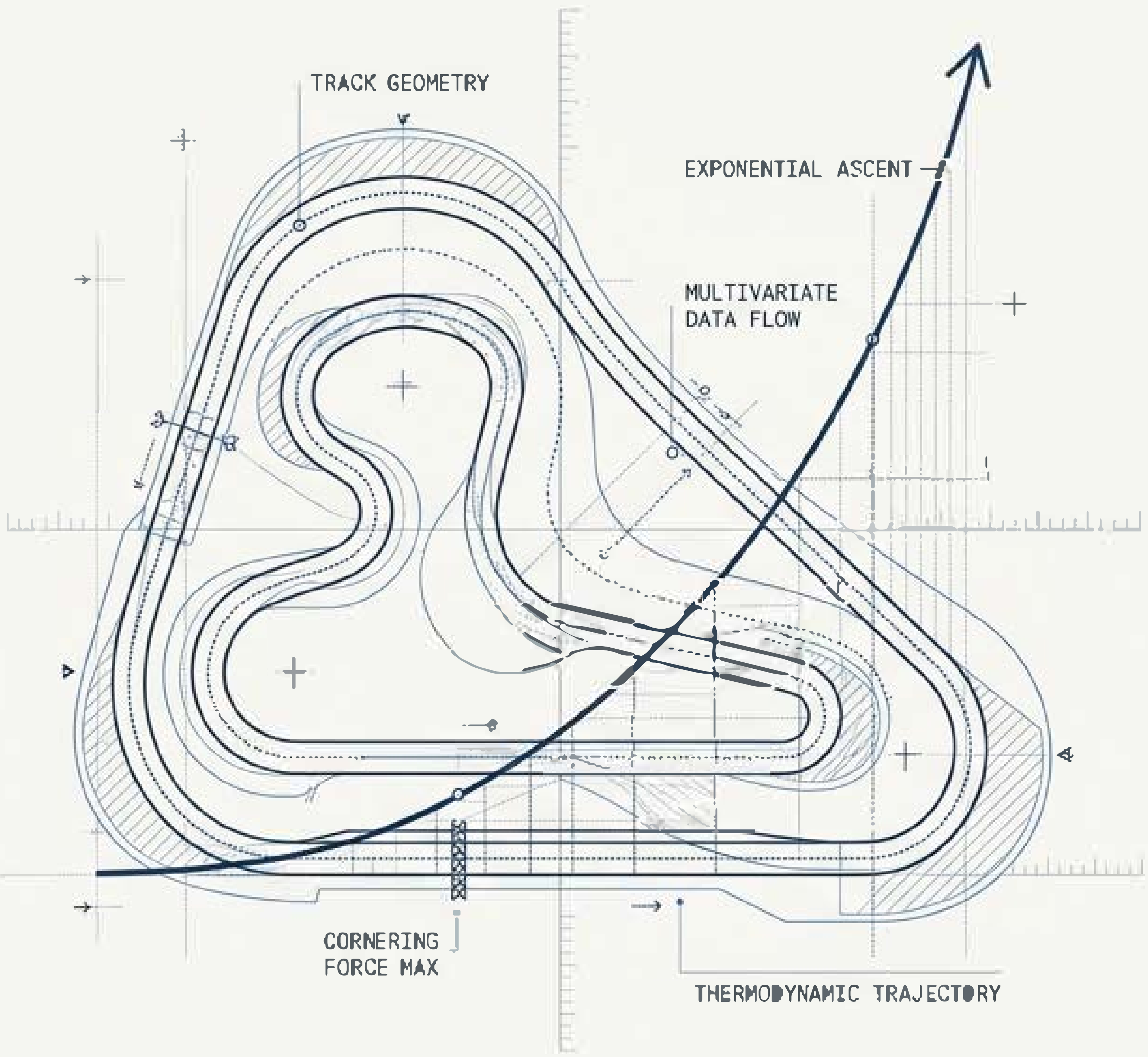
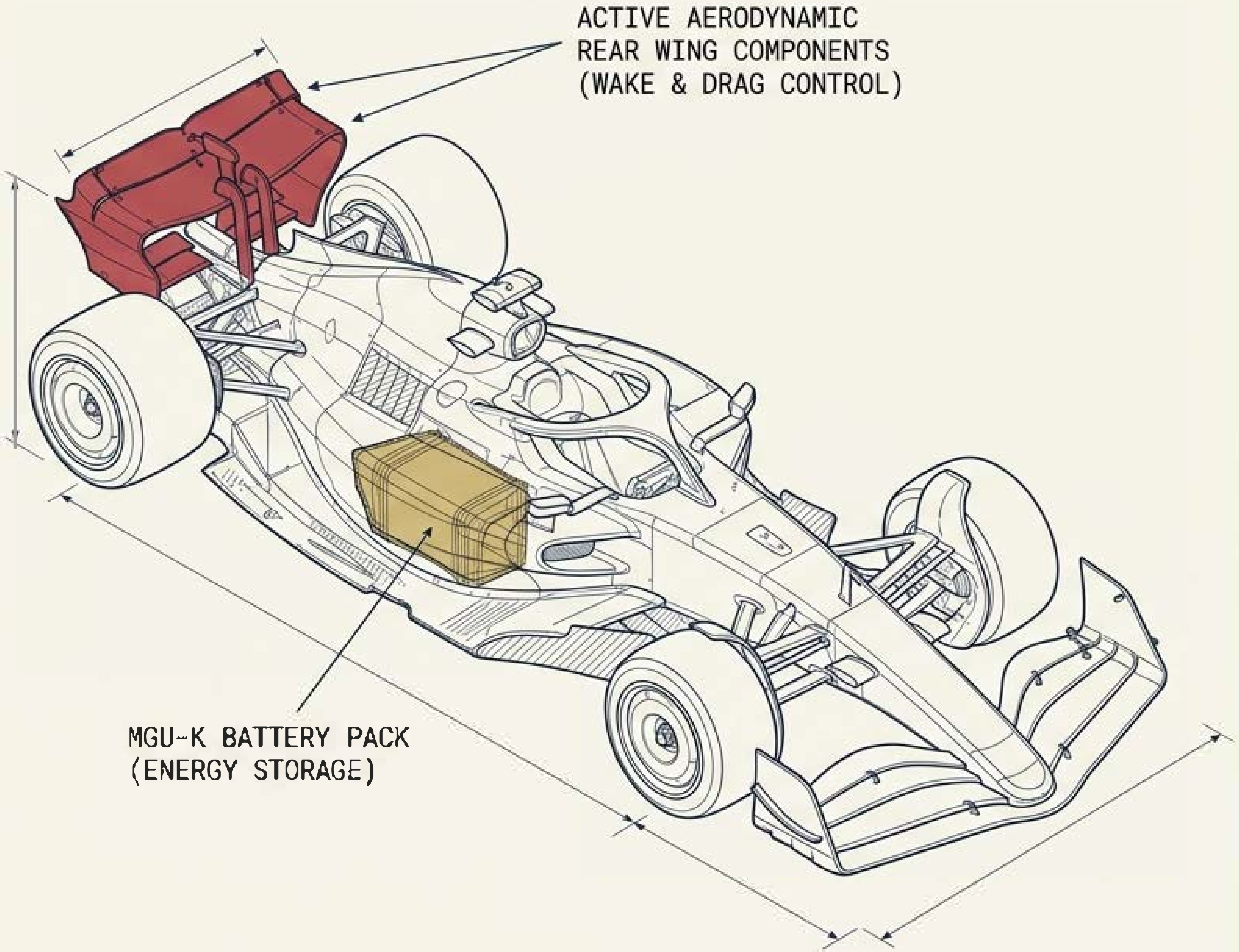


