction delay and persistent switching costs. The attention-restoration and task-re-engagement stage is therefore introduced to close the loop between affective support and recovery of the driving task.

When the system detects movement of the lead vehicle or traffic flow after the ego vehicle has met a stable-standstill condition, the HMI presents a brief visual pulse near the instrument edge or speed area, accompanied by concise text such as "Lead vehicle moving" or "Traffic flow restored." The prompt does not obscure speed or warnings. The background theme does not switch immediately; it gradually returns to the normal interface after the ego vehicle resumes stable movement. The exact pulse duration is a prototype value. The governing principle is that the cue should be comprehensible, predictable, and subordinate to the information hierarchy [17,18].

Ambient lighting and HMI provide one brief, low-intensity synchronized cue. Luminance increases only moderately from the current level and returns to the previous state after the cue ends. The cue does not use persistent flashing or replace hazard-warning colors with an auxiliary cue color. Its dynamic form should avoid the abrupt high-frequency stimulation identified by Kim et al. [21]. If the driver actively operates the vehicle, disables the mode, or receives a safety warning, the system immediately exits the affective state and restores the default information hierarchy.

Figure 3 provides a low-fidelity visualization of changes in the front HMI information area and ambient-lighting coverage across the three stages. In each panel, the upper area represents route and traffic status, and the lower area represents instrument information and state prompts. All stages retain speed, gear position, necessary route status, and critical warnings; only information hierarchy, visual emphasis, light-strip location, and illuminated-zone coverage are adjusted. The figure does not represent a final visual style or production form.

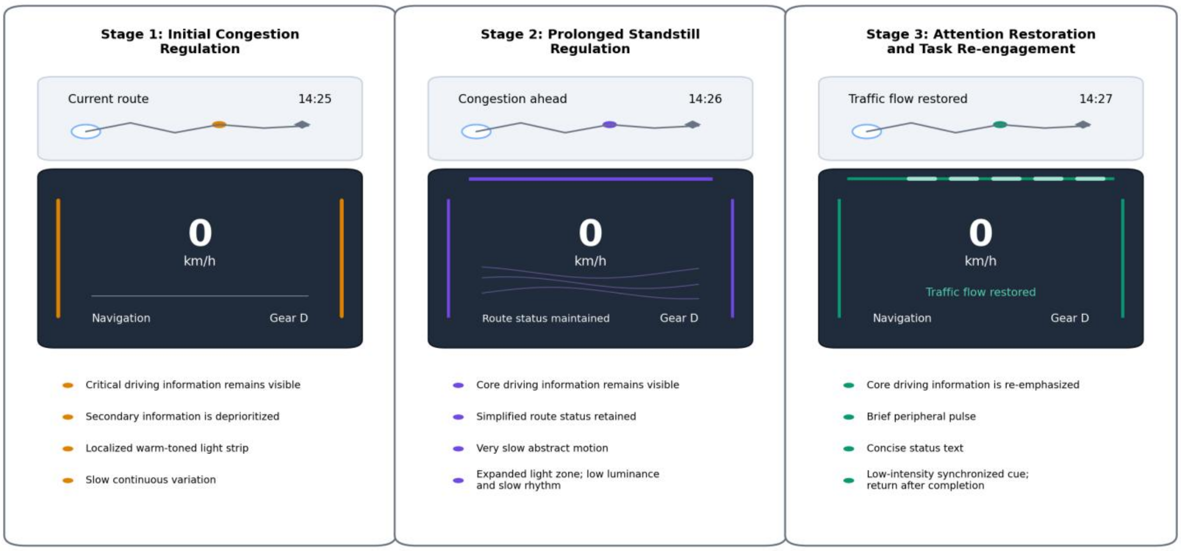

Figure 3. Low-Fidelity Concept for Three-Stage HMI and Ambient-Lighting Adaptation

4.5. State Transitions, Safety Interruption, and User Control

The three-stage solution should be implemented as finite-state logic rather than as three independent visual themes. After normal driving enters sustained low speed or standstill, the system enters initial congestion regulation. After continuous standstill reaches the reference condition, it enters prolonged standstill regulation. When traffic flow resumes, it enters attention restoration and task re-engagement. After the ego vehicle resumes stable movement, the system returns to the normal-driving state. This rule-based structure is consistent with adaptive-HMI implementation that orchestrates information according to discrete contextual states [14]. Figure 4 illustrates the principal states and transitions.

