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Structural Equation Model Analysis for the Identification of the Safety Tolerance Zone

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Introduction

- Road safety is a **critical issue** that affects communities worldwide, as the growing number of vehicles on the roads has led to increased risks of crashes, injuries and fatalities
- It is essential to ensure **all road users' safety** (i.e. drivers, passengers, cyclists and pedestrians) which requires not only proper infrastructure and traffic management but also awareness and responsibility from individuals
- Road safety is **influenced by multiple factors** such as the driving behaviour of individuals, the condition of vehicles, the design and maintenance of roads and the surrounding environmental conditions

Safety Tolerance Zone

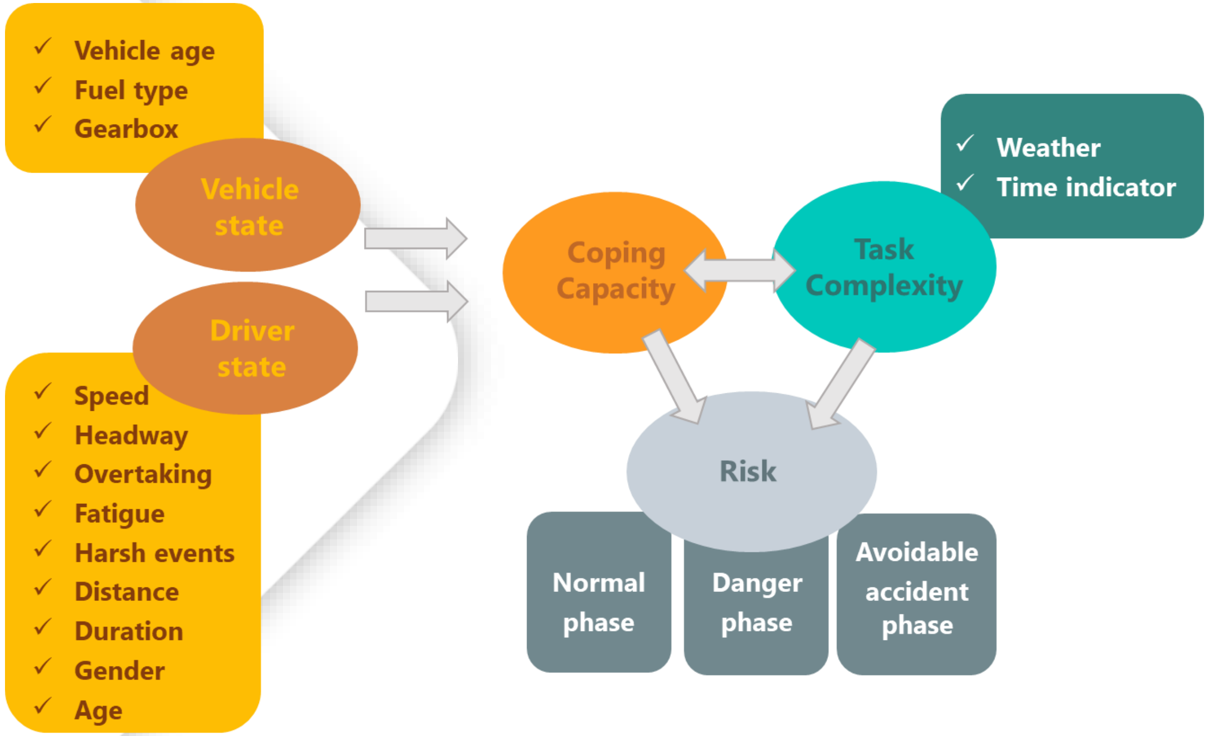
- Safety Tolerance Zone (STZ) is the **time/distance available** to implement safe response actions in the event of a potential crash

- A '**multi-phased' construct**, consisting of three different phases:

  - ✓ **Normal driving** phase: there is no indication that a collision scenario is likely to unfold at that time
  - ✓ **Dangerous** phase: the potential for developing a collision scenario is detected
  - ✓ **Avoidable accident** phase: a collision scenario is actually starting to develop, but the driver still has the potential to intervene and avoid a crash