TyrePIML: Real-Time Physics-Informed Machine Learning and Game Theory for Multi-Agent Motorsport Strategy

A novel edge-computing framework for predicting non-linear tire degradation and dynamic rival responses under 2026 energy constraints.

Mina R. Narman
Acıbadem Mehmet Ali Aydınlar University

Husnu S. Narman
Marshall University



The 2026 Challenge: Beyond Intuition

Telemetry Overload

Hundreds of high-frequency sensors transform strategy from human intuition into a rigorous computational problem.

The 2026 Energy Constraint

New power unit regulations drastically increase reliance on electrical energy (MGU-K) and introduce active aerodynamic wake penalties.

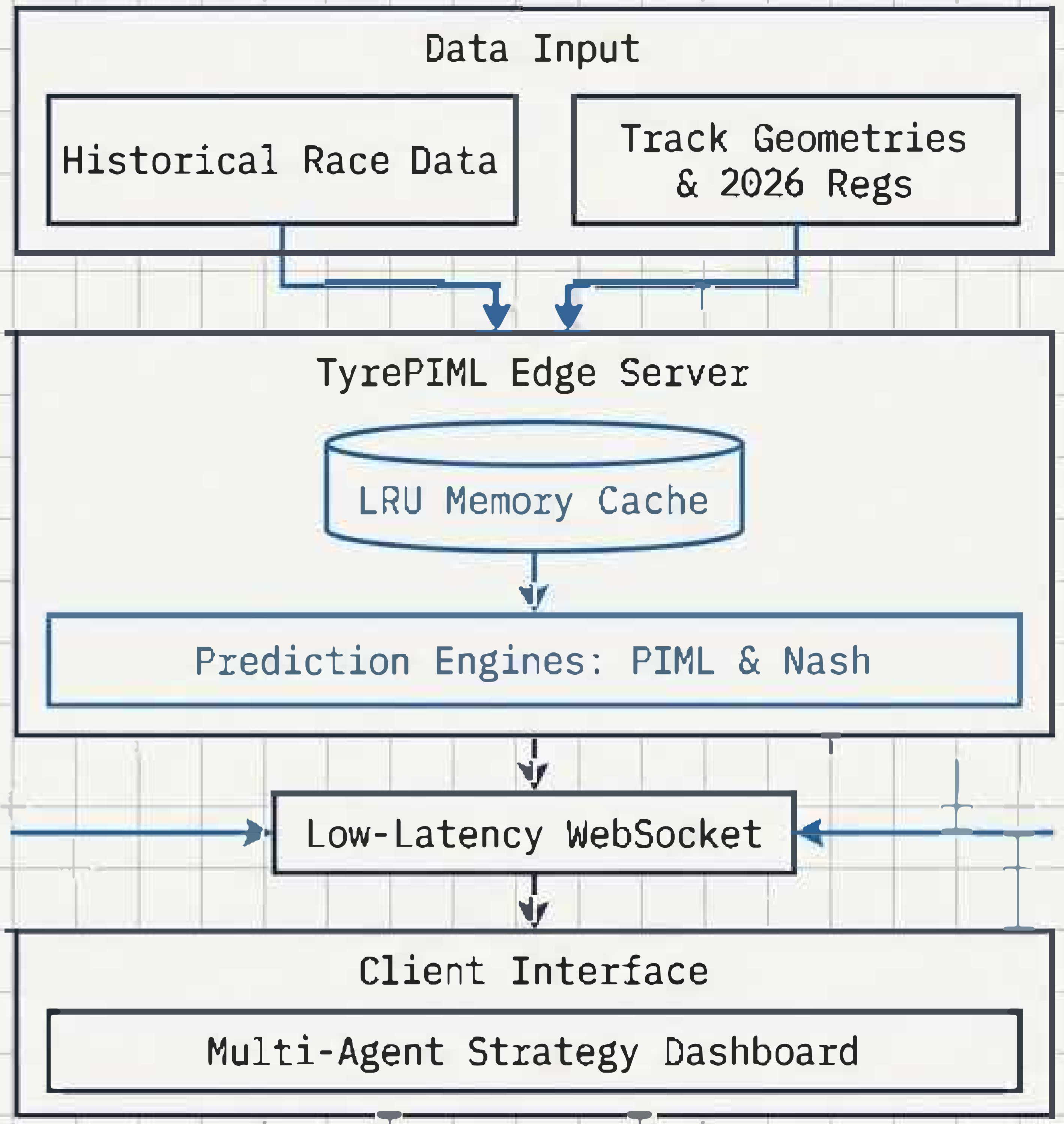
The Multi-Agent Reality

Racing is an adversarial game. Traditional static models fail to anticipate dynamic rival actions and real-time physical constraints.

The Research Gap Matrix

Dimension	Traditional Models	TyrePIML Innovation
Data Approach	Pure historical lap time extrapolation	Real-time physical & thermodynamic constraints
Tire Modeling	Purely data-driven RNNs; consistently misses the failure cliff	Physics-Informed Machine Learning (PIML)
Game Theory	Offline or mathematically cooperative models	Real-time, Energy-Constrained Nash Equilibrium
Architecture	HTTP Polling (High I/O storage bottlenecks)	WebSocket + LRU Edge Cache (Near-zero latency)

