Analysis of Risk Factors Affecting the Driver Safety Tolerance Zone Using Driving Simulator Data for Enhanced Mobility Resilience

Eva Michelaraki[1]*, George Yannis[1]

1. National Technical University of Athens, Department of Transportation Planning and Engineering, 5 Heroon Polytechniou str., 15773, Athens, Greece
* Corresponding author: evamich@mail.ntua.gr

1. Introduction

Insufficient headway, the gap between two vehicles, is a major contributor to traffic collisions, as a gap that is too small limits a driver's ability to react to sudden braking (Fu et al., 2024). Headway can be expressed in time or distance (Risto & Martens, 2013) and maintaining an adequate gap helps drivers manage both physical and cognitive demands by providing time to respond to changing traffic. This reduces stress, cognitive load and supports situational awareness.

The aim of this work is to develop a context-aware Safety Tolerance Zone (STZ), which defines the point at which self-regulated driving remains safe (Michelaraki et al., 2021). The STZ reflects the balance between driving task demands (task complexity) and the driver's ability to cope with them (coping capacity). It includes three phases: normal driving, where crash risk is low and the driver adapts effectively; danger, where changing conditions increase crash risk but a collision is not yet inevitable; and avoidable accident, where a crash is unfolding but corrective action can still prevent it.

Within the above framework, this study aims to improve driver STZ through the analysis of road, vehicle and behavioural risk factors. The objective of this work was to determine the interactions among road, vehicle and driver risk factors for the STZ identification. More specifically, the impact of task complexity and coping capacity on crash risk was investigated. For that purpose, a large dataset spanning four months from simulator driving experiment was exploited.

2. Data Overview

To fulfill the objective of this work, a simulator experiment was conducted with 55 participants and data from 165 trips were collected and analyzed. Key explanatory variables related to risk and the most reliable indicators of task complexity (e.g. weather,

time of the day) and coping capacity (e.g. headway, speed, harsh brakings) were evaluated. Figure 1 presents the conceptual framework used for risk prediction, focusing on task complexity and coping capacity.

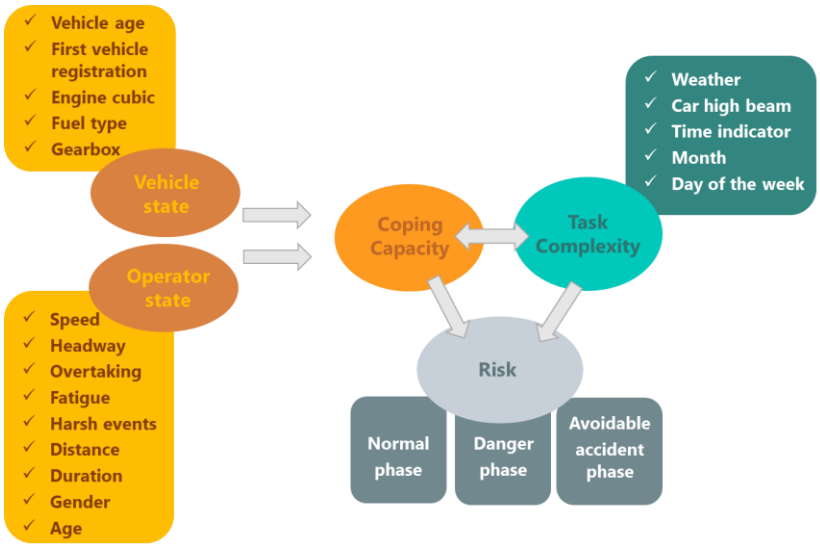

Figure 1: Conceptual framework for risk prediction of task complexity and coping capacity

3. Methodology

Structural Equation Modelling (SEM), or path analysis, is a multivariate technique used to test hypotheses about relationships among observed and latent variables (Harrison & Friston, 2007). Observed variables are directly measurable, while latent variables represent underlying constructs. SEM consists of two components: the measurement model, which assesses how well observed variables capture latent constructs and the structural model, which examines causal relationships, including direct and indirect effects (Stein et al., 2011). This combined framework allows SEM to evaluate complex variable interactions beyond what standard regression can capture.

In order to evaluate the model, several goodness-of-fit measures were used. These include GFI and AGFI, which assess how well the model matches the observed covariance matrix and RMSEA, where values $\leqslant 0.05$ indicate a close fit. Comparative indices such as CFI and TLI compare the hypothesised model against an independence model, with values above 0.90 considered indicative of good fit. Lastly, AIC and BIC were examined to balance model fit with model complexity, with lower values reflecting better models.

4. Results

Risk was assessed using the three STZ headway levels (normal driving, dangerous driving and avoidable accident). Task complexity was represented by trip duration and distance travelled, while coping capacity was measured through driver state indicators such as TTC, average speed, hands-on events and fatigue.

