Safety Assessment and Behaviour Modelling of Take-Over Dynamics in Automated Driving: From Human Response to Network-Level Simulation

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Doctoral Dissertation Extended Abstract

A key challenge **in conditional automation** is ensuring that drivers can safely and effectively resume control during a **Take-Over Request** (TOR). The transition from automated to manual driving is a multi-stage process shaped by the interaction between the driver, the Human-Machine Interface (HMI), vehicle-state dynamics and the surrounding traffic environment. Under SAE Level 2 and SAE Level 3 automation, drivers frequently demonstrate reduced monitoring of the driving environment and diminished readiness to intervene. These factors introduce substantial variability in the time required for re-engagement and in the stability of the manoeuvre that follows. The **objective of this dissertation** is to explain how take-over response is shaped by transition characteristics, driver state, HMI interface design and vehicle-state dynamics. To achieve this aim, the dissertation integrates evidence synthesis, simulator experimentation, data-driven modelling, behavioural profiling and network-level safety analysis into **one continuous analytical framework**.

Figure 1 summarises the full analytical workflow, linking **the systematic review, the driving-simulator experiment, the data-driven modelling stages and the network-level safety assessment**. The process begins with a meta-analysis that synthesises experimental findings on take-over performance at SAE Levels 2 and 3 and identifies the critical variables and evidence gaps. It then advances to a simulator-based experimental framework comparing a baseline interface with the multimodal HADRIAN HMI interface using synchronised driving measurements, eye-tracking and safety-related Key Performance Indicators (KPIs). Subsequently, an XGBoost-SHAP modelling pipeline quantifies the determinants of Take-Over Time (TOT), while Principal Component Analysis (PCA), k-means clustering and Linear Discriminant Analysis (LDA) reveal stable behavioural profiles. The framework concludes with a calibrated highway microscopic simulation and a spatial safety assessment based on a surrogate safety measure.