Pillar 1: Asynchronous Edge Architecture



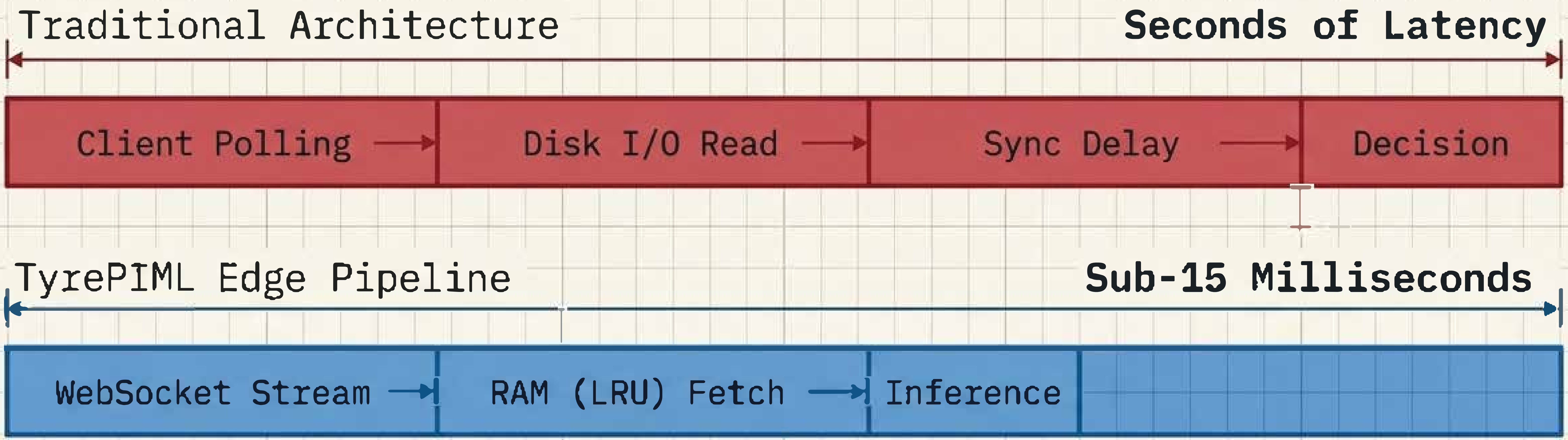
WebSocket Tunnel

Replaces HTTP request-response cycles with a persistent, bidirectional tunnel. Telemetry is actively pushed the exact millisecond a lap completes.

LRU In-Memory Cache

Eliminates disk retrieval times by loading active race subsets directly into Random Access Memory (RAM), transforming the engine into a true edge-computing node.

