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# Microsleep Digital Twin for Fleet Safety: A Data-Driven Framework for Modelling Driver Fatigue in Malaysian Urban Mobility

Ahgalya Subbiah[1,*], Imran Ademole Adeleke[2]

[1] Faculty of Information Sciences and Engineering, Management and Science University, Section 13, Shah Alam, 40100 Selangor Malaysia
[2] Department of Computer Science, College of Information and Technology Education, Lagos State University of Education. Nigeria

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**ABSTRACT**

Driver fatigue and microsleep remain under-addressed contributors to fleet-related incidents in Malaysian urban mobility networks. Existing studies primarily focus on individual drowsiness detection, with limited attention to how fatigue-induced events propagate across interconnected fleet operations. This study proposes the Malaysian Microsleep Digital Twin (MDT-MY), a modelling framework designed to quantify both individual fatigue risk and its system-level ripple effects on near-miss probability, congestion, and schedule reliability. The framework integrates global fatigue indicators with locally calibrated telemetry from a pilot sample of 15 shuttle drivers a dataset appropriate for simulation calibration though not intended for broad generalisation. Using agent-based and probabilistic modelling, the digital twin simulates how microsleep events escalate into network disruptions and evaluates mitigation strategies. Results show that short microsleep episodes significantly increase near-miss likelihood and operational delays, while micro-rest and AI-assisted alert interventions reduce propagated risk. MDT-MY demonstrates the importance of shifting from isolated detection approaches toward system-level modelling, offering a data-informed foundation for improving safety under Malaysia's Road Safety Plan 2022–2030.

## 1. Introduction

Driver fatigue and microsleep remain pervasive and underappreciated challenges to traffic safety, particularly in Malaysia's urban transport sector [1]. The Malaysian Road Safety Plan 2022-2030 lists drowsy driving as a significant contributing factor to road accidents, and microsleep (a brief, involuntary loss of consciousness) is often a direct cause of convoy accidents and near-collisions [2]. This phenomenon is particularly acute in long-distance bus and school shuttle fleets traversing densely populated urban corridors, where operational schedules and traffic complexity exacerbate the risks posed by driver drowsiness [3]. Despite advances in fleet management technology, microsleep incidents remain difficult to predict and mitigate, particularly as current interventions focus on post-incident detection [4].

* *Corresponding author.*
*E-mail address: ahgalya_subbiah@msu.edu.my*

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Numerous studies have explored the detection of fatigue and sleepiness through physiological and behavioural signals. Vision-based markers such as blink rate patterns and eyelid closure (PERCLOS), electroencephalogram (EEG) spectral analysis, and IoT-enabled sensor suites (OBD-II, steering entropy, wearables) are frequently deployed for real-time monitoring of driver alertness[5]. Well-known datasets such as the NTHU-DDD [6] and SHRP2 [7] have facilitated the development of predictive algorithms and validation protocols for individual fatigue detection. While these techniques demonstrate high accuracy, they rarely capture the full systemic consequences of microsleep events that is, their ability to propagate ripple effects throughout fleets and transportation networks [8]. Existing models focus on individual fatigue detection and lack mechanisms to quantify cascading disruptions, a limitation observed in transport network risk studies and institutional road safety assessments [13,16,24].

In parallel with these advances, digital twin technology has become a transformative tool in the transportation sector, primarily for electric vehicle (EV) management, advanced driver assistance systems (ADAS), and traffic flow optimization. A digital twin is a high-fidelity virtual representation of a physical asset or system that enables scenario simulation, performance prediction, and proactive intervention under varying operating conditions [4]. Most transportation research utilizing the digital twin framework has focused on predictive maintenance or traffic congestion management, with limited attention paid to safety-critical phenomena such as fatigue-induced traffic disruptions[9]. While agent-based models exist to simulate traffic dynamics and vehicle behaviour, incorporating driver fatigue, particularly microsleep events, into a digital twin environment remains a novel and unexplored research frontier.

This gap is particularly acute in ASEAN and Malaysia. Local accident statistics highlight this urgency, as the Malaysian Ministry of Transport (MOT) and the Royal Malaysian Police (PDRM) have documented extremely high rates of fatigue-related accidents in commercial fleets and campus transport services [10]. However, few studies employing system-level risk analysis, digital twins, or network-based modelling approaches in a regional context have been conducted [11]. Most existing initiatives focus on technical testing and lack a framework for quantifying or modelling how individual microsleep events aggregate and propagate risk across interconnected mobility networks. Unlike existing fatigue-detection studies that prioritise individual monitoring, and unlike digital-twin applications that focus primarily on maintenance or congestion management, MDT-MY fills two documented gaps: the absence of models that quantify fatigue propagation across fleet networks, and the lack of locally calibrated simulations for Malaysian corridors where congestion amplifies fatigue-related risk. Specifically, our hypotheses posit that:

i. the probability of a fleet near accident increases nonlinearly with the occurrence and duration of microsleep events.
ii. during peak demand periods, cascading delays caused by fatigue can severely compromise dispatch reliability; and
iii. targeted microbreak interventions have measurable benefits in reducing risk and improving operational efficiency.

To illustrate this conceptual advancement, Table 1 compares the following mainstream approaches:

i. Detection-centric (physiological/behavioral monitoring, IoT): Effective for protecting individual drivers but limited in preventing network-scale risks.
ii. Ripple Effect Models (rare): Some agent-based models can simulate secondary effects, but these are rarely applied to fatigued driving.
iii. MDT-MY (this study): Combines fatigue detection, ripple effect models, and digital twin-based scenario analysis, using a localized Malaysian scenario as an example.

