F1 ERS Deployment Analytics Project

This document provides a complete explanation of the F1 ERS Deployment Analytics Project, covering the intricacies of a Formula 1 hybrid powertrain, the role of the Energy Recovery System (ERS), and how Data Science (DS), Machine Learning (ML), Reinforcement Learning (RL / Agentic AI), and Generative AI (GenAI) come together in this portfolio project.

# 1. Understanding the F1 Hybrid Powertrain and ERS

Modern Formula 1 cars use a hybrid power unit that combines a turbocharged internal combustion engine (ICE) with electric motor-generator units (MGUs). These MGUs recover energy under braking (MGU-K) and from exhaust gases (MGU-H). The recovered energy is stored in the Energy Store (ES) and can later be deployed to boost performance.

Key ERS components:  
- MGU-K: Motor Generator Unit – Kinetic. Harvests braking energy.  
- MGU-H: Motor Generator Unit – Heat. Recovers energy from the turbocharger.  
- ES: Energy Store (battery).  
- CE: Control Electronics, governing energy flow.  
- Deployment: Using stored energy to provide additional power (up to 160hp boost).  
- Harvesting: Regenerating energy during braking zones or from exhaust gases.

Deciding when to harvest and when to deploy is crucial. Over-harvesting can reduce speed, while suboptimal deployment wastes precious energy. Teams carefully map ERS strategies for straights, corners, overtakes, and defensive scenarios.

# 2. Project Motivation

The project simulates F1 telemetry to explore where and how ERS should be deployed to maximize lap time gains. It addresses questions such as:  
- Where on the lap is deployment most effective?  
- How much lap time can be saved with optimal deployment?  
- How efficient is the ERS system in terms of seconds gained per MJ deployed?

# 3. Data Science (DS)

Data Science forms the backbone of the project. We generate synthetic telemetry for Monza, including speed, throttle, brake pressure, gear selection, battery state, harvested energy, and deployed energy. This synthetic dataset mimics real telemetry while being self-contained.

Feature engineering steps:  
- Brake %, throttle %, and battery % normalization.  
- Segmentation of lap into fixed-length segments.  
- Aggregation of deployed/harvested energy and estimated time saved.  
- Lap-level summaries including lap time and efficiency (s/MJ).

# 4. Machine Learning (ML)

Machine Learning techniques help analyze correlations in the data. Examples:  
- Predicting lap times with/without deployment.  
- Analyzing the efficiency distribution across laps.  
- Identifying patterns where deployment leads to the most gains.

# 5. Reinforcement Learning (RL / Agentic AI)

The project implements a PPO (Proximal Policy Optimization) agent using Stable-Baselines3. The RL environment simulates battery charge, braking events, and lap progression. The agent learns a deployment strategy that balances harvesting, deployment, and lap time minimization.

Reward shaping:  
- Negative reward for time spent (penalizes longer laps).  
- Bonus for deploying ERS effectively.  
- Penalty for braking (encourages energy efficiency).

The PPO learning curve (ppo\_real\_rewards.png) shows cumulative rewards per lap, indicating how the agent improves its policy.

# 6. Generative AI (GenAI) and Retrieval-Augmented Generation (RAG)

The project integrates a RAG pipeline to allow natural language queries over ERS deployment events. FAISS is used to build a vector index from deployment summaries. A SentenceTransformer encodes text, enabling semantic search. Queries retrieve relevant events, which are passed into a local LLM (optional via ctransformers).

This component demonstrates how GenAI can act as a conversational race engineer, answering questions like:  
- 'Which lap had the best ERS efficiency?'  
- 'Where should I deploy for overtaking?'

# 7. Visualization and Gradio Dashboard

The Gradio dashboard ties everything together with interactive tabs:  
- ERS Analysis: Show deployment events and lap summaries.  
- RL / Agent: Display PPO episode reward learning curve.  
- Assistant: Query the LLM about deployment strategy.  
- Report: Auto-generated summary combining DS, ML, RL, and GenAI insights.

Screenshots:  
- PPO Rewards Plot (ppo\_real\_rewards.png): Shows learning progression.  
- Dashboard Tabs: Allow hands-on exploration of ERS strategies.

# 8. Conclusion

This project illustrates how diverse AI disciplines converge in applied scenarios:  
- DS for structured telemetry.  
- ML for insights.  
- RL / Agentic AI for decision-making.  
- GenAI for natural language explanations.

By combining these pillars, the project provides a holistic demonstration of AI applied to the intricacies of F1 hybrid powertrains.

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