Improving Driver Safety Tolerance Zone through Holistic Analysis of Road, Vehicle and Behavioural Risk Factors: A Comparison using Driving Simulator and Naturalistic Data

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Introduction

One of the **primary contributors to road crashes** is insufficient headway, the gap between two vehicles, which, when too narrow, restricts the following driver's ability to respond to sudden braking by the vehicle ahead. Maintaining an adequate headway is essential for managing both the physical and cognitive demands of driving, as it provides drivers with sufficient time to react to abrupt changes.

Driver workload, often considered a mediating variable between driving difficulty and performance, reflects the **driver's capacity to meet task demands**

Objectives

- Investigate the impact of **task complexity and coping capacity** (in terms of both vehicle and driver state factors) on crash risk
- Determine the interactions **among road, vehicle & driver** risk factors for the identification of the STZ
- Develop a context-aware **Safety Tolerance Zone (STZ)** for both simulator and on-road driving experiments

The Experiments

For the purpose of this analysis, an **on-road driving experiment** was carried out involving 135 car drivers (with total duration of 4 months) and a large database of 31,954 trips was collected. In addition, a **simulator experiment** was carried out involving 55 drivers (with total duration of 2 months) and a database consisting of 165 trips (55 drivers x 3 driving scenarios) was created. The most prominent driving behaviour indicators, such as speeding, headway, duration, distance and harsh events were assessed. The field trials were structured into four phases, while the simulator trials consisted of three phases, as depicted in Figures 1 and 2.

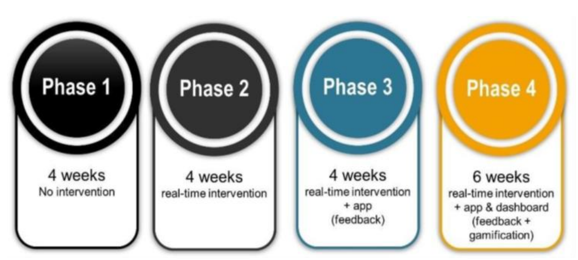


Figure 1: Four phases of the on-road experiment

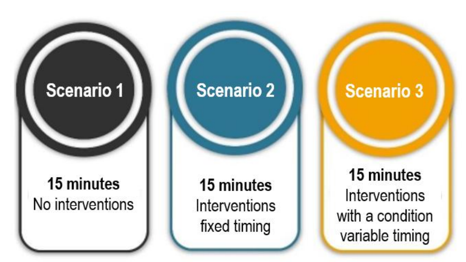


Figure 2: Three scenarios of the simulator experiment

Figure 3 provides an overview of the technologies and systems fitted in the windshield of a vehicle. Moreover, a custom car simulator **developed by DriveSimSolutions** was designed. It is also visualized on a triple monitor setup consisting of three 49 inch 4K monitors, providing an 135° field of view (Figure 4).

Figure 3: CardioDashcam and (b) Mobileye fitted in the windshield of a vehicle

Figure 4: Car simulator developed by DriveSimSolutions, using OEM Peugeot 206 parts

Data Overview

In relation to the STZ concept, a **comprehensive system of monitoring technologies** was utilized. The technology described in Figure 5 measures the environment, vehicle and driver indicators used to define task complexity and coping capacity in order to calculate which phase of the STZ the driver is operating within. Vehicles were equipped with Mobileye and CardioDashcam systems to continuously monitor road environment and behaviour. For monitoring the driver's physiological state, CardioWheel and the PulseOn wearable were used.

Key explanatory variables related to risk and the most reliable indicators of **task complexity** (e.g. weather, time indicator), **coping capacity - vehicle state** (e.g. gearbox, vehicle age, fuel type) and **coping capacity - driver state** (e.g. headway, speed, harsh brakings) were evaluated. Figure 6 presents the conceptual framework used for risk prediction.