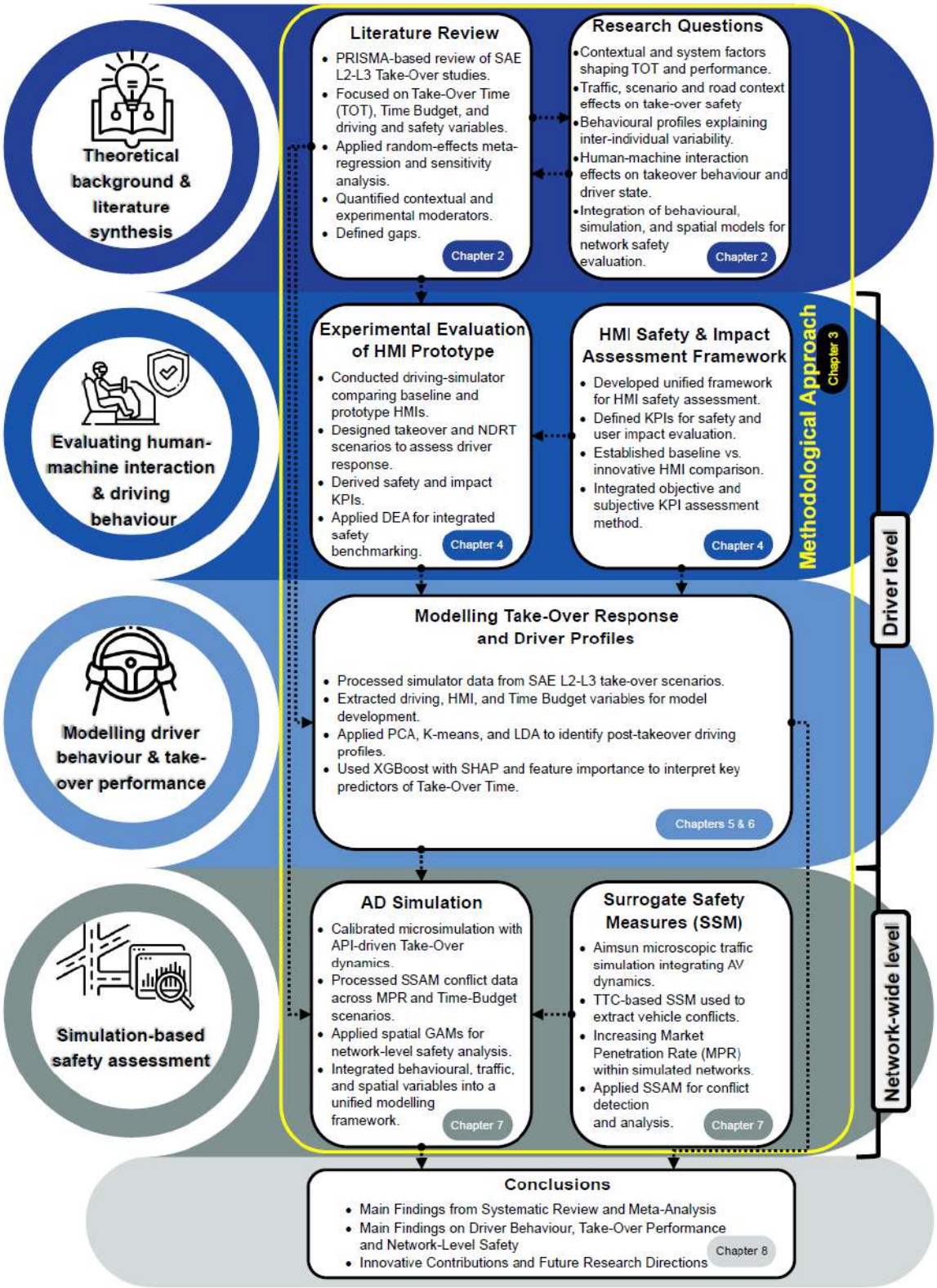


Figure 1: Graphical representation of the overall methodological framework of the doctoral dissertation

The dissertation is organised around **five research questions** derived from gaps in existing literature evidence. These questions structure the transition from conceptual synthesis to controlled experimentation and from data-driven modelling to network-level safety evaluation. RQ1 examines how automation level, road type and traffic conditions influence the time required for drivers to regain control. RQ2 analyses how the available Time Budget and surrounding traffic shape safety-critical interactions during take-over. RQ3 investigates whether data-driven behavioural profiling can capture

inter-individual variability in take-over performance and reveal mechanisms underlying post-transition behaviour. RQ4 explores how human-machine interaction affects take-over behaviour, driver state and the subjective experience of automated driving. RQ5 integrates these layers by examining how behavioural modelling, microscopic simulation and spatial safety analysis can be combined into a unified multi-level framework for evaluating network-wide safety during automation transitions. The research questions are listed below.

RQ1. How do contextual and system factors such as automation level, road type and traffic volume influence the time required for drivers to regain control after automation disengagement and take-over performance?

RQ2. How do available time budget, penetration of automated traffic, and road characteristics, together with vehicle-interaction patterns, influence safety-critical interactions during take-over phases and shape the propagation of risk along the traffic flow?

RQ3. How can data-driven behavioural profiling capture inter-individual variability in take-over performance and describe mechanisms underlying post-transition driving behaviour?

RQ4. How does human-machine interaction influence take-over behaviour, driver state and subjective experience during automated-driving transitions?

RQ5. How can behaviour modelling, analysis of take-over performance and take-over response be combined with the aforementioned approaches and incorporated into a wider traffic simulation, and how can spatial safety analysis support their integration into a unified multi-level framework for evaluating network-wide safety during automation transitions?

Figure 2 depicts the **sequential stages of the take-over process**, including perception, cognitive processing, decision-making, motor preparation and physical intervention. The available Time Budget defines the temporal window for re-engagement, and failure to respond within this interval may lead to critical safety occurrences.