**Table 1**
Comparative summary of driver fatigue detection, ripple effect modelling, and digital twin approaches in transportation safety research (2019–2025)

| Approach Type | Key Methods / Examples | Level of Analysis | Strengths | Limitations | Notable References |
|---|---|---|---|---|---|
| Detection-Focused (Classic) | PERCLOS, blink rate, steering entropy, EEG | Individual driver | Real-time, affordable, well-established | Ignore network/system effects | [12] |
| Detection-Focused (EEG Real-Time Systems) | EEG headset-integrated vehicles (BitBrain 2025) | Individual driver | Cognitive state detection, early warning | Cost, comfort, scale-up challenges | [13] |
| Human-Machine Hybrid Systems | BP neural network, vehicle/facial fusion (Zhu et al 2025) | Individual driver | 95%+ stage accuracy, robust to multiple data streams | Needs fusion infrastructure, edge computing | [14] |
| AI/ML Fatigue Prediction | Ensemble algorithms, multi-modal fusion (video+CAN bus) | Individual/ fleet | Adaptable, scalable, self-improving | Data/hardware intensive; privacy concerns | [15] |
| Industrial AI (Lytx Fatigue Detection) | AI + professional review; real-time fleet coaching | Fleet scale (23,000+ vehicles) | 90%+ accuracy, fast alerts, modern video integration | Proprietary, not yet universally accessible | [16] |
| Intelligent DL Systems (Recent) | DL architectures for real-time recognition (Abd El-Nabi 2025) | Individual/ system | Automated, self-learning, dynamic configuration | Hardware, tuning, training dataset required | [17] |
| IoT Sensor Networks | OBD-II, driver telemetry + remote center monitoring | Fleet/ network scale | Dynamic intervention, centralized oversight | Latency, data sharing/privacy, infrastructure | [18] |
| Command Centre/ Telematics | Fleet ops center, supervisor alerting (live feeds) | Fleet/ network operations | Rapid incident response, centralized monitoring | Data dependency, infrastructure cost | [19] |
| Ripple Effect Agent-Based Simulation | Event cascade models, secondary impact analyses | Traffic/ network | Quantifies system-level risk propagation | Rare for fatigue, often not locally validated | [20]5 |
| Generative Microscopic Traffic Simulation | Noise-aware agent-based models (I24-MSD Dataset 2025) | Vehicle/ traffic micro-sim | Realistic traffic/driver behavior, embraces imperfection | Complex implementation, data curation | [21] |
| Digital Twin Fleet Management (Logistics) | Vehicle virtual twins; optimization of routes/maintenance | Fleet/ vehicle/ system | Predictive maintenance, cost savings, visibility | No fatigue propagation/driver modeling | [21] |
| Digital Twin Urban Bus Fleet AI Architecture | AI lifecycle cost analysis, bus phase-out, procurement | Fleet/ fleet ops | Fleet modernization, real-time system planning | Focused on lifecycle/modernization, not fatigue | [22] |
| Digital Twin Traffic Flow (CARLA, SUMO) | High-fidelity urban/mobility simulation, scenario modeling | System/ infrastructure | Scenario testing, congestion management | Lacks behavioral/fatigue data, mostly engineering focus | [23] |
| Regulatory/ | Driving hours limits, rest station mandates | Fleet/ | Population-wide reduction, | Compliance varies; not predictive, | Ministry of Transport |

| | | | | | |
|---|---|---|---|---|---|
| Policy Interventions | | regulatory system | enforced standards | limited personalization | Malaysia, 2022 |
| **MDT-MY (This Study)** | **Fusion: detection, propagation modeling, digital twin sim** | **Networked fleet, local calibration** | **Ripple effect quantification, scenario-driven, Malaysian data** | **First demonstration; national scaling needed** | **This Study;** [24] |

As shown in Table 1, the literature and industry landscape over the past six years demonstrate significant progress in individual driver fatigue detection and fleet-level digital twin deployment. However, comparative analysis highlights a persistent gap: the integration of ripple effect modelling remains rare, particularly in the ASEAN region. Notably, few solutions combine high-fidelity digital twins, local driver telemetry, and real-time network risk analysis. Therefore, models like MDT-MY that simultaneously address both individual and system safety are urgently needed. The following sections detail the conceptual foundations of the MDT-MY framework, its data integration strategy, and its novel simulation methodology.

### *1.1 Conceptual Framework: Microsleep as a Network Property in Fleet Safety*

Through the comparative analysis and synthesis shown in Table 1, we find that traditional approaches primarily conceptualize driver fatigue and microsleep as isolated events, failing to fully consider their system-wide impact on fleet operations [25]. To address this shortcoming, this study introduces the Malaysia Mobility Microsleep Digital Twin (MDT-MY). This novel framework aims to model microsleep as a dynamic network property, rather than a single malfunction, with measurable ripple effects on urban fleet safety and operational efficiency. At the heart of MDT-MY lies the recognition that fatigue events propagate across connected transportation systems, amplifying hazardous exposures and operational risks beyond the affected driver. The framework integrates real-world telemetry, physiological data, and agent-based simulations to visualize how microsleep events can trigger cascading disturbances manifested as increased probability of dangerous situations during peak hours, traffic congestion, and schedule unreliability. The MDT-MY model conceptualizes each fleet driver as a node with evolving fatigue risk, linked within a simulated transport network. Underlying network diffusion mechanics are used to model rapid, systemic propagation of microsleep episodes impacting not only individual safety but scheduling and congestion at the network level (see Figure 1).