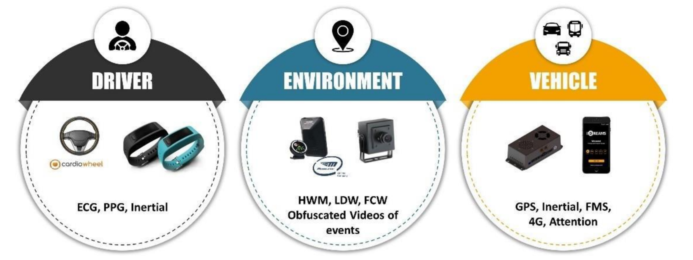


Figure 5: Technologies used to measure driver, environment and vehicle state

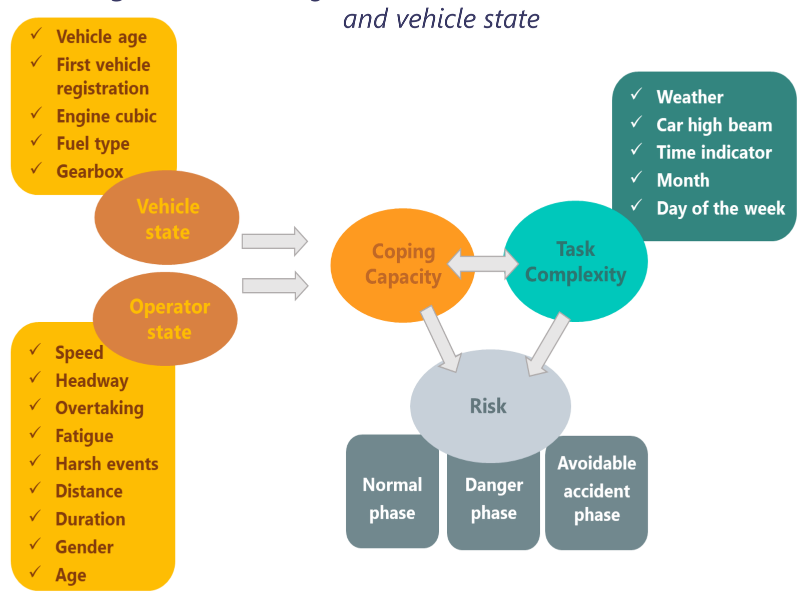


Figure 6: Conceptual framework for risk prediction in function of task complexity and coping capacity

Methodology

- ✓ **Generalized Linear Models (GLMs)** were applied to investigate the relationship between speeding and several explanatory variables of task complexity and coping capacity (both vehicle and operator state).
- ✓ **Structural Equation Models (SEMs)** were used for modelling complex and multi-layered relationships between observed and unobserved variables.
- ✓ **Goodness-of-Fit measures** (AIC, BIC, CFI, TLI, RMSEA) were assessed for the model selection.

Regression Analyses (GLM)

Table 1: Parameter estimates and multicollinearity diagnostics of GLM - simulator

Variables	Estimate	Std. Error	z-value	Pr(|z|)	VIF
(Intercept)	0.859	0.221	3.896	< .001	-
Time indicator	-0.690	0.318	-7.443	< .001	1.209
Average speed	0.742	0.080	9.231	< .001	1.020
Time to collision	0.004	3.116	14.300	< .001	1.018
Duration	-5.658	1.395	-4.057	< .001	1.040
Fatigue	5.088	1.587	3.206	0.001	1.114
Hands on wheel	5.369	2.311	2.323	0.020	1.076
Summary statistics					
AIC	4546.08				
BIC	4141.62				
Degrees of freedom	33820				

Table 2: Parameter estimates and multicollinearity diagnostics of GLM – on-road

Variables	Estimate	Std. Error	z-value	Pr(|z|)	VIF
(Intercept)	-0.339	0.003	-14.275	< .001	-
Time indicator	-4.713	1.527	-3.086	0.002	1.001
Weather	-0.059	0.007	-2.852	< .001	1.003
Fuel type - Diesel	-3.432	1.906	-8.094	< .001	3.888
Vehicle age	3.194	1.601	9.942	< .001	4.765
Gearbox - Automatic	-5.122	1.213	-4.032	0.003	2.851
Duration	8.283	3.969	19.871	< .001	1.279
Harsh brakings	5.707	2.456	32.562	< .001	3.396
Harsh accelerations	4.590	2.201	25.239	< .001	3.404
Average speed	7.686	5.019	36.273	< .001	1.103
Gender - Female	-2.097	1.349	-2.775	< .001	1.495
Age	3.764	1.879	3.203	< .001	6.119
Summary statistics					
AIC	568996.72				
BIC	339955.85				
Degrees of freedom	822,164				

The indicators of **task complexity**, such as time indicator and wipers were negatively correlated with headway in both experiments. It was found that lower headway events occurred at night compared to during the day. This may probably be due to the fact that there is no heavy traffic during night hours.