The Latency Bottleneck: Seconds vs. Milliseconds

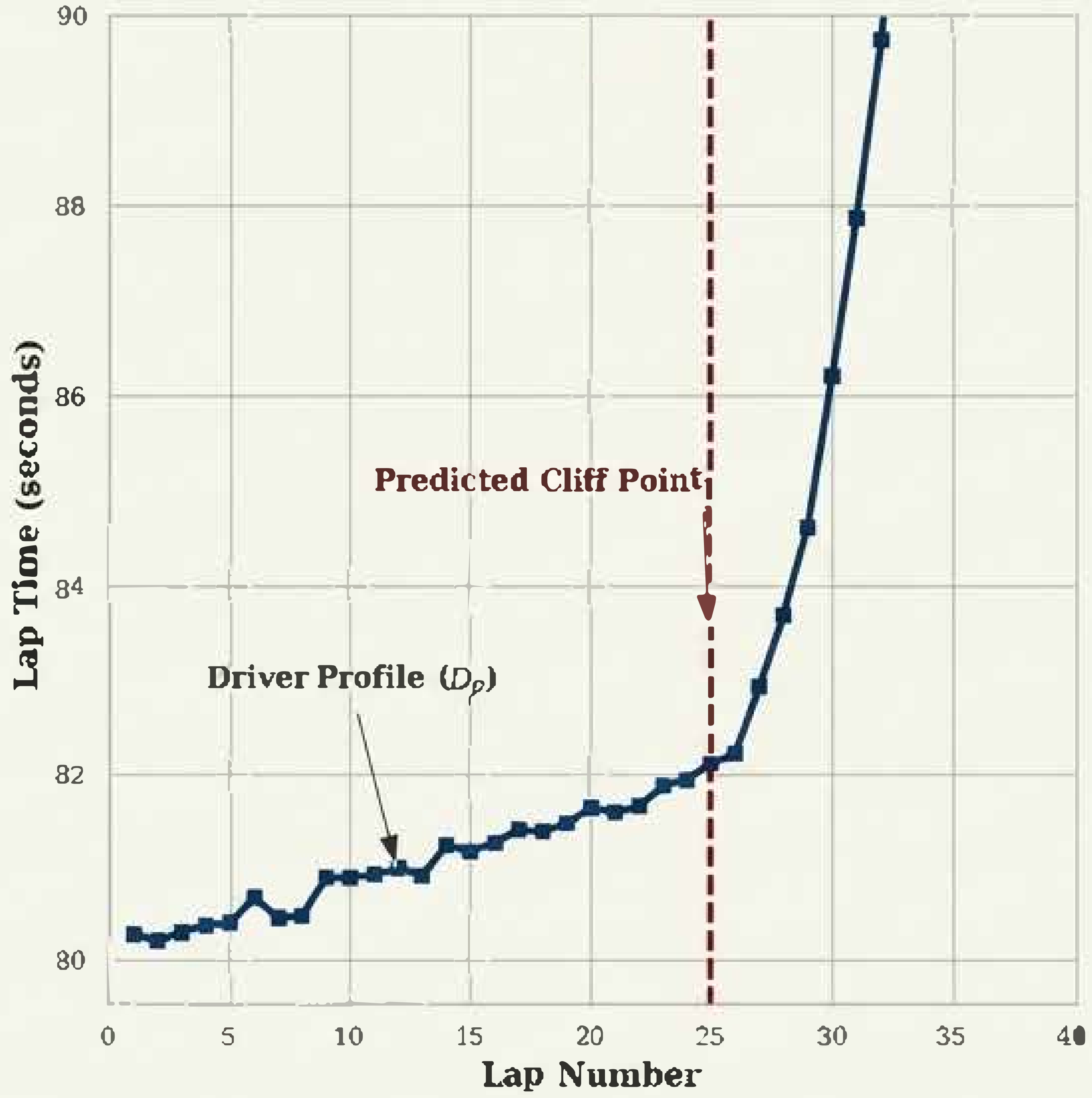


In competitive motorsport and intelligent transportation networks, a latency of mere seconds renders a strategic pit-wall decision physically obsolete. TyrePIML executes inference without halting live telemetry feeds.

Pillar 2: Thermodynamics & The Cliff

The Thermodynamic Reality

Degradation is not purely a function of time or distance. It is a highly sensitive, non-linear thermodynamic process.



Physics-Informed LSTM

By embedding real-time physical parameters, TyrePIML prevents the neural network from generating mathematically valid but physically impossible straight-line extrapolations.