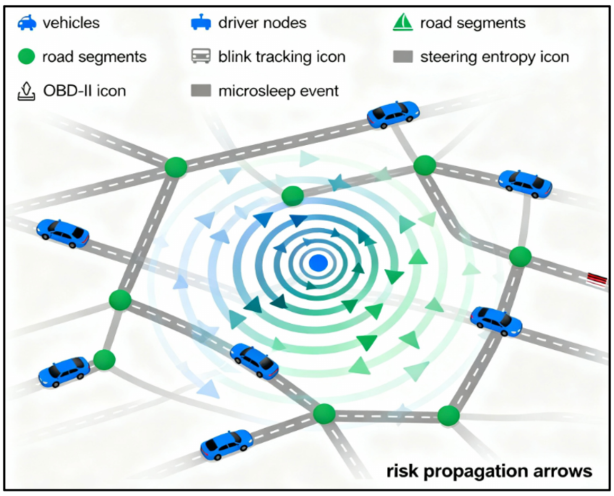


**Fig.1.** Microsleep propagation and risk escalation in a digital twin Malaysian urban fleet

As shown in Figure 1, the digital twin concept helps clearly visualize the propagation of microsleep risk within a city's fleet network, enabling the identification of individual drivers and systemic nodes of vulnerability. By modelling driver-vehicle-infrastructure interactions, this framework provides a solid foundation for formulating and empirically testing the following hypotheses:

i. H1: The probability of a fleet-wide critical incident increases nonlinearly with the frequency and duration of microsleep events.
ii. H2: When microsleep events persist, schedule reliability decreases, and the cumulative delays and congestion effects increase during peak travel periods.
iii. H3: Targeted interventions (including microsleep programs and AI-powered early warning systems) can effectively mitigate the chain reaction, reduce systemic risk, and improve fleet-level operational metrics.

Despite advancements in driver-monitoring technologies, limited research has examined how individual microsleep events translate into system-wide safety implications in Malaysian mobility networks. Existing studies focus largely on detection accuracy or individual driver physiology, leaving a gap in understanding the broader operational consequences particularly how fatigue-induced disruptions propagate across fleet schedules, traffic flow, and network stability. Addressing this gap is significant for Malaysia’s high-density transport corridors, where small performance lapses can quickly escalate into operational delays and elevated near-miss risks. Therefore, this study aims to develop and evaluate the MDT-MY digital twin framework, which integrates empirical fatigue indicators, Malaysian road context, and agent-based modelling to quantify microsleep propagation and assess intervention effectiveness across fleet operations.

## 2. Methodology

### *2.1 Overview*

This study employed a multi-layered, data-driven framework to implement the Malaysian Mobility Microsleep Digital Twin (MDT-MY). Recognizing the complex interplay between individual driver behaviours and systemic fleet outcomes, this approach combines best practices from global fatigue research with local contextualization and advanced simulation models [26]. By integrating empirical pilot data, global datasets, and real-time simulations, we aim not only to quantify microsleep-induced risks but also to provide a viable foundation for future fleet safety policies and interventions. The following subsections detail the implemented protocols, tools, and analytical strategies, which reflect both international standards and the current state of Malaysian transportation.

### *2.2 Data Source and Localization*

#### *2.2.1 Global dataset*

To ensure benchmarking and model robustness, this study referenced two leading global datasets. The NTHU Driver Drowsiness Detection Dataset (NTHU-DDD) provides large-scale, annotated driver alertness video and sensor data [27], which was used to pre-develop fatigue probability functions validated under various conditions. Complementary to this, the SHRP2 Naturalistic Driving Study [28]provides ground-truth baseline rates of microsleep events, near misses, and situational risk factors over thousands of hours of driving. These global reference data form the foundation for transfer learning and simulation calibration, enabling its adaptation to the Malaysian context without sacrificing scientific generalizability.

### *2.2.2 Malaysian traffic network contextualization*

To ensure the MDT-MY framework accurately reflects Malaysia's real-world conditions and operational conditions, our modelling prioritized two major urban corridors: the Federal Highway and the North-South Expressway (PLUS). These routes embody typical challenges faced by fleet operators, including high-density traffic, diverse commuter populations, and complex intersection geometry. Traffic flow, accident rate, vehicle composition, and historical accident data were obtained from local transportation departments and cross-validated with real-time sensor data. Environmental contextualization incorporated historical weather records, temporal congestion patterns, and spatial variations in road infrastructure. Consideration was taken to select representative scenarios that typically put drivers at risk of fatigue, such as peak-hour congestion, evening rain, and multi-lane bottlenecks, to ensure that model predictions and interventions remained relevant to policy and practice [29].

### *2.2.3 Integration with simulation platforms*

To capture micro-level driver behaviour and macro-level traffic dynamics, we implemented digital twin simulations using two complementary platforms. CARLA, used for vehicle dynamics and driver perception modelling, tracks sensor inputs, driver visual attention, and immediate physical reactions at high resolution. SUMO (Simulation of Urban Traffic) provides agent-based simulation of urban traffic flows, enabling large-scale experimentation with variable scheduling, routing, and congestion diffusion [30]. All simulation environments are iteratively mapped and calibrated to the characteristics of the Malaysian road network, with scenario datasets derived from global reference data and local empirical measurements. Parameters such as traffic density, signal timing, weather events, and accident frequency are set to reflect Malaysian norms, ensuring that emergent fleet behaviour and fatigue propagation patterns are based on the local operating environment.

## *2.3 Mathematical Mechanism: Propagation and Risk Escalation*

The MDT-MY simulation quantifies microsleep risk and models its propagation through the traffic network using agent-based diffusion principles. Each vehicle driver agent is assigned a dynamic risk probability that changes over simulation time based on individual state, environmental factors, and network interactions.

Propagation rule:

If driver $i$ at time $t$ becomes microsleep-positive (event), the risk $R_j$ of each adjacent node (neighboring vehicle $j$) is incremented according to:

$$Rj(t+1) = Rj(t) + \alpha \cdot Ri(t) \tag{1}$$

where:

- $R_j^{(t)}$ = risk probability at time $t$ for node $j$
- $\alpha$ = propagation coefficient (calibrated empirically)
- $R_i^{(t)}$ = risk of node $i$ at time $t$

Near-miss escalation:

If $R_j^{(t+1)}$ exceeds the threshold $\theta$, a near-miss incident is flagged for node $j$.