Regarding the indicators of **coping capacity – vehicle state**, vehicle age was found to be positively correlated with headway, meaning that as vehicles get older, the likelihood of headway incidents increases. On the other hand, fuel type and gearbox were negatively correlated with headway.

It was demonstrated that parameters of **coping capacity – operator state**, such as speed had a positive relationship with headway. Results revealed that females tended to maintain larger headways, while older drivers were associated with more frequent headway events.

Latent Analyses (SEM)

Following the exploratory analysis, the variables related to the latent variables "task complexity" and "coping capacity" were estimated from various indicators. **Risk was measured by means of the STZ levels for headway** (level 1 refers to 'normal driving' used as the reference case; level 2 refers to 'dangerous driving' while level 3 refers to 'avoidable accident driving'). The respective path diagrams of SEM analysis for simulator and on-road experiment are presented in Figures 7 and 8, respectively.

Results from the simulator and on-road driving experiments illustrated complicated effects of task complexity and coping capacity on risk. In particular, both simulator and on-road analyses revealed a **positive correlation between task complexity and crash risk**, influenced by factors such as time of day and adverse weather, which amplify the difficulty of driving tasks and contribute to reduced attention and slower reaction times. Drivers experienced increased cognitive workload when dealing with in-vehicle systems or navigating complex environments, further heightening the risk of a crash. Table 3 summarizes the model fit of SEM applied for headway per driving experiment.

On the other hand, **coping capacity had a negative correlation with crash risk** in both experiments, meaning that higher coping capacity was associated with a lower likelihood of crashes. This can be attributed to the fact that drivers with greater coping abilities are more capable of managing demanding driving situations. They are generally better at handling stress, making quick and accurate decisions and maintaining effective vehicle control, all of which support safer driving. Drivers with lower coping capacity may find it difficult to manage complex scenarios, resulting in a heightened risk of crashes.

The latent analysis also demonstrated a **positive relationship between task complexity and coping capacity**, suggesting that drivers' ability to cope tended to increase as driving tasks became more demanding. When faced with challenging conditions, such as driving in adverse weather, drivers appeared to engage more actively with the driving task, effectively regulating their responses to potential hazards. This increased focus encouraged the development of advanced driving strategies and skills, enabling them to navigate difficult situations more efficiently. As a result, exposure to complex driving scenarios contributed to enhanced driving competence and a stronger ability to respond to unforeseen challenges on the road. It was also found that task complexity had a stronger influence on risk than coping capacity. In addition, a positive correlation between risk and the STZ indicators was observed, with the highest values appearing in the normal driving phase (STZ level 1).

Overall, the performance and insights from the on-road and simulator experiments **revealed key interesting findings**. Specifically, the average speed in on-road trials was lower compared to the simulator experiments. Real-world driving involves navigating traffic, dealing with road hazards and adhering to strictly enforced speed limits, all of which necessitate frequent speed adjustments.

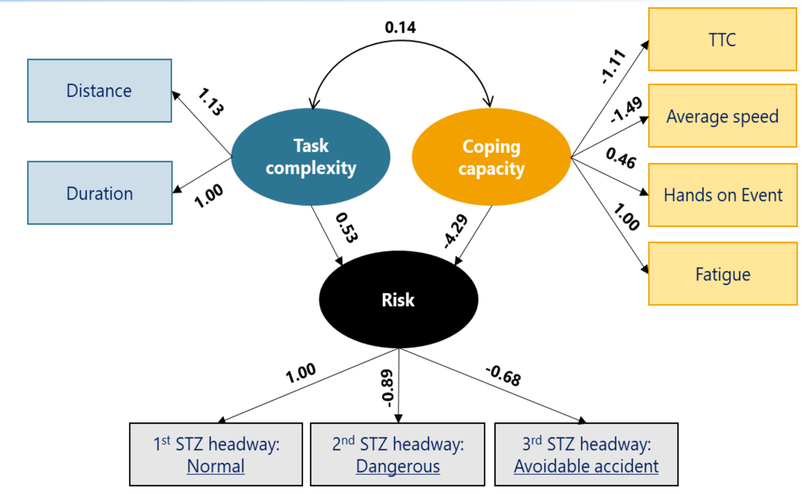


Figure 7: SEM results of task complexity and coping capacity on risk (STZ headway) - simulator experiment