$$X_t = [\ L_t,\ T_{track},\ C_{type},\ D_p\ ]$$

L_t: Elapsed Laps

Current lap number during the stint.

T_track: Dynamic Track Temp

Real-time surface temperature measurement.

C_type: Categorical Compound Coefficient

Encoded value for specific tyre compound.

D_p: Driver Management Profile

A continuous scalar comparing ego-vehicle drop-off against the grid average.

$D_p > 1.0$ = Poor management, mathematically accelerating the predicted cliff.

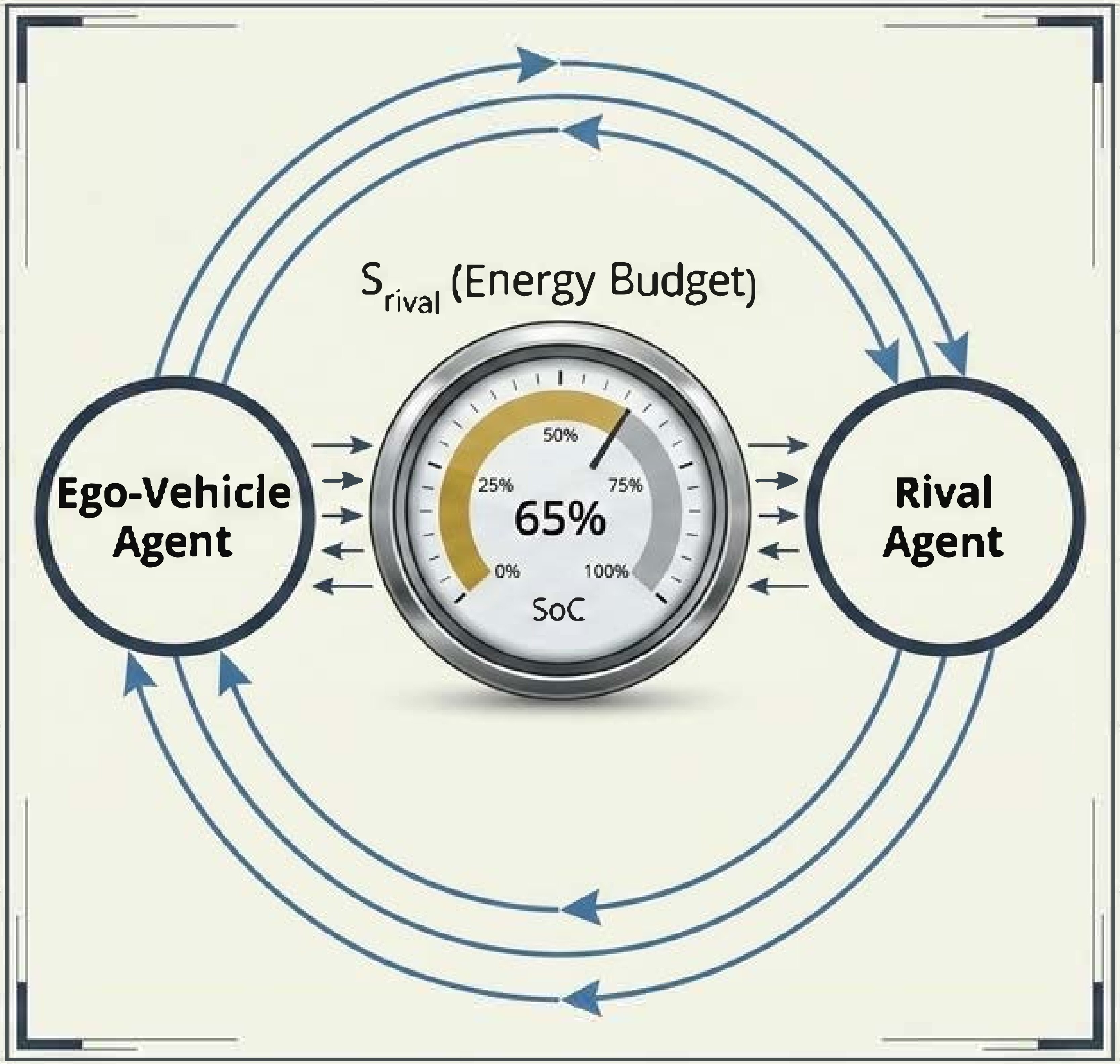
This input vector heavily constrains the network, forcing highly reliable Remaining Useful Life (RUL) outputs.

