2. Architectural Design Foundations

Architectural Restrictions

- **Regulatory Compliance**: GDPR for EU data privacy (anonymized federated learning mandatory); OMF/GBFS interoperability enforced for MaaS APIs; EU Green Deal standards for EV fleets (30% emission tracking required).
- **Technological Constraints**: No proprietary lock-in—open-source core (PyTorch/Flower); edge devices limited to low-power (TinyML <1W); 5G V2X mandatory for telemetry, but fallback to 4G for rural pilots.
- **Scalability Limits**: Initial deployment capped at 1.5K units (3 countries); fractal scaling via Kubernetes, but no more than 10K concurrent streams without sharding.
- **Budget/Deployment**: Greenfield capex €150M; cloud-agnostic (AWS/GCP hybrid); no custom hardware beyond Jetson edges.

Functional Requirements

High-level capabilities derived from PBB PBIs, focusing on core AI orchestration and MaaS flows.

ID	Requirement	Description	Priority

FR-01	Multi-Modal Routing	Generate predictive trip tapestries (e.g., scooter-to-van chains) with <5s latency, integrating GTFS/OMF data.	Must
FR-02	Predictive Rebalancing	Forecast demand and auto-queue vehicle/hub redistributions based on heatmaps (e.g., 30% utilization boost).	Must
FR-03	Equity Optimization	Apply dynamic subsidies and audits for non-citizen/underserved access (e.g., 40% inclusion metrics).	Must
FR-04	Edge Maintenance	Prioritize battery swaps via IoT anomaly detection (e.g., 40% fewer depletions).	Should
FR-05	Habit Personalization	Learn user patterns for mode nudges and green credits (e.g., 35% repeat usage).	Should

Non-Functional Requirements

Quality attributes ensuring resilience, performance, and sustainability in a 100K-unit global scale.

Performance	Real-time predictions; handle 1M daily events.	<3s latency (p95); 95% uptime (SLA).
Scalability	Horizontal auto-scaling for fractal growth.	Support 10x user spike; Kubernetes pods <5s spin-up.
Reliability	Fault-tolerant edge-cloud sync; no single point of failure.	99.9% availability; automated failover in <1 min.
Security	End-to-end encryption; differential privacy for ML.	GDPR/CCPA compliant; zero-trust via Istio.
Maintainability	MMF auto-evolutions; modular microservices.	<20% code churn/year; CI/CD with 80% test coverage.
Sustainability	Energy-efficient edge AI; carbon tracking.	<10% fleet energy waste; 30% emission reduction via optimizations.

Architectural Mechanisms

Cross-cutting enablers for requirements, implemented via design patterns and tools.

Mechanism	Description	Technologies

Event-Driven Communication	Asynchronous streams for telemetry and nudges.	Apache Kafka; MQTT for edge.
Data Privacy & Federation	Anonymized aggregation without central hoarding.	Federated Learning (Flower); Differential Privacy.
Resilience & Monitoring	Circuit breakers for failures; predictive logging.	Istio service mesh; Prometheus/Grafana.
Integration & API Gateway	Standardized handoffs for MaaS.	OMF/GBFS APIs; Kong Gateway.
Deployment & Orchestration	Containerized, auto-scaling pipelines.	Kubernetes; GitOps with ArgoCD.

Architectural Styles Candidates

Evaluated for fit with MaaS demands (scalability, AI integration); selected hybrid for optimal balance.

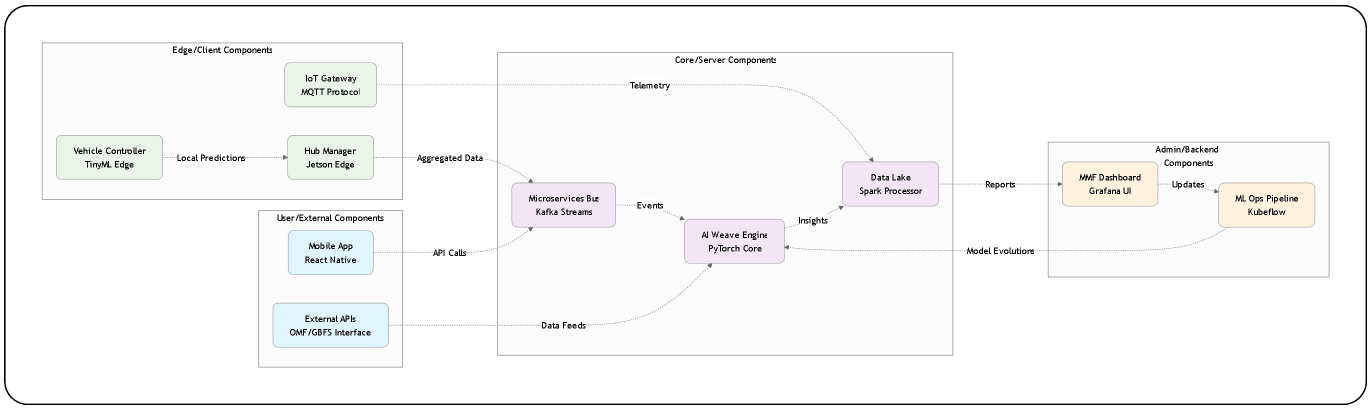
Style	Pros	Cons	Suitability

Microservices	Independent scaling; fault isolation for edge/cloud layers.	Overhead in inter-service calls.	High—core for fractal modularity (chosen).
Event-Driven Architecture	Real-time reactivity for predictions/rebalancing.	Complexity in state management.	High—complementary to microservices.
Serverless	Cost-efficient for sporadic surges (e.g., tourist peaks).	Vendor lock-in risks; cold starts.	Medium—hybrid for non-critical lambdas.
Monolithic	Simpler initial dev for pilots.	Poor scaling for global fleets.	Low—avoided for greenfield ambition.

Primary: Microservices + Event-Driven hybrid, enabling 30% efficiency gains over monolithic peers.

Mermaid UML Components Diagram

This component diagram illustrates key architectural components, interfaces, and dependencies, focusing on the AI Weave Engine as the central orchestrator.



↳ Expand functional requirements

↳ Explore event sourcing

↳ more concise tables