

Theory of Personalized HMI Design for Promoting Safe Driving Using Structural Equation Modeling

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KEY WORDS: Human engineering, human machine interface, driver characteristics, Structural Equation Modeling [C2]

Many current Human-Machine Interfaces (HMIs) rely on uniform physical vehicle dynamics, presenting a challenge by easily inducing user discomfort. Furthermore, recent "black-box" AI approaches obscure intervention rationales, ultimately reducing system trust. To address these challenges, we propose a personalized HMI design theory integrating latent psychological factors (personality traits) and manifest physical factors (driving behaviors) using Structural Equation Modeling (SEM). This highly explanatory driving evaluation model visualizes causal relationships between driver personalities and risky maneuvers, proposing an explicit scoring logic to foster metacognition and voluntary compensatory behaviors through persuasive information presentation. We analyzed one-week real-world driving data (116 trips) and personality surveys (Big Five and DSQ) from 19 drivers. Using Savitzky-Golay filtering, we extracted 95th-percentile values for travel speed, deceleration, and lateral acceleration. This approach accurately captures realistic worst-case physical behaviors while intentionally excluding temporary sensor noise.

Fig. 1 shows the constructed SEM model. In this model, psychological traits are strongly associated with physical driving behaviors; relationships where overconfidence and extroversion exacerbate dangerous driving, whereas cautiousness and consideration for others suppress it are visualized. Based on these causal structures, we formulated a transparent scoring logic integrating internal traits and external behaviors to quantify driving risk. The personal trait score, P_R , is calculated using Equation (1). Variables F_1 through F_4 represent the driver's latent traits: overconfidence, cautious driving, consideration for others, and extroversion. The numerical coefficients are path coefficients derived directly from the SEM model, indicating each trait's contribution to overall risk. Similarly, the physical behavior score, V_R , is derived from real-time vehicle state variables as expressed in Equation (2). Here, A , V , and L represent real-time deceleration, travel speed, and lateral acceleration, respectively. The denominators (0.31, 71.3, and 0.27) are the maximum 95th-percentile values from the experimental dataset, acting as normalization constants to render the metrics dimensionless. To evaluate overall risk, we define the total dangerous driving level, D_R , on a 100-point scale in Equation (3), where $P'_R = P_R \cdot 50.0$ and $V'_R = V_R \cdot 50.0$. This equal 1:1 weighting ratio prevents the evaluation logic from leaning excessively toward either internal traits or external physical behaviors, maintaining harmony between subjective risk perception and objective vehicle maneuvers to preserve system trust.

$$P_R = \{(F_1 \cdot 0.16) + (F_2 \cdot (-0.18)) + (F_3 \cdot (-0.08)) + (F_4 \cdot 0.30) + 26\} \cdot \frac{1.0}{76} \quad (1)$$

$$V_R = \left(\frac{|A|}{0.31} \cdot 0.99 + \frac{|V|}{71.3} \cdot 0.87 + \frac{|L|}{0.27} \cdot 0.56 \right) \cdot \frac{1.0}{2.42} \quad (2)$$

$$D_R = P'_R + V'_R \quad (3)$$

Implementing HMI feedback based on scoring the total dangerous driving level D_R and latent variables (F_1 – F_4) enables the explanation of driving behaviors in relation to individual driver characteristics. Rather than merely issuing warnings about outcomes, this approach explicitly clarifies the underlying rationale for "why the danger occurred" by connecting it to internal traits. An example of the post-drive feedback interface applying this logic and radar chart visualization is illustrated in Fig. 2. The core novelty of this design theory lies in explicitly separating and visualizing internal psychological factors and external physical maneuvers. While traditional HMIs relying solely on physical thresholds induce only temporary operational corrections, this transparent framework clarifies intervention rationales by revealing the causal link between external risky behaviors and internal traits; for instance, demonstrating that inherent overconfidence (F_1) subconsciously triggers speed overshoots (V). This multidimensional evaluation effectively fosters metacognition, motivating drivers to adopt voluntary compensatory behaviors, successfully achieving both enhanced user trust and long-term safe driving growth.

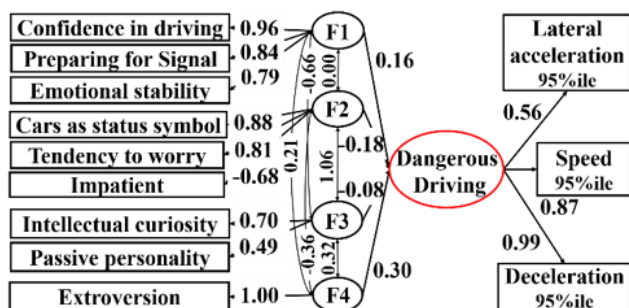


Fig.1 SEM Model Building Result

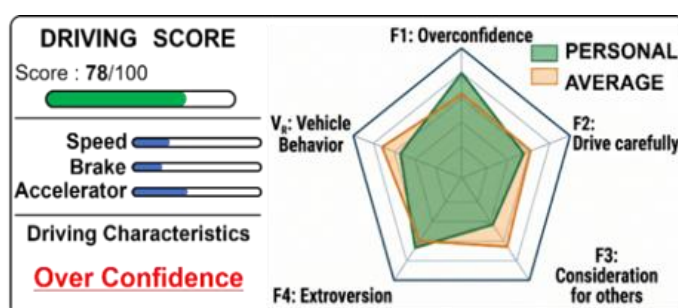


Fig.2 Example of Feedback After Driving for Metacognition