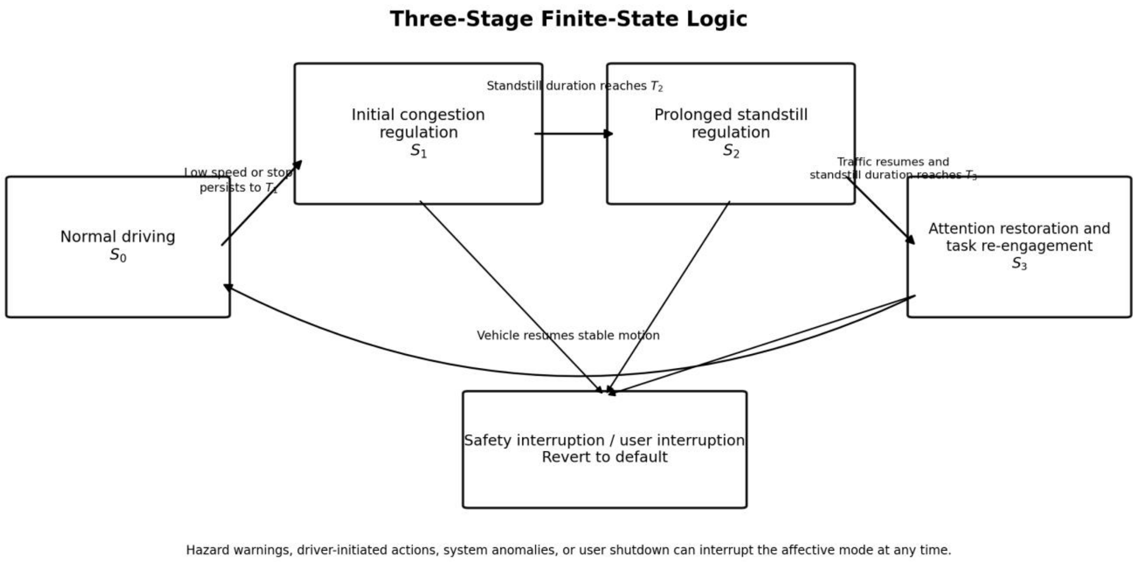

Figure 4. Finite-State Logic for the Three-Stage Adaptive Affective Interaction

State transitions must comply with the safety-first principle. Hazard warnings, active driver operation, system anomalies, and user deactivation all have higher priority than the affective mode and can interrupt the current state at any time. When the system cannot reliably determine traffic status, it should retain or restore the default interface and should not intensify affective feedback. Brief speed fluctuations should not trigger an immediate stage transition. These constraints are consistent with principles of consistency, predictability, and safe control for in-vehicle dialogue [17,18].

User control includes a switch for automatic intervention, intensity adjustment, theme selection, and state explanation. The system should enable the driver to understand why a mode was triggered while avoiding direct psychological labels such as "You are anxious" or "You are angry." Reviews indicate that emotion regulation must jointly consider context, interaction method, user acceptance, and evaluation boundaries [6,7]. Affective computing should improve the interaction method rather than make unquestionable psychological judgments on the user's behalf.

4.6. Reference Parameters and Evidence Sources

Several illustrative reference parameters are provided to clarify framework operation. Table 3 draws on the 21 sources retained in this study. Temporal conditions are based on recent congestion experiments, evidence from related waiting contexts, and field behavior studies.

HMI, lighting, and prompting methods are based on adaptive information management, cognitive-load research, dynamic-lighting research, current standards, and Chinese engineering studies. The evidence is explicitly classified as direct or related-context evidence, directional evidence, or a prototype reference so that literature findings are not conflated with unvalidated design values.

Table 3. Reference Parameters, Evidence Sources, and Use Boundaries

Parameter	Reference value	Main evidence	Evidence type and boundary
Initial-regulation trigger	Low speed (<5 km/h) for approximately 30 s	A congestion experiment used <5 km/h to activate intervention, and adaptive-HMI research supports rule-based orchestration using vehicle and environmental states [5,14].	The low-speed condition has a direct experimental example. The 30-s debounce value is a prototype reference without direct validation.
Prolonged-standstill trigger	Continuous standstill for approximately 180 s	Frustration and risky behavior increased after waits longer than 3 min at congested railway level crossings [12].	Evidence is from a related long-wait context. It supports stage segmentation but not a universal urban-congestion stress threshold.
Attention-restoration activation	Approximately 10 s after stable standstill	Drivers may shift to phones or other secondary activities while waiting, and task switching produces persistent costs [13,16].	Indirect behavioral and cognitive evidence. The 10-s value is an engineering reference that prevents activation immediately after stopping.
HMI information hierarchy	Core information always visible; secondary content progressively downgraded	Contextual priority orchestration, distraction and cognitive-overload studies, and standards require safe, stable, and predictable information presentation [14,15,17,18].	Strong directional and standards-based support. Specific retained items must still follow driving-task and hazard-warning priorities.
Interface transition	Continuous gradient of approximately 1-2 s	International and Chinese standards emphasize consistent and predictable feedback, stable images, and limits on complex dynamic content [17,18].	Literature supports continuous, non-abrupt transitions. The 1-2-s duration is a candidate prototype value.
Lighting	Medium-to-low	In-vehicle lighting research	Functional and engineering directions