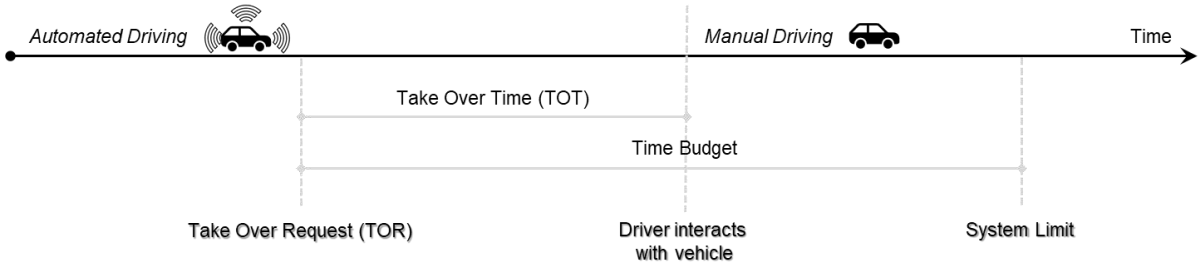


Figure 2: Take-over procedure from AD to manual control and critical time points.

The first methodological stage synthesises existing evidence on take-over response through a **systematic review** following PRISMA guidelines and a **meta-analysis** using random-effects meta-regression. The analysis shows that Time Budget, scenario urgency, driver alertness, traffic conditions, roadway characteristics, demographic composition and HMI design systematically influence take-over time. The **meta-regression** and accompanying sensitivity analysis quantify the magnitude and direction of each effect, highlighting the conditions that consistently prolong or shorten re-engagement. At the same time, the review synthesis reveals substantial inconsistencies across studies, including missing variability measures, incomplete driving, safety and behavioural measurements and inconsistent definitions of take-over constructs. These issues restrict cross-study comparability and underscore the need for harmonised indicators, aligned protocols and controlled experimental conditions. The meta-regression model estimating mean take-over time is shown below.

$$
\begin{aligned}
Mean\,TOT_{ij} = {} & 3.080 - 0.684 \cdot Traffic\,Volume_i \\
& + 0.034 \cdot Mean\,Age_i + 0.900 \cdot Unequal\,Gender\,Distribution_i \\
& - 4.081 \cdot Driver\,Alert_i + 0.111 \cdot Time\,Budget_i \\
& + 0.898 \cdot Lanes\,Per\,Direction_i \\
& + 2.318 \cdot Takeover\,Urgency\,(Yes)_i \\
& + 0.307 \cdot Automated\,Driving\,Level\,(Level\,3)_i \\
& - 0.934 \cdot HMI\,Type\,(HUD)_i \\
& - 0.111 \cdot HMI\,Type\,(Touchscreen\,interface)_i + u_i + e_{ij}
\end{aligned}
$$

The simulator driving experiment evaluates how a baseline interface compares with the multimodal innovative HADRIAN HMI, which is designed to provide clearer system awareness, more structured communication and more adaptive feedback across SAE Levels 2 and 3. The HMI setup includes visual, auditory and haptic cues, eye-tracking, hands-off-wheel detection and adaptive feedback, enabling detailed observation of both perceptual and behavioural parameters. Figure 3 presents the driving simulator setup and environment and the interface components used in the experiment.

Figure 3: Components of the multimodal innovative HMI and simulator setup.

The experiment reveals that the multimodal interface **reorganises the transition**. Awareness time decreases, indicating faster recognition of the request. Take-over duration becomes longer and more deliberate, reflecting better use of available time. Distraction decreases, and interactions at small time to collision values occur less frequently. To quantify this improvement, safety-related KPIs and perceived-impact indicators are synthesised using Data Envelopment Analysis (DEA), creating comparable safety-efficiency scores. Figure 4 shows the resulting benchmarking: the multimodal interface achieves a clear safety improvement relative to the baseline. Although subjective impressions remain more varied, the objective safety indicators consistently improve.

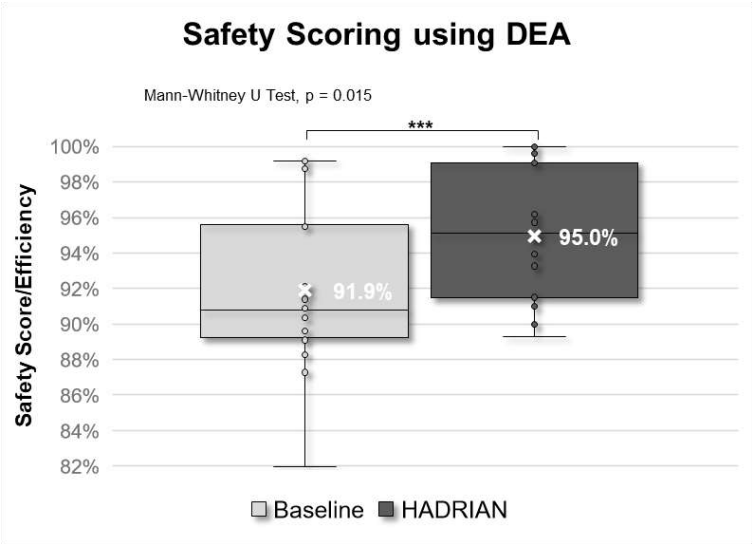


Figure 4: Safety Scoring using DEA for the different conditions.