Objectives

- Development of an **integrated model** to identify the impact of task complexity and coping capacity on crash risk
- Provide a holistic approach by modelling how **road, vehicle and driver**-related risk factors interact within the STZ framework
- Investigation of how **explanatory variables** of task complexity (e.g. time of the day, weather conditions) and coping capacity (e.g. fuel type, vehicle age, speeding, harsh events) are correlated with the dependent variable of risk in order to predict STZ levels



Experiment Design

Driving simulator experiment:

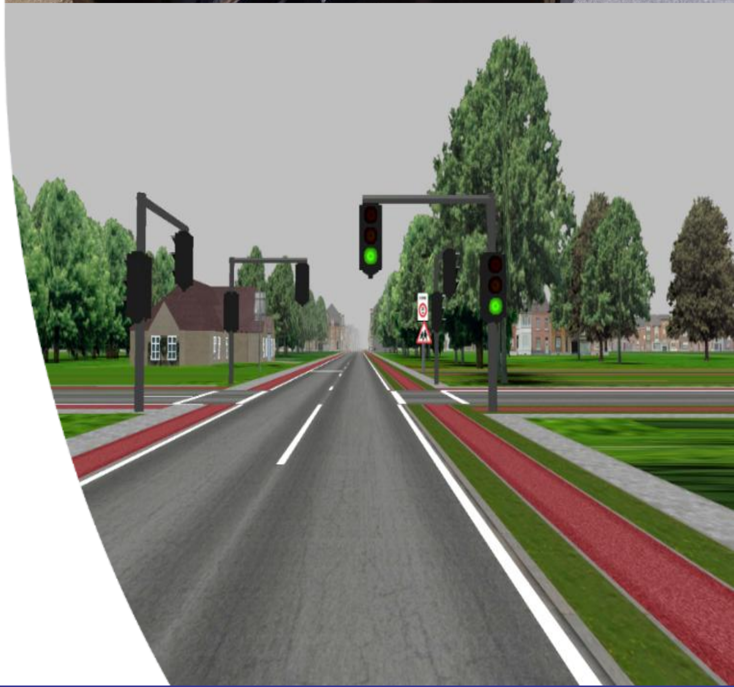
- 55 drivers
- 165 trips across different road environments
- 2 months

Three location types:

- Six-lane two-way highways
- Rural undivided two-lane roads
- Urban single-lane roads

Three consecutive scenarios:

- Customized interventions in safety-critical situations (i.e. close to the boundary of the STZ) were proposed
- Real-time and in-vehicle warnings



Experiment Phases

Scenario 1 (Baseline)	• **Intervention:** NO • **Description:** a reference period to monitor driving behaviour without interventions • **Duration:** 15 minutes
Scenario 2	• **Intervention:** Real-time • **Description:** an intervention scenario influencing driving behaviour with fixed timing thresholds (and/or message and/or display) • **Duration:** 15 minutes
Scenario 3	• **Intervention:** Real-time • **Description:** an intervention scenario with modifying condition influencing driving behaviour with variable timing thresholds (and/or message and/or display) • **Duration:** 15 minutes

Methodology

- Explanatory analyses such as **Generalized Linear Models (GLM)** were performed to examine key correlations among driving performance metrics
- Latent analyses such as **Structural Equation Models** (SEM) were employed to establish relationships between observable risk factors (i.e. number of speeding events) and latent or unobserved variables (i.e. crash risk)
- Risk levels were assessed using the STZ framework, categorizing driving behaviour into three levels:
  - **normal (low risk)**
  - **dangerous (moderate risk)**
  - **avoidable accident (high risk)**