Pillar 3: Energy-Constrained Game Theory

The Adversarial Ecosystem

Motorsport is a non-cooperative game. An aggressive maneuver like an undercut forces dynamic rival counter-actions.

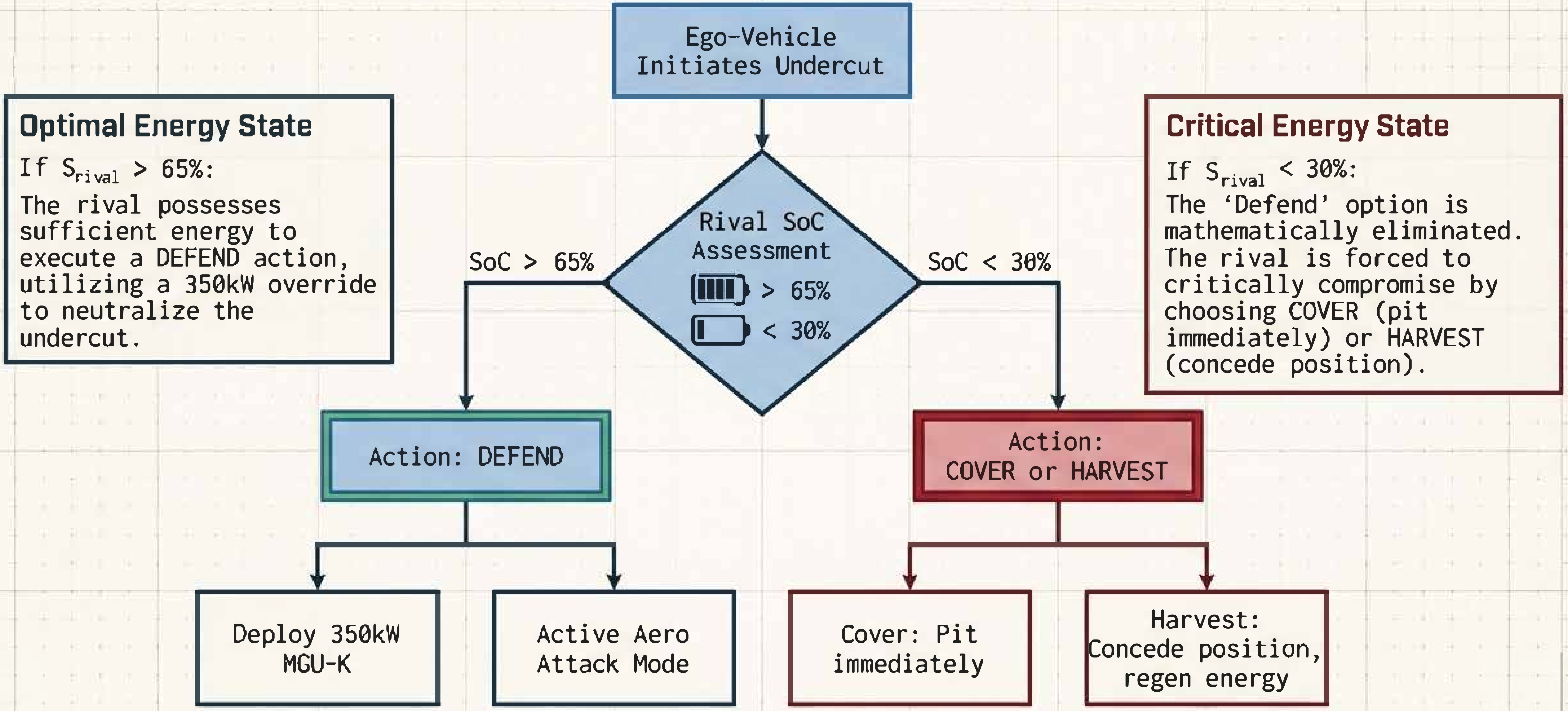
TyrePIML utilizes Nash Equilibrium to maximize track position utility.