The dissertation then shifts to **data-driven modelling of take-over response** using the aforementioned high-frequency driving simulator data. An XGBoost-SHAP pipeline quantifies how automation level, dynamic driving measurements, obstacle conditions, time budget and interface design shape take-over duration. Automation level is the dominant determinant, with Level 3 conditions producing longer and more variable responses due to extended automation availability and reduced driver attentiveness. Dynamic measurements such as deceleration patterns and speed-variability also contribute strongly. Environmental elements related to obstacle type and scenario-context influence how the response develops. Figure 5 presents the feature-importance ranking derived from the modelling.

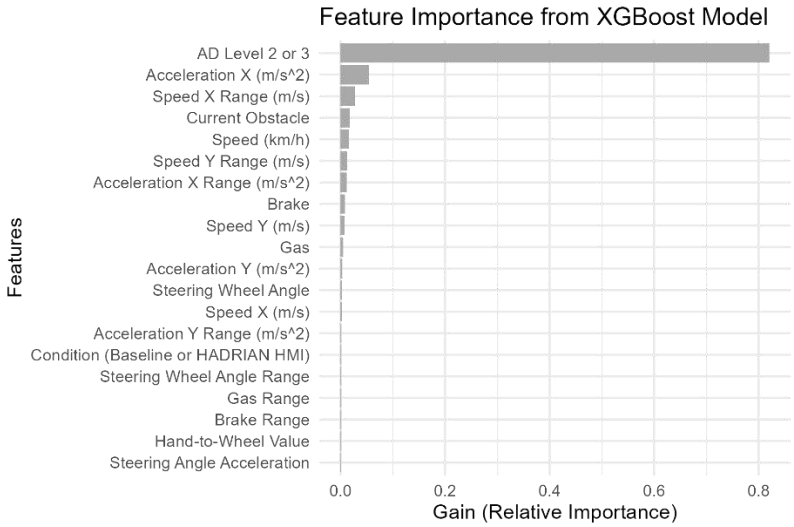


Figure 5: Feature importance from XGBoost algorithms for TOT.

The next analytical stage **identifies behavioural profiles that appear after the transition**. A combination of PCA, k-means clustering and LDA reveals three stable post-takeover patterns that persist across automation levels. The passive-slow profile is marked by long take-over durations, low speed-variability and mild accelerations. The nervous-moderate profile shows intermediate response times but high variability, with abrupt changes in deceleration. The normal-quick profile is characterised by short take-over durations, moderate variability and smoother adjustments. These patterns reflect distinct modes of controlling the vehicle after the transition and capture core behavioural differences in stabilising the manoeuvre. Figure 6 shows the distribution of take-over duration by driving profile and automation level.