Parameter	Reference value	Main evidence	Evidence type and boundary
luminance and illuminated zone	luminance; local coverage with moderate expansion	supports organization by function, location, and user group; engineering research addresses light-strip layout, color mixing, and uniformity [19,20].	are supported. No universal percentage luminance is specified because hardware conditions differ.
Dynamic rhythm	Stage 1: approximately 3-5 s; Stage 2: approximately 5-7 s	Sudden high-frequency dynamic lighting produced greater tension, and the Chinese standard restricts complex dynamic effects that could compromise safety [18,21].	The low-frequency continuous principle has direct support. The exact cycle ranges require prototype comparison.
Color theme	Low-saturation candidate themes with user-selectable alternatives	Color and position preferences vary across populations, and cockpit feedback should be organized according to affective needs [2,10,19].	No single color should be claimed as universally optimal. Users should be able to select an alternative, reduce intensity, or disable the function.
Attention-restoration cue	Brief dual-channel pulse plus concise text	Task-restoration research and standards support comprehensibility, priority, and safety, while dynamic lighting should avoid abrupt high-frequency changes [16-18,21].	Directional and safety support. Exact pulse duration and repetition count are parameters for later prototype comparison.

Note: Approximately 30 s is a state-machine debounce reference and has not been established as a universal psychological threshold. Approximately 180 s is supported by evidence from a related long-wait context. Approximately 10 s is mainly an engineering reference for stable standstill and attention-restoration activation. All visual parameters are candidate values for subsequent prototype comparison rather than validated optima.

4.7. Summary of Three-Stage Design Strategies

Table 4 summarizes the traffic state, affective goal, HMI strategy, lighting strategy, and safety requirements of each stage. It can guide the design of interface pages, light-strip positions, and mode transitions in a later high-fidelity prototype.

Table 4. Coordinated HMI and Ambient-Lighting Strategies across Three Stages

Stage	Traffic and task state	Interaction goal	HMI strategy	Ambient-lighting strategy	Safety requirement
Initial congestion regulation	Low speed, brief stops, and frequent stop-and-go movement; continuous road monitoring remains necessary.	Reduce tension caused by sudden obstruction.	Retain critical data; deprioritize secondary content; use smooth transitions.	Localized, medium-to-low luminance, low-frequency variation.	No full-screen immersion; warnings remain continuously visible.
Prolonged standstill regulation	Vehicle remains stationary for a longer period; irritation, boredom, and perceived waiting accumulate.	Ease sustained waiting and reduce unnecessary stimulation.	Further simplify content; use extremely slow, non-chasing motion; retain critical states.	Moderately expand the illuminated zone; maintain low saturation, low luminance, and slow rhythm.	Avoid entertainment-oriented or excessive immersion; allow immediate user exit.
Attention restoration and task re-engagement	Traffic flow resumes; the driver must re-enter the driving task.	Restore task-related vigilance and smoothly exit regulation.	Use a brief peripheral cue and concise text; return to the normal theme after stable movement.	Provide a low-intensity synchronized cue and then restore the prior state.	Do not conflict with hazard colors; safety-related operation can interrupt immediately.

5. Discussion

5.1. From Single-Medium Feedback to Cross-Channel Coordination

The value of coordinating HMI and ambient lighting does not lie in changing both to the same color simultaneously but in differentiated expression under a shared goal. HMI has high semantic precision and is suited to explaining vehicle status, organizing information, and providing control entry points. Ambient lighting lies in peripheral vision and the spatial environment and is suited to continuous atmosphere and low-intrusion cues. Li et al. [7] identified multimodal emotion regulation as an important direction for intelligent cockpits, whereas Tufano et al. [14] emphasized that output channels and layouts should follow contextual state and information priority. Cross-channel coordination differs from simple visual decoration only when the channels share stage goals, intensity relationships, and exit conditions.

The three-stage framework places cross-channel relationships within a temporal process. In the initial-congestion stage, HMI reduces information competition and ambient lighting provides localized environmental cues. During prolonged standstill, both channels slow down and reduce stimulation. In the attention-restoration stage, they re-establish task-related vigilance through brief synchronization. The design question therefore shifts from "Which color should be used?" to "When should the system intervene, how should channels divide functions, and how should the system exit?" This logic also responds to Chinese research on scenario-based intelligent-cockpit interaction and affective-computing processes [1,2].