The MGU-K Constraint

The rival's action space ($A = \{\text{Defend, Cover, Harvest}\}$) is strictly dictated by their real-time MGU-K battery state.

Nash Equilibrium Decision Matrix: Rival SoC Constraints



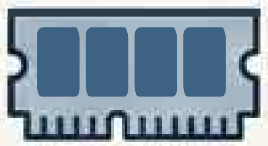
Synthesis: The 15-Millisecond Execution Loop

1. Ingestion

Telemetry triggers via continuous WebSocket.

2. Edge Fetch

LRU Cache loads track & compound physics directly to RAM.



3. PIML Inference

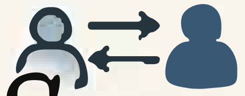
LSTM processes X_t and D_p, forecasting the exact non-linear cliff point.

X_t

D_p

4. Nash Evaluation

Game Theory module assesses S_{rival} and predicts adversarial responses.



S_{rival}

5. Output

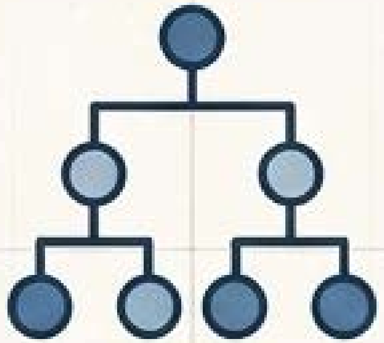
Optimal unified strategy pushed to Client Strategy Strategy Dashboard.

Total Execution Time: < 15.0 ms

Experimental Setup & Baselines

Simulation Environment

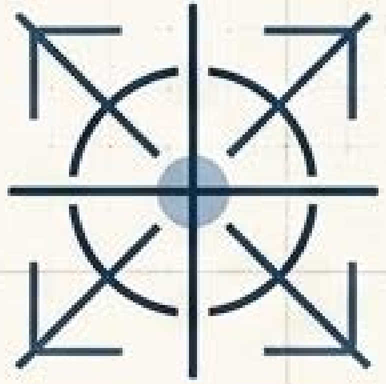
Historical telemetry datasets strictly modified to reflect anticipated **2026** aerodynamic wake and electrical deployment parameters.



Baseline Competitors

Validated against non-physical models:

- **Baseline RF**: Purely data-driven Random Forest.
- **Standard LSTM**: Deep learning without the D_p scalar or thermodynamic constraints.



Evaluation Metrics

Evaluated strictly on:

- Predictive accuracy of the non-linear cliff (**Mean Absolute Error**).
- Computational **latency** required for live telemetry edge deployment (**ms**).