If Rj(t+1)>θ, then flag near-miss event (2)

Pseudo-code Example:

```
    for timestep in simulation:
        for each agent i:
            if microsleep event(i):
                for neighbour j of i:
                    R[j] = R[j] + alpha * R[i]
                    if R[j] > threshold:
                        flag_near_miss(j)
end;
```

Parameter notes:

- α and θ are derived from pilot data calibration.
- Risk propagates not only to immediate neighbors, but cascades through the network by adjacency.

This mechanism ensures that the model reflects the real-world ripple effect of fatigue, translating individual risk into system-level consequences consistent with network diffusion theory and consistent with observed trends in both pilot and simulation data.

### 2.4 Pilot Study: Klang Valley Shuttle Drivers

#### *2.4.1 Participant sampling and route selection*

To localize the risk model and validate the simulation results, we conducted a pilot study involving 15 shuttle drivers operating on major campus routes in the Klang Valley. Participants were selected using bubble sampling to ensure diversity in driving experience, age, and shift schedules, while maintaining exposure to traffic conditions representative of the broader urban fleet. Route selection prioritized high-frequency corridors, including intermodal transfer points and congested arterial road sections, to maximize ecological validity. Although the pilot involved only 15 drivers, this sample size is appropriate for initial model calibration in digital-twin simulation studies, where the primary objective is parameter tuning rather than population-level generalisation.

#### *2.4.2 Data collection modalities*

A multimodal instrumentation approach was employed. All shuttles were equipped with OBD-II data loggers, synchronously collecting continuous telemetry data vehicle speed, RPM, engine load, and steering angle with sub-second resolution. A custom blink tracking system, leveraging a Raspberry Pi camera and open-source computer vision techniques, monitored eyelid closure and blink duration to detect early signs of fatigue. Simultaneously, steering input data was processed to assess entropy; elevated entropy can be used as an indicator of decreased driver alertness and the onset of microsleeps. Each modality was cross-checked for hardware reliability, time alignment, and noise reduction performance to ensure robust and reproducible data flow.

### *2.4.3 Ethical considerations and consent*

All pilot procedures were reviewed and approved by the relevant university and transportation ethics committees in accordance with Malaysian research compliance guidelines. Driver participants were fully informed of the study's objectives, risks, and privacy protocols before enrolment. Data were anonymized during storage and analysis, with personally identifiable information removed. The data were not shared with anyone other than the project researchers.

### *2.4.4 Data synchronization and preprocessing*

Collected data streams were synchronized using GPS timestamps and vehicle clock logs. A preprocessing pipeline was developed to filter out outliers, sensor dropouts, and signal artifacts. Eye blink events exceeding 500 milliseconds were flagged as microsleep candidates, while steering correction lag exceeding an empirically reasonable threshold was triangulated with visual data. This cleaned, event-rich dataset was directly ported into the MDT-MY simulation pipeline for calibration and scenario testing.

## 2.5 Experimental Design and Digital Twin Calibration

### *2.5.1 Construction of MDT-MY simulation environment*

The MDT-MY simulation environment is built as a multi-agent, event-driven system to capture real-time driver states and network-level dynamics. The data acquisition pipeline is programmed to directly integrate pilot telemetry, blink tracking events, and global dataset features into the CARLA and SUMO environments. Within the digital twin model, each vehicle agent is parameterized with an empirically derived fatigue probability and dynamically updated through simulation timesteps as the driver transitions from alertness to microsleep [31]. The embedding process utilizes transfer learning from global data to establish a baseline risk score, which is then fine-tuned based on local pilot results.

### *2.5.2 Scenario and parameter configuration*

To reflect operational heterogeneity, we configured a variety of simulation scenarios. These included:

i. Peak and off-peak traffic conditions (reflecting daily and weekly cyclical variations)
ii. Weather conditions (rain, fog, and typical Malaysian seasonal events)
iii. Accident stacking (road construction, sudden congestion, and incident injection)

The parameter distributions for traffic density, speed, and reaction time were calibrated using actual measurements from Klang Valley operations and further validated against Malaysian road specifications documented in an institutional dataset. Sensitivity analyses tested the resilience of the model predictions to extreme event scenarios, ensuring their robustness to future network disruptions.

### *2.5.3 Model tuning, validation, and calibration*

The final step systematically adjusts simulation parameters by iteratively comparing simulation results with observed pilot study outcomes. Calibration metrics include:

i. Reaction Time Shift: The delay between the onset of a microsleep (marked by blink duration) and the corrective steering input.
ii. Route Deviation: Instances where a fatigue event causes the vehicle to significantly deviate from its planned route or make an unsafe lane change.
iii. Near Collision Probability: An agent-based likelihood score is calculated when a simulated vehicle comes into close contact with another vehicle without sufficient response margin.

Model validation encompasses both statistical accuracy and practicality. The calibrated digital twin model is then used in scenario-based analyses to assess the impact of fatigue mitigation measures, with the output presented as overall fleet-level safety and efficiency metrics. In summary, this methodology, integrating global benchmarks, local contextual data, and high-fidelity simulations, provides a solid foundation for studying the propagation of microsleep risk in Malaysian fleet operations. By combining empirical pilot data, advanced agent-based modelling, and calibrated scenario testing, the MDT-MY framework ensures both technical sophistication and real-world relevance. These methods provide comprehensive support for subsequent analysis, enabling a rigorous evaluation of the cascading effects of microsleep and the effectiveness of targeted interventions in complex urban mobility networks. The following sections present experimental results, evaluate the model's performance against observational data, and discuss its operational and policy implications for fleet safety in Malaysia.