Results showed that distance and duration were positively correlated with task complexity. Hands-on events and fatigue were positively associated with coping capacity, suggesting that fatigued drivers may adopt more cautious behaviours. In contrast, TTC and average speed were negatively correlated with coping capacity, indicating reduced ability to manage driving demands at longer TTC and higher speeds.

SEM findings revealed a positive relationship between task complexity and coping capacity (coefficient = 0.14), implying that drivers tend to increase their engagement as task demands rise. Task complexity showed a strong positive association with risk (0.53), whereas coping capacity showed a strong negative association with risk (-4.29), indicating that higher coping ability reduces crash likelihood. The corresponding SEM path diagram is shown in Figure 2.

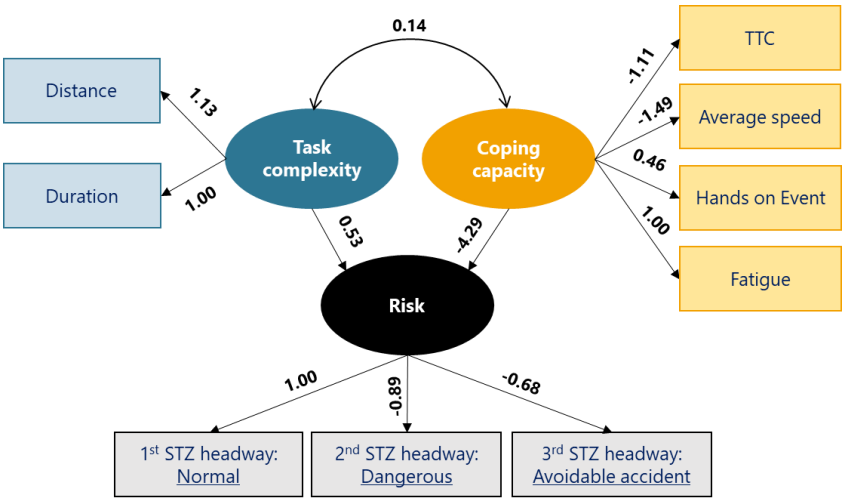

Figure 2: SEM results of task complexity and coping capacity on risk (STZ headway)

The resulting GFI was 0.973 and AGFI was 0.952, both exceeding the conventional threshold of 0.90, indicating a very good model fit. Additional indices, including the CFI = 0.966, TLI = 0.944 and RMSEA = 0.079, further support the adequacy of the model and confirm the robustness of the latent structure. Table 1 summarizes the model fit of SEM applied for headway, while residual variances details are presented in Table 2.

Table 1: Model Fit Summary for STZ headway per driving experiment

Model Fit measures	Values
CFI	0.966
TLI	0.944
RMSEA	0.079
GFI	0.973
AGFI	0.952
Hoelter's critical N (α = .05)	247.93
Hoelter's critical N (α = .01)	300.04
AIC	65281.04
BIC	65445.96

Table 2: Residual variances STZ headway per driving experiment

Variable	Estimate	Std. Error	z-value	P(>|z|)
Distance	0.108	0.024	4.576	< .001
Duration	0.107	0.023	4.542	< .001
Fatigue	0.950	0.024	39.002	< .001
TTC	0.939	0.025	38.280	< .001
Average speed	0.890	0.026	33.990	< .001
HandsOnEvent	0.989	0.024	40.565	< .001
Headway_STZ_level_0	-0.242	0.059	-4.082	< .001
Headway_STZ_level_1	0.177	0.049	3.652	< .001
Headway_STZ_level_2	0.422	0.029	14.344	< .001

5. Conclusions

This study aimed to improve the Driver Safety Tolerance Zone (STZ) by analysing road, vehicle and behavioural risk factors using driving simulator data. Towards that end, data from a simulator experiment were collected and analysed.

SEM revealed that task complexity significantly increased crash risk, especially under demanding conditions such as adverse weather, night-time driving or complex

environment. In contrast, coping capacity showed a strong negative relationship with crash risk, indicating that drivers with higher coping ability are better equipped to manage challenging situations. The analysis also showed a positive relationship between task complexity and coping capacity, suggesting that drivers tend to become more engaged and adaptive when confronted with complex driving tasks. Although coping capacity helps reduce crash likelihood, task complexity exerted a stronger overall influence on risk. A positive association between risk and STZ indicators was also observed, with the highest values appearing during normal driving, highlighting the dynamic nature of risk perception even in seemingly safe conditions.

Overall, the study offers a holistic view of driver safety by integrating driver, vehicle and environmental factors within a unified mobility resilience framework. The STZ proved effective for understanding how drivers respond to changing task demands and coping requirements. Future work with larger, more diverse datasets could improve the generalisability and applicability of this approach.

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Declaration

The authors declare that they have no conflict of interest.

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