Empirical Results: Performance Validation

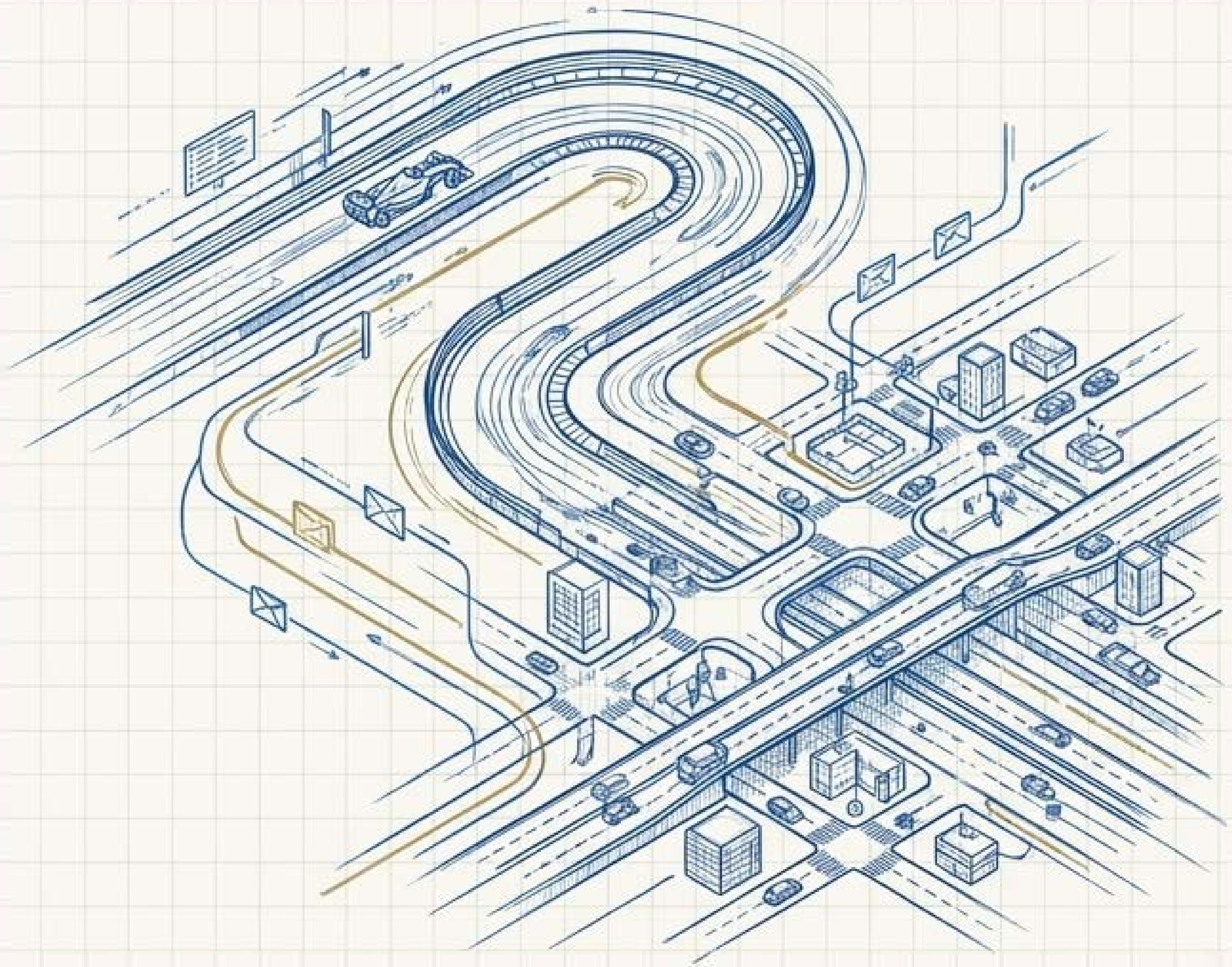
	Cliff Pred MAE	Latency
Baseline RF	Cliff Pred MAE = 3.8 Laps	Latency = 45.0 ms
Standard LSTM	CliffPred MAE = 2.4 Laps	Latency = 22.5 ms
TyrePIML - Proposed	**Cliff Pred MAE = 1.2 Laps**	**Latency = 14.2 ms**

Key Insight: Integrating the D_p scalar and thermodynamic constraints halves the prediction error compared to a standard LSTM. The LRU/WebSocket edge architecture **cuts polling latency by 68%**.

Systemic Limitations & Future Work

Sensor Noise Reality	Deterministic vs. Stochastic	Future Integration
The current framework assumes highly accurate data streams. Real-world telemetry pipelines are inevitably susceptible to packet loss and sensor noise.	The Game Theory module currently relies on fixed deterministic MGU-K thresholds. It fails to account for stochastic driver errors or unpredictable race interruptions (Safety Cars).	Transitioning from static Nash Equilibrium matrices to active Reinforcement Learning (RL) agents capable of dynamically adapting to volatile, probabilistic environments.

Broader Impacts: Intelligent Transportation (ITS)



Connected & Autonomous Vehicles (CAVs)

Multi-agent adversarial racing mathematically mirrors non-cooperative trajectory planning in dense, high-speed traffic.

Commercial Fleet Optimization

Real-time energy prediction and game-theoretic modules can dynamically optimize battery SoC routing for commercial hybrid-electric fleets.

V2X Infrastructure

The ultra-low latency WebSocket pipeline serves as a scalable, edge-computed blueprint for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication.

The TyrePIML Paradigm

Successfully bridging the gap between offline data analytics and the real-time physical realities of 2026

The Core Achievement

By unifying asynchronous edge-computing, physics-informed machine learning, and dynamic game theory, TyrePIML reduces predictive error by 50% and latency to under 15 milliseconds.

The Final Takeaway

Extreme motorsport engineering yields scalable, physics-informed computational solutions for the future of autonomous mobility.