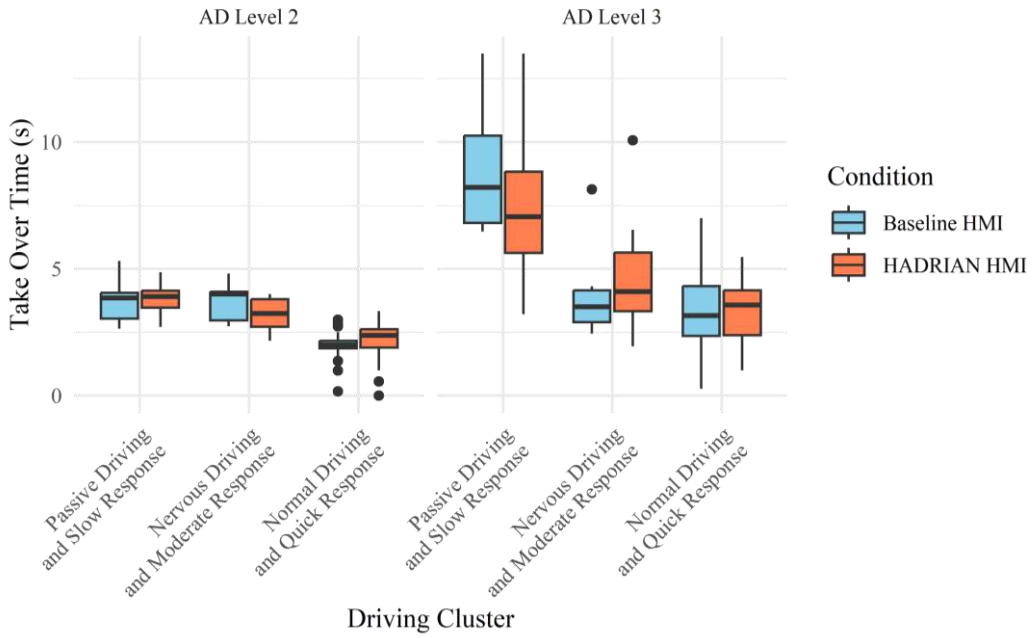


Figure 6: Boxplot of TOT by driving profile.

These behavioural parameters are then imported into a **calibrated microscopic simulation** of a real 50km highway corridor forming part of the Athens-Thessaloniki route. The simulation reproduces Level 2 and Level 3 transitions using custom API-scripts, scenario-specific triggers and dynamic parameter-updates reflecting the take-over window and behavioural profile. Figure 7 illustrates the logic for parameter activation and restoration during take-over events.

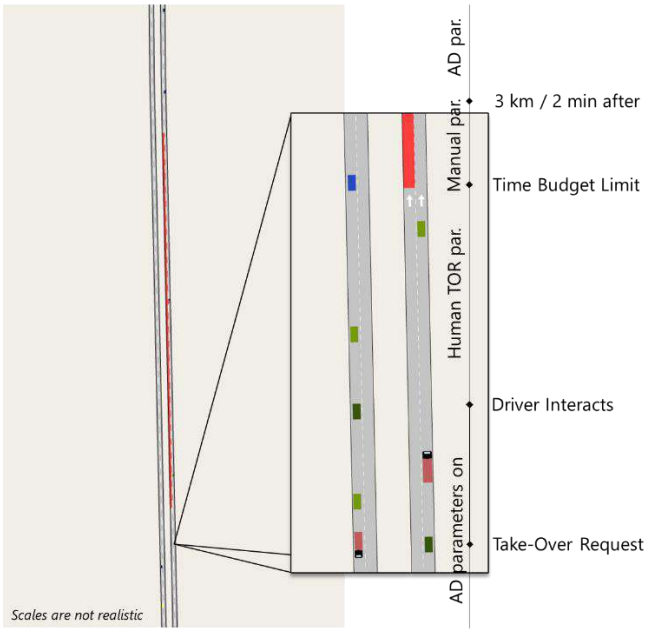
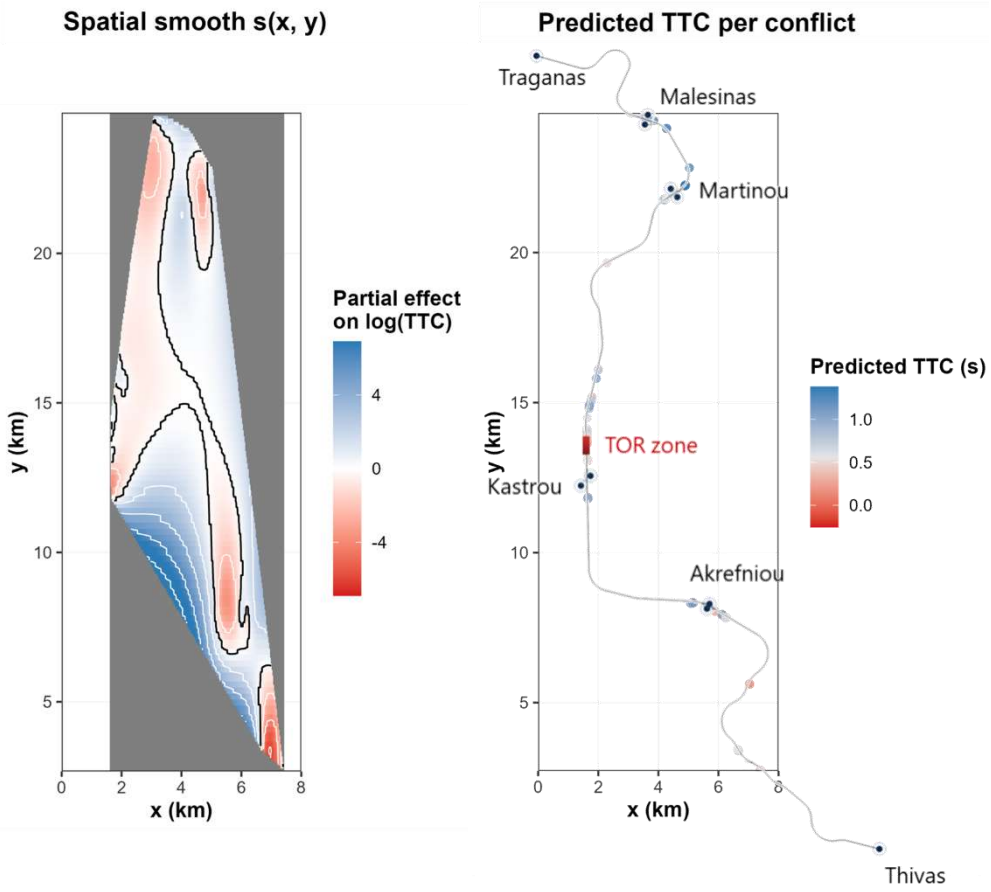