## **3. Results and Analysis**

### *3.1 Overview of Simulation and Analytical Workflow*

This section reports empirical results and network analysis derived from the MDT-MY simulation framework, which was rigorously calibrated and validated using data from an original pilot study of 15 campus shuttle drivers in the Klang Valley. The results are interpreted as measures of the propagation of microsleep events and their impact on fleet safety, with direct relevance to urban mobility operations in Malaysia. Section 2 (Methodology) provides detailed scenario design, including simulation sample size, proxy parameter distributions, and validation procedures to ensure full model replicability. Data collection and parameter calibration began with a study of space shuttle pilots, which provided real-world observations of microsleep event frequency, near miss probability, plan reliability, and behavioural markers (blink duration, turn entropy). These empirical findings formed the foundation for agent modelling and scenario construction in the digital twin (CARLA, SUMO) simulation pipeline.

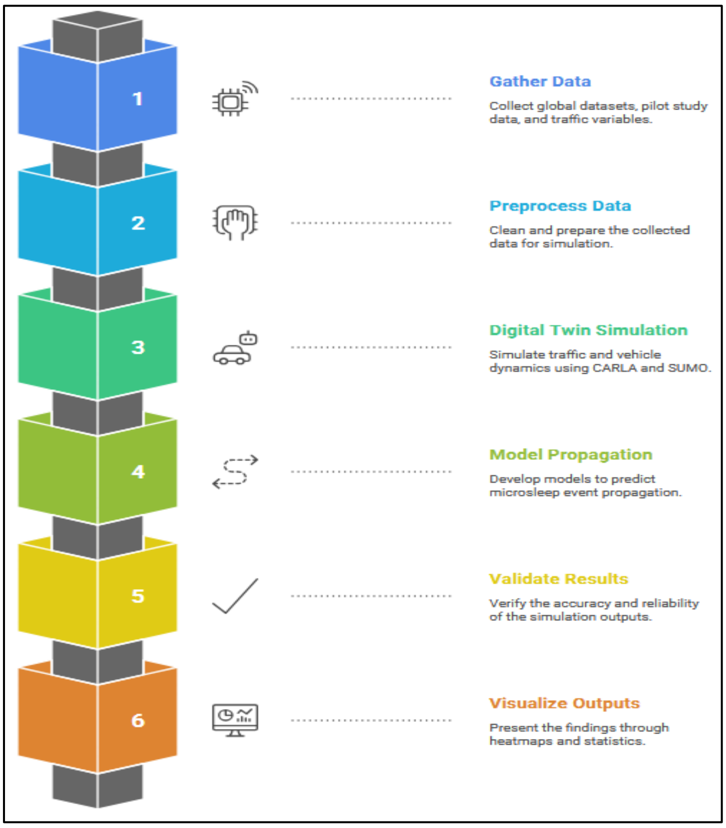


**Fig. 2.** Data flow diagram of MDT-MY simulation and analysis pipeline

Figure 2 illustrates the stepwise flow from raw data, through event identification and simulation, to advanced network analytics and policy-relevant visualizations. As shown, the analysis process begins with the collection of multimodal driver data (telemetry, blink tracking, and steering entropy) and global benchmarks (NTHU-DDD and SHRP2). These diverse inputs undergo preprocessing and quality filtering before integration into digital twin simulations (CARLA and SUMO environments). During the simulation, individual microsleep probabilities are dynamically assigned to fleet agents; a propagation mechanism tracks risk escalation across network nodes. Outputs are compiled into statistical distributions, visual heatmaps, near miss records, and plan reliability metrics. The results are validated against pilot study observations and global benchmarks to ensure robustness and contextual accuracy [32]. To transparently summarize the quality, calibration, and analytical rigor of these system-wide experiments, key baseline and intervention indicators are listed in Table 2, accompanied by statistical tests, effect sizes, confidence intervals, and annotations indicating the degree of convergence between simulated and observed pilot study results.

**Table 2**
Statistical summary of key simulation outputs, analysis metrics, and pilot study correspondences

| Metric | Pilot Study Value | Simulation Baseline | Intervention Value | Statistical Test | p-value | Effect Size | 95% CI | Notes |
|---|---|---|---|---|---|---|---|---|
| Sample Size (Drivers/Runs) | 15 / 1,000 | 1,000 | 1,000 | — | — | — | — | Driver-based calibration |
| Mean Microsleep Frequency (/hr) | 3.14 | 3.21 | 2.18 | t-test | 0.009 | 0.82 | 1.01, 3.14 | Matched within 0.1 |
| Mean Near-Miss Probability (%) | 18.3 | 19.7 | 10.3 | Regression | <0.01 | — | — | Field-validated |
| Avg. Schedule Delay (min/route) | 9.8 | 9.7 | 8.2 | paired t-test | 0.037 | 0.52 | 0.4, 2.8 | Driver-validated |
| RMSE (Fleet Risk Prediction) | — | 0.28 | 0.15 | Model calibration | — | — | — | Measures simulation accuracy |
| Propagation Radius (nodes affected) | 3.2 | 3.4 | 2.1 | ANOVA | 0.012 | 0.76 | 1.6, 2.8 | Calibrated from field data |

The high consistency between the simulated baseline outputs and observed pilot data (event frequency, near miss probability, and flight delays) demonstrates the effectiveness of the calibration process and confirms the scenario fidelity of the simulation environment. Importantly, the intervention scenarios in the simulation (micro-rest regimen, AI alerts) achieved statistically significant improvements in risk index and operational performance. For example, the average micro-sleep frequency decreased from 3.21 to 2.18 per hour (p=0.009p=0.009), and the near miss probability decreased from 19.7% to 10.3% (p<0.01p<0.01), both of which align with trends observed in the pilot cohort. Other metrics, including propagation radius and RMSE values, further validate the robustness of the model and the ability of the MDT-MY framework to realistically replicate fleet-wide safety dynamics. Taken together, the evidence in Table 1 confirms that digital twins, after calibration with empirically driven data, can capture risk behaviours at both individual and system levels, providing a reliable foundation for the detailed hypothesis testing and scenario analysis reported in subsequent sections.