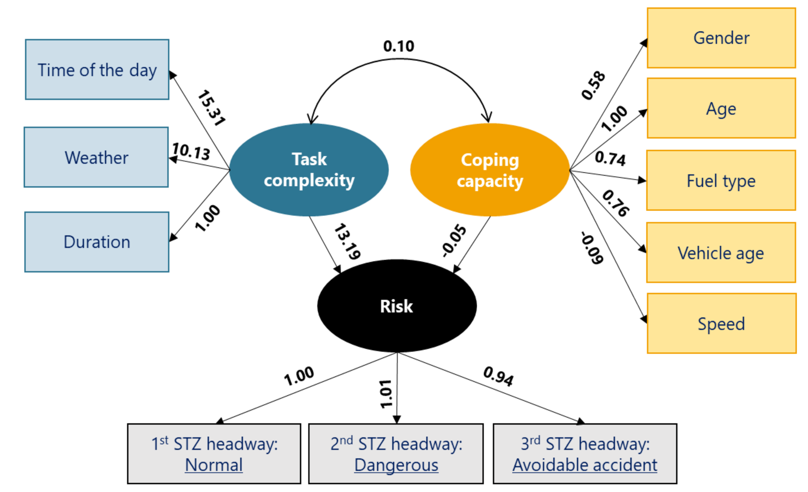
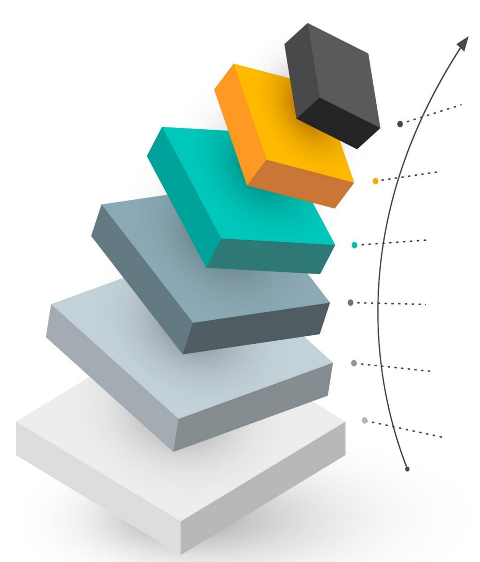


Figure 8: SEM results of task complexity and coping capacity on risk (STZ headway) – on-road driving experiment

Table 3: Model Fit Summary for STZ headway per driving experiment

Model Fit measures	Values	
	Simulator Experiment	On-road Experiment
CFI	0.966	0.945
TLI	0.944	0.927
RMSEA	0.079	0.106
GFI	0.973	0.921
AGFI	0.952	0.914
Hoelter's critical N (α = .05)	247.93	224.06
Hoelter's critical N (α = .01)	300.04	241.36
AIC	65281.04	2.043×10+7
BIC	65445.96	2.043×10+7

Conclusions



- ➢ This study presents a **holistic approach to road safety** by conceptualizing the environment, vehicle and driver as interconnected components of a unified system.
- ➢ Taking into account both **on-road and driving simulator data** and applying the STZ concept, the research captured the dynamic interplay between task complexity, coping capacity and crash risk.
- ➢ The findings demonstrated that these variables are not only individually impactful but also positively interrelated, suggesting that drivers tend to compensate for **complex driving conditions through increased engagement**.
- ➢ This integrated perspective enhances the accuracy of risk assessment and supports the development of more effective, **targeted safety interventions**.
- ➢ Overall, the **Safety Tolerance Zone (STZ) models proved to be a robust t**ool to understand driver behaviour under varying conditions and provided a valuable foundation for data-driven safety planning, Intelligent Transport System design and informed policy-making.
- ➢ As per future research, imbalanced learning, factor analysis and models taking into account **unobserved heterogeneity** could be explored for the understanding of the relationship between task complexity, coping capacity and crash risk.

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