5.2. Balancing Affect Regulation and Driving Safety

Affect regulation does not imply that the system should become increasingly proactive or soothing. Irritation during congestion should be moderated, but the driver remains responsible for traffic monitoring and moving off again. Zhang et al. [5] indicated that both excessively low and excessively high arousal can be detrimental and that a moderate return toward normal driving levels is more reasonable. Xu et al. [16] showed that task transitions create persistent attentional costs. The framework therefore includes an attention-restoration stage so that reducing irrelevant tension and restoring necessary vigilance form one continuous process.

Safety boundaries are also reflected in information priority and interruption mechanisms. Speed, gear position, navigation, and hazard warnings remain stably visible, and no affective mode may cover or replace safety information. Hazard warnings, active driver operation, and system anomalies can terminate affective feedback immediately. The design positions affective interaction as an auxiliary layer supporting the driving task rather than as an independent entertainment layer, consistent with safety requirements concerning distraction, cognitive load, and successful in-vehicle interaction [15,17].

5.3. User Control and Application Significance

The acceptability of affective interaction depends on user control. Drivers should be able to disable automatic intervention, reduce luminance and dynamic intensity, select alternative themes, and understand why a mode was triggered. Weirich et al. [19] demonstrated population differences in preferences for in-vehicle lighting color, position, and dynamics. Lai et al. [10] likewise showed that cockpit affective needs should be interpreted through real usage and feedback data. The system should therefore neither treat one visual theme as a universal answer nor force regulation on users through frequent prompts.

From an intelligent-cockpit design perspective, the framework can serve as a common language linking interface design, lighting design, and interaction logic. Chinese studies have translated user states and affective needs into cockpit-function configurations and interface solutions through interaction reviews, affective-computing frameworks, and multimodal data-driven design [1,2,10]. Design teams can first define task goals for each stage and then determine page information, light-strip location, and transition rhythm separately, preventing expressive conflicts when HMI and ambient lighting are integrated late in development.

5.4. Limitations and Future Work

The three-stage adaptive affective interaction framework was developed primarily from representative studies published since 2016, a foundational affect model, current standards, and design translation. Its actual use has not been validated through a high-fidelity prototype, expert evaluation, or user study. The results therefore comprise stage segmentation, functional allocation between HMI and ambient lighting, state transitions, and conceptual design solutions rather than empirical conclusions concerning affect-regulation effectiveness or improvements in driving safety.

In addition, the study focuses on the two visual channels of HMI and ambient lighting and does not systematically incorporate audio, haptics, seats, or climate-control feedback. The framework is limited to low-speed urban congestion and is not intended for high-speed driving or complex hazardous scenarios. Future research can develop a high-fidelity interactive prototype and conduct expert evaluation or a small-scale user study to examine the three-stage segmentation, HMI-lighting coordination, mode-transition logic, and overall acceptance. These evaluations are future work, and their outcomes are not presupposed here.

6. Conclusion

This study addressed driver irritation, waiting stress, and attentional change during urban congestion by using a narrative literature review, comparative analysis, and design translation to construct a three-stage adaptive affective interaction framework for intelligent-cockpit HMI and ambient lighting. Recent affect and driving research was used to define the regulatory direction as reducing task-irrelevant tension while maintaining or restoring task-related vigilance. Adaptive information management, cognitive-load research, in-vehicle lighting research, and current standards were used to constrain interaction methods and safety boundaries.

According to task changes across congestion, the framework comprises initial congestion regulation, prolonged standstill regulation, and attention restoration with task re-engagement. HMI is responsible for critical data, information hierarchy, state explanation, and control entry points, while ambient lighting is responsible for spatial atmosphere, peripheral visual feedback, and supplementary cues. The stages are connected through finite-state logic and include safety interruption and user-control mechanisms. Cross-channel coordination is therefore defined not as simple synchronized color change but as functional complementarity under a shared goal.

The framework translates dispersed research on driver affect, adaptive HMI, cognitive load, and in-cabin lighting into a conceptual design solution containing a system architecture, low-fidelity visual concepts, stage structure, and strategy mappings. It also distinguishes the evidential status of temporal and visual parameters. The present conclusions are a design synthesis at the conceptual-framework level and do not constitute proof of effectiveness. Future high-fidelity prototypes, expert evaluations, and small-scale user studies can test the framework's rationality, comprehensibility, and acceptance.

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