Figure 7: Time sequence for parameter activation and restoration during TOR events.

Surrogate safety measures, particularly **Time To Collision (TTC)**, are extracted for all interactions across different market penetration rates and time budget conditions. Spatial Generalised Additive Models interpret these interactions, revealing **how conflict-risk varies along the corridor**. The analysis shows that take-over phases systematically compress temporal safety margins, regardless of the available time budget. Lane closure and Operational Design Domain (ODD) exit scenarios

produce concentrated zones of reduced TTC, while merge areas and transition zone intensify these effects. Higher penetration of automated vehicles increases average TTC but does not eliminate the bottlenecks created by re-engagement dynamics. Figure 8 shows the spatial surface of the fitted GAM and the corresponding predicted conflict values along the route.



(a) **(b)**

Figure 8: (a) Spatial smooth surface of partial effects on log(TTC) across the simulated corridor. (b) Predicted TTC per conflict along the same route, with major locations and the TOR zone highlighted in red.

Taken together, the results show that **take-over behaviour is shaped by a layered combination of driver-related, interface-related, vehicle-related and environment-related influences**. The findings emphasise that transitions from automated to manual control remain the dominant constraint for safety in mixed traffic. Even with higher automation penetration, variations in take-over duration, behavioural profile and geometric context determine where temporal margins decrease.

The final part of the dissertation synthesises the methodological and empirical advances achieved across all chapters and presents **five innovative contributions** that structure the work's added value, as illustrated in Figure 9.