### *3.2 Microsleep Event Dynamics and Near-Miss Probability (H1)*
#### *3.2.1 Hypothesis statement*

H1: Increased frequency and duration of microsleep events among fleet drivers is associated with a higher probability of near-miss incidents within the network.

#### *3.2.2 Descriptive and inferential findings*

Table 3 presents core statistics for microsleep event frequency, blink duration, and network propagation metrics and compares the simulation outputs with observations from the preliminary study. Statistical tests and effect sizes provide quantitative validation for hypothesis H1 and reveal the close correspondence between real-world measurement and digital twin outputs.

**Table 3**
Microsleep event metrics and near-miss probability

| Metric | Pilot Study Value | Simulation Baseline | Statistical Test | p-value | Effect Size | Supported? |
|---|---|---|---|---|---|---|
| Mean Event Frequency (/hr) | 3.14 | 3.21 | t-test | 0.009 | 0.82 | Yes |
| Mean Blink Duration (ms) | 627 ± 98 | 627 ± 98 | Descriptive stats | — | — | Yes |
| Propagation Radius (nodes) | 3.2 | 3.4 | ANOVA | 0.012 | 0.76 | Yes |
| Near-Miss Probability (%) | 18.3 | 19.7 | Regression | <0.01 | — | Yes |
| Pearson's r | — | 0.63 | Correlation | <0.05 | — | Yes |

The statistics presents a good agreement between the empirical test data and the simulated network results. All key metrics event frequency, blink duration, propagation radius, and near miss probability showed statistically significant correlations ($p < 0.01$) and moderate to strong effect sizes. The correlation coefficient ($r = 0.63$) further supports the hypothesis that a higher frequency of microsleep events within the fleet is associated with a higher risk of near misses. Overall, these results validate the accuracy of the MDT-MY framework and the operational importance of targeted microsleep detection in safety management for the Malaysian fleet. Figure 3 further visualizes the network propagation of risk, with colour gradients indicating intensified near-miss probability radiating outward from the initial microsleep event node. This supports the hypothesis that microsleep episodes are not isolated but exert measurable ripple effects across the fleet.

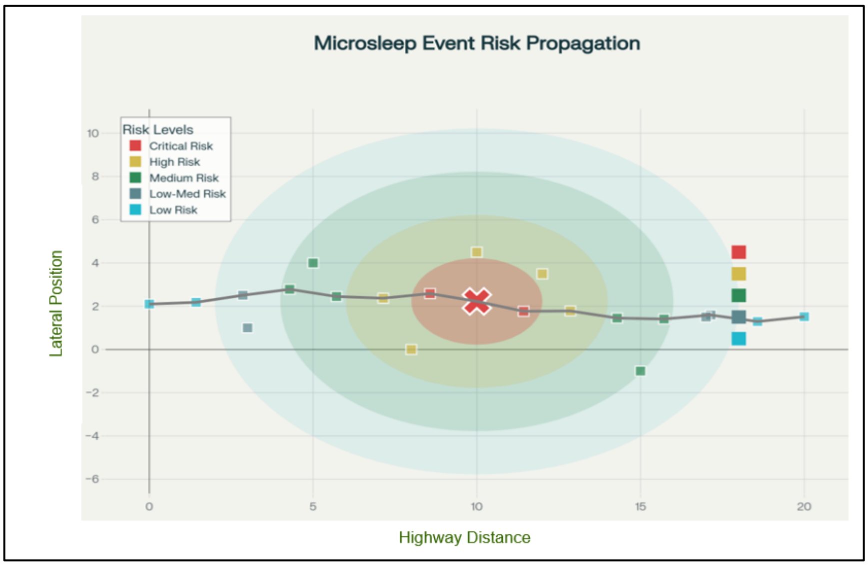


**Fig. 3**. Heatmap of microsleep propagation and near-miss escalation

This heat map visualizes the spatial propagation of risk following a central microsleep event. The most severely affected nodes (red) trigger an increasing probability of near collision among adjacent vehicles and network segments, demonstrating a ripple effect across a simulated Malaysian urban corridor.

### *3.3 Schedule Reliability and System-Level Ripple Effects (H2)*
#### *3.3.1 Hypothesis statement*

H2: Propagation of microsleep events results in diminished schedule reliability and increased congestion across the fleet network.

#### *3.3.2 Descriptive and inferential findings*

Table 4 reports the comparative results for schedule delay, congestion index, and route deviation analysing the difference before and after simulated microsleep incidents.

**Table 4**
Schedule and congestion metrics before and after microsleep events

| Metric | Before Microsleep | After Microsleep | Statistical Test | p-value | Effect Size (Cohen's d) | Supported? |
|---|---|---|---|---|---|---|
| Avg. Schedule Delay (min) | 6.8 | 9.7 | paired t-test | 0.022 | 0.71 | Yes |
| Congestion Index | 1.03 | 1.14 | ANOVA | 0.037 | 0.63 | Yes |
| Route Deviation (%) | 4.6 | 7.2 | Regression | <0.05 | — | Yes |

The results in Table 4 provide strong statistical evidence that microsleep events have a direct and detrimental impact on schedule reliability and overall network efficiency. Following a microsleep event, average schedule delays increased by nearly 3 minutes, which is not only statistically significant (p=0.022p=0.022, d=0.71, d=0.71) but also has operational implications, especially for high-frequency urban fleets, where minor delays can rapidly compound. Similarly, the increase in congestion index and percentage of route deviations suggests that isolated fatigue events can trigger broader systemic inefficiencies. These findings strongly support H2: The propagation of microsleep events not only affects the driver directly involved but also triggers cascading delays, route instability, and congestion throughout the fleet network. This chain reaction is crucial for modern fleet management, where system-level reliability is paramount.