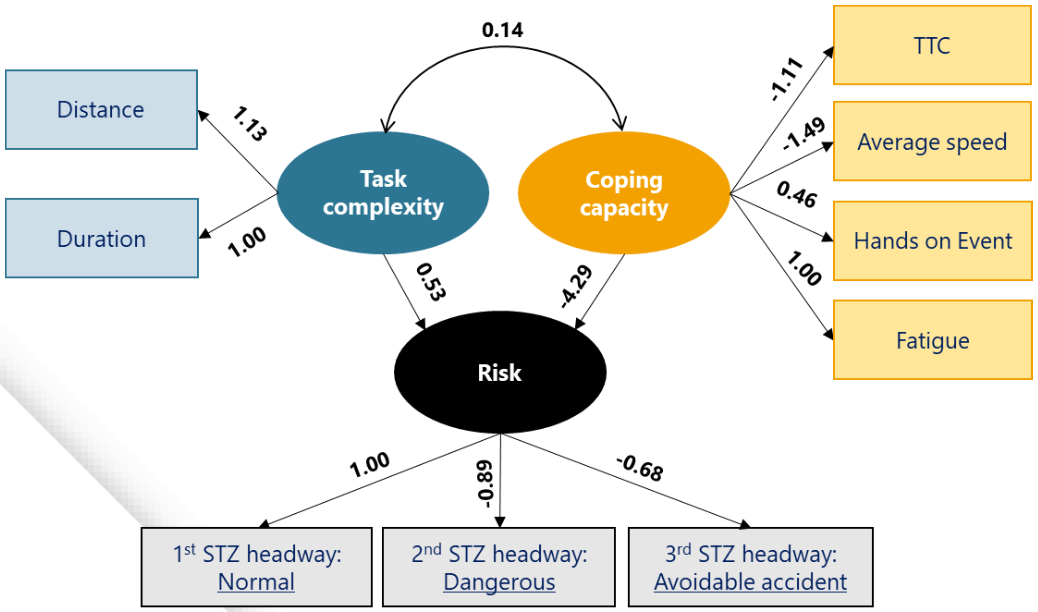
Generalized Linear Model Results

- Time of the day was **negatively correlated with headway**, which means that drivers tend to keep safer distances from the vehicle in front of them during the night
- Coping capacity indicators showed that **higher average speed and shorter TTC** increased the likelihood of headway events
- Fatigue and hands-on events were also **positively correlated**, suggesting that impaired alertness or re-engagement with the steering wheel often leads to reduced following distances
- In contrast, **trip duration was negatively associated with headway events**, indicating that longer drives promote steadier patterns and fewer adjustments in following distance

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

Structural Equation Model Results

- **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')
- **Task complexity**, represented by trip duration and distance travelled, was positively correlated with risk
- **Coping capacity**, measured through TTC, average speed, hands-on events and fatigue, showed mixed effects: fatigue and hands-on events correlated positively, suggesting drivers may compensate by adopting more cautious behaviour, while higher TTC and faster speeds were negatively associated, indicating reduced ability to manage driving demands under such conditions



Model Fit measures	Value
CFI	0.966
TLI	0.944
RMSEA	0.079
GFI	0.973
Hoelter's critical N (α = .05)	247.929
Hoelter's critical N (α = .01)	300.037
AIC	65281.042
BIC	65445.959

Discussion

- Results demonstrated that headway is a **critical determinant of safety**, with observable factors such as speed, fatigue, time-to-collision and driver distraction significantly influencing unsafe following distances
- SEM analysis further revealed that **increased task complexity was associated with higher crash r**isk, while greater coping capacity had a protective effect, enabling drivers to adapt their behaviour and mitigate risk
- Future research should include larger and more diverse samples and **advanced methods** (e.g. deep learning) to enhance the predictive power of the STZ concept

Conclusions

- Recommendations arising from this research include the need to incorporate task complexity and coping capacity indicators into driver **assistance systems and real-time monitoring technologies**, ensuring that drivers receive timely feedback and support when their STZ is shifting towards danger
- Training programmes should also **emphasize awareness** of headway, fatigue or distraction as key determinants of safety
- Further research avenues should concentrate on evaluating the **long-term effects of interventions**, assessing real-time systems and considering other human factors and driver engagement

Thank you for your attention!

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