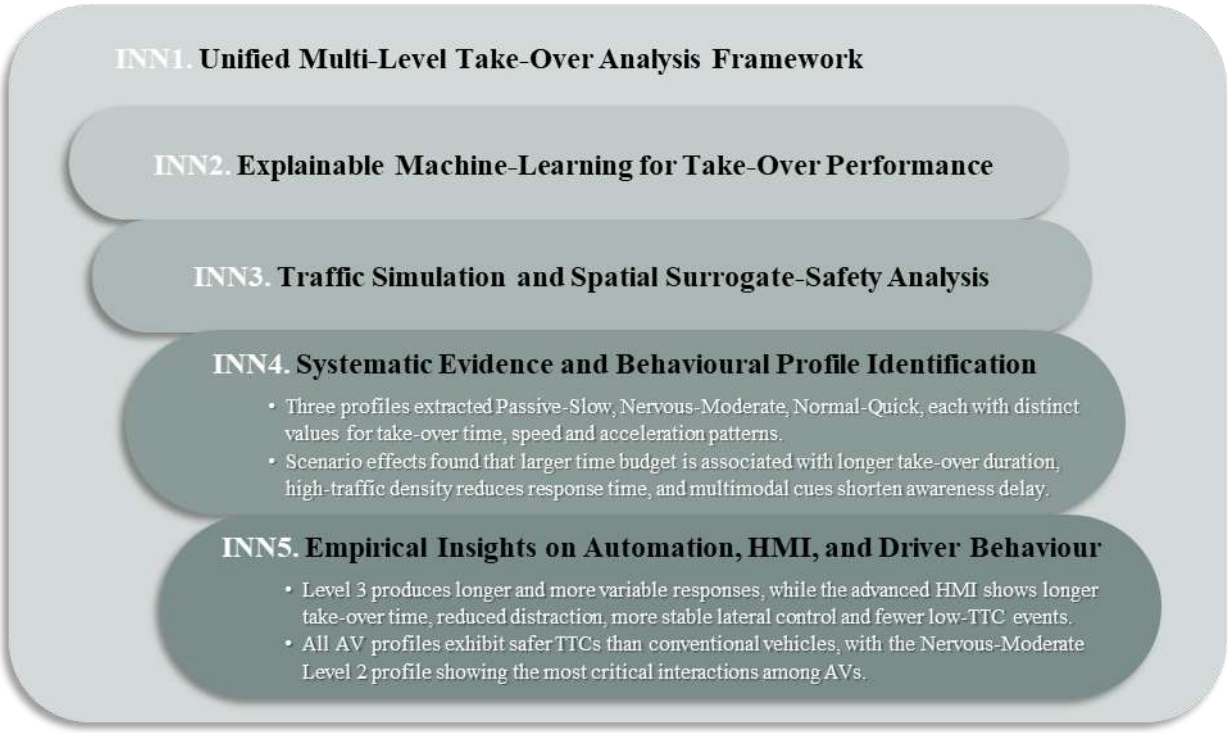


Figure 9: Innovative contributions of the dissertation.

These contributions reflect the full analytical chain developed in the dissertation, from evidence synthesis to simulator experimentation, data-driven modelling, behavioural clustering and spatial network-level safety assessment. Together, they form a clear set of innovations that clarify how drivers re-engage during transitions, how interaction design and automation level shape performance, and how these mechanisms propagate across mixed traffic. The contributions are summarised below.

INN1. A unified multi-level framework for analysing take-over dynamics and human-automation interaction

The dissertation connects literature synthesis, simulator experimentation, data-driven modelling and network-level safety analysis into one continuous framework for examining take-over transitions across cognitive, behavioural and system layers.

INN2. A data-driven and interpretable modelling framework for take-over performance

A modelling pipeline combining XGBoost and SHAP quantifies how dynamic driving variables, scenario-conditions, time budget and interface design shape take-over duration in a transparent and reproducible way.

INN3. A traffic simulation and spatial surrogate-safety framework capturing automation-transition risks

Behavioural parameters, time budget conditions and automation levels are embedded into a calibrated microsimulation, with spatial GAM analysis revealing how take-over disturbances propagate across mixed traffic.

INN4. A systematic synthesis and identification of post-takeover behavioural patterns

The dissertation unifies empirical synthesis with behavioural clustering to identify three stable post-takeover profiles, capturing inter-individual differences in speed regulation, control stability and reaction timing.

INN5. New empirical evidence on how automation level, interface design and driver behaviour jointly shape take-over safety

The results clarify how automation level, HMI support and behavioural profiles influence take-over quality and temporal margins, explaining how driver variability interacts with roadway context to affect network-wide safety.

Overall, the dissertation offers an integrated and empirically grounded foundation for understanding take-over response at SAE Levels 2 and 3. It demonstrates how driver-state, interface-support, behavioural-variability and roadway-context interact during the transition and how these interactions influence safety both at the vehicle level and across the traffic network. The framework and findings support the design of adaptive take-over management strategies and transition-aware automated driving systems that promote more stable, predictable and safe re-engagement in future mobility environments.