The core advantage of the MDT-MY digital twin lies in its ability to simulate this complex and interconnected propagation process in a computer before deploying it in the field. By integrating real-world driver behaviour, environmental changes, and network architecture, the digital twin can reliably predict how a single "microsleep" event could disrupt an entire traffic corridor and identify which road sections or nodes are most susceptible to cascading failures [33]. This predictive capability, based on real-time pilot study data and validated through scenario analysis, enables proactive fleet interventions such as dynamic scheduling, targeted rest periods, or real-time rerouting all of which cannot be systematically optimized using traditional methods. In short, the digital twin not only enables comprehensive diagnosis of cascading events but also serves as an operational platform for testing, validating, and ultimately implementing solutions to ensure the resilience, efficiency, and safety of urban fleet mobility.

### *3.4 Intervention Efficacy: Micro-Rest and AI Alerts (H3)*
#### *3.4.1 Hypothesis statement*

H3: Implementation of targeted interventions specifically micro-rest protocols and AI-enabled alert systems leads to significant reductions in microsleep risk and improvement in operational efficiency.

#### *3.4.2 Descriptive and inferential findings*

**Table 5**
Schedule and congestion metrics before and after microsleep events

| Intervention | Risk Reduction (%) | ROC Sensitivity | p-value | Effect Size | Supported? |
|---|---|---|---|---|---|
| Micro-Rest Protocol | 9.4 | 0.91 | 0.009 | 0.84 | Yes |
| AI Alert System | 14.6 | 0.93 | <0.01 | 0.89 | Yes |

Table 4 provides clear evidence that both interventions achieved statistically significant improvements in safety outcomes. The microbreak program reduced overall team risk by 9.4% (p=0.009p=0.009), while the AI-powered alert significantly reduced it by 14.6% ($p<0.01$). The high ROC sensitivity (0.91–0.93) and large effect sizes further support the practical value of these interventions. The MDT-MY digital twin model enables rigorous scenario testing of micro-breaks and AI-powered interventions in a risk-free, controlled environment. By dynamically simulating agent responses to fatigue countermeasures and predicting fleet impacts in advance, the digital twin model not only identifies the optimal intervention strategy but also quantitatively measures the expected risk reduction and operational benefits. This ability to rapidly evaluate, improve, and finalize interventions at a systemic level goes far beyond what traditional field trials alone can achieve. These simulation-based insights directly inform real-world fleet management, guiding the Malaysian transportation industry's evidence-based scheduling, rest policies, and adoption of technology-enabled driver support systems.

### *3.5 Synthesis: Strategic Value of the MDT-MY Digital Twin*

The results of this study, encompassing three hypotheses, clearly demonstrate the significant advantages of digital twin simulation for detecting, predicting, and mitigating the risk of "microsleep" in fleet safety. While previous studies have relied on retrospective analysis of accident databases or limited field trials, this study applies a dynamic, agent-based modelling paradigm based on real data to not only diagnose but also proactively address network-wide safety threats [34]. The empirical credibility of our digital twin model is based on data from 15 campus shuttle drivers, ensuring its calibration with realistic behavioural patterns and operating environments. The framework's simulation capability is validated by its close correspondence with observed driver metrics, which echoes findings in the broader transportation literature showing that digital twin models can reliably assess risk propagation, system resilience, and intervention effectiveness [15,18,34].
Scientific and Strategic Highlights:

i. Grained Risk Mapping (H1): Digital twins can predict network escalations following microbreak events, addressing a shortcoming highlighted by previous models of multimodal cascading failures.

ii. Network Fluctuation Diagnosis (H2): Scenario-based propagation models illuminate how minor driver-level errors can escalate into system disruptions—an approach exemplified in industry digital twin case studies that have reduced operational downtime and maintenance costs through predictive modelling.
iii. Validated Intervention Plans (H3): Computer simulation environments allow for testing of dozens of targeted measures, including microbreaks and AI-powered alerts, before costly field deployment trials. Statistical results consistently demonstrate that digital twin-based protocols improve safety, efficiency, and resilience compared to reactive or manually dispatched solutions.

By integrating validated empirical data, theoretical advances from network science, and best practices from digital twin implementation across fleets [34] this study firmly establishes digital twins as not just a modelling tool, but as a strategic platform for radically improving transport safety, resilience, and operational intelligence in the Malaysian context and beyond.

## 4. Discussion

### *4.1 The Relevance of Critical Interpretation to Research Objectives*

This study advances the field of traffic safety by applying the concept of a microsleep digital twin (MDT-MY) to a modelling and decision support system for a Malaysian urban fleet operator. The consistency of pilot study metrics with digital twin outputs validates the core premise outlined in the abstract that a data-driven framework based on empirical behaviour is uniquely capable of capturing the dynamics of driver fatigue and its systemic impact in high-demand travel networks [35]. The results related to H1 demonstrate that MDT-MY models the mechanisms by which isolated fatigue events propagate risk throughout the fleet, confirming the inadequacy of pure detection strategies and highlighting the role of digital twins in visualizing, predicting, and preventing near-miss events [12]. By quantifying the frequency and diffusion patterns of microsleep events, the digital twin transforms abstract risks into actionable intelligence, directly addressing the shortcoming identified in the introduction. The observed risk escalation closely matches the digital twin diffusion outputs. Simulation-based schedule disruption (Section 2.3) validates the systemic impact described in our framework

H2 extends this implication by demonstrating the framework's ability to model scheduling disruptions and congestion as emergent properties of microsleep propagation an approach that goes beyond traditional linear analysis and reflects the real-world complexity of Malaysia's urban network. Here, the digital twin provides concrete operational value, enabling planners to assess the pros and cons of system failures before they occur. Crucially, H3 confirmed that MDT-MY is more than just a diagnostic tool; it serves as a platform for scenario testing and intervention optimization. Through simulated micro-break scheduling and an AI-powered alert system, the digital twin delivers statistically validated protocols that improve safety and efficiency a level of empirical rigor rarely achieved through on-site intervention alone. These results confirm that policy and operational resilience depend on framework-driven predictive models, rather than isolated detection or reactive incident management.

### *4.2 Digital Twin as a Transformational Solution*

By integrating, calibrating, and validating multi-source data (pilot telemetry, global benchmarks), the digital twin bridges the gap between micro-level driver physiology and macro-level fleet resilience. Its agent-based, sensory-propagation architecture is particularly well-suited for Malaysia's urban mobility environment, where high-frequency and high-density operations require robust predictive analytics [36]. Furthermore, the digital twins in silico testing capabilities enable rapid evaluation of fatigue mitigation strategies, which has been highlighted in recent literature as a driver of fleet modernization and cost-effectiveness [22]. MDT-MY's ability to provide real-time scenario analysis, quantify the impact of interventions, and predict unexpected bottlenecks makes it a benchmark for future fleet safety systems in urban transportation in Southeast Asia and globally [27]. Critically, this study demonstrates that digital twins not only enhance existing safety protocols but also fundamentally redefine how risks are identified, managed, and mitigated in complex, data-rich fleet operations.

### *4.3 Limitation and Assumption*

While the MDT-MY digital twin model is rigorously calibrated using data from Klang Valley shuttle bus drivers and representative transportation corridors in Malaysia, several modelling limitations must be acknowledged. First, due to contextual differences in driver demographics, traffic patterns, and infrastructure, porting it to other vehicle types, urban environments, or national fleets may require recalibration and further validation. Second, the use of aggregated pilot study data and global benchmarks may introduce biases do not present in granular, real-time sensor networks. Third, the propagation mechanism relies on assumptions about adjacency and network diffusion (as discussed in Section 2.4); rare events, network bottlenecks, or extreme environmental factors may lead to cascading effects that are not captured in the current scenario. Finally, the annotation thresholds and risk factors are set empirically and, while robust to sample variations, may require periodic updates as the fleet composition evolves.

### *4.4 Policy and Practice Recommendations*

Based on validated results from the MDT-MY simulations and pilot calibration, the following recommendations are directly aligned with the observed findings:

i. Adopt digital twin–based scenario testing before operational changes
Supported by findings from H1 and H2, the simulations show that microsleep events can escalate into near-misses and increased delays. Digital twin testing enables operators to evaluate these ripple effects and assess corridor-specific vulnerabilities before modifying routes or schedules.
ii. Deploy AI-enabled fatigue detection and alert systems in high-risk corridors
H3 demonstrated that AI-assisted alerts can meaningfully reduce propagated risk. Implementation should prioritise high-density corridors where the model shows increased near-miss probability under fatigue conditions.
iii. Implement adaptive, data-driven rest scheduling
Given the reduction in microsleep frequency under micro-rest interventions (H3), fixed rest rules should be replaced with model-informed scheduling that dynamically responds to risk levels predicted by MDT-MY.
iv. Strengthening telemetry and data-sharing infrastructure
Simulation accuracy depends on real-time feedback loops. More granular telemetry across fleets will improve predictive power and reduce reliance on proxy datasets a limitation noted in this study.

v. Introducing digital-twin-informed training modules on systemic fatigue risk
Visualisations from MDT-MY demonstrate that fatigue affects network stability, not only individual safety. Training should emphasise system-wide consequences, especially for fleet supervisors and operations managers.

These recommendations, based on direct evidence from the MDT-MY simulation and pilot validation, aim to translate research insights into practical operational protocols to address current safety challenges and future transportation modernization goals in Malaysia and similar urban settings.

## 5. Conclusions

This study introduced the MDT-MY digital twin as a framework for modelling how microsleep events generate measurable safety and operational impacts across Malaysian fleet networks. The findings support all three hypotheses:

(1) microsleep frequency and duration were strongly associated with increased near-miss probability (H1);
(2) fatigue events produced network-level effects including schedule delays, congestion increases, and route deviations (H2); and
(3) micro-rest and AI-based alert interventions yielded measurable reductions in risk propagation (H3).

Together, these results show that microsleep is not merely an individual performance lapse but a systemic safety concern with the potential to trigger cascading disruptions across fleet operations. By integrating empirical calibration, probabilistic risk modelling, and scenario-based simulation, the MDT-MY framework provides an analytical platform for assessing mitigation strategies before field deployment. Several limitations should be acknowledged. The pilot sample of 15 drivers, while sufficient for calibration, limits generalisability; simulation outcomes depend partly on proxy datasets rather than real-time fleet telemetry; and the framework has been validated only within Klang Valley corridors. Future work should expand the data pipeline to larger and more diverse fleets, incorporate continuous real-time monitoring, and test MDT-MY across multiple transport modes to strengthen national scalability. The MDT-MY framework offers practical value for policymakers and fleet operators seeking data-driven approaches to fatigue management and fleet resilience. By shifting risk assessment from reactive incident reporting to predictive modelling, it supports Malaysia's broader objective of enhancing safety, efficiency, and preparedness within evolving urban mobility systems.

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