Beacon-X: Autonomous Adaptive Traffic Light System

Present Technology

Intensifying climate extremes are placing increasing strain on public infrastructure. Rising global temperatures are projected to contribute to approximately 250,000 additional deaths annually between 2030 and 2050 [1], while wildfire activity is expected to increase by up to 30 percent by 2050, heightening the need to support large-scale rescue operations [2].

Conventional traffic control systems are grid-powered and centrally managed, optimized for routine operation rather than disaster conditions, with short-duration lead-acid backups inconsistently deployed and inequitably distributed (Figure 1). During power outages, the traffic systems often fail, leaving intersections dark or flashing red. While many “smart city” initiatives enhance everyday traffic efficiency, they fall short during severe crises, as most systems remain dependent on grid power and centralized control, with backup power treated as a temporary fallback rather than a critical operating mode [3].

Figure 1. Present Intersection

History

Traffic control evolved from manual police signaling and mechanical semaphores in the late nineteenth to electrically powered lights in the 1910s, enabling standardized signal timing and improved safety [4]. In mid-twentieth century, automation emerged to synchronize signal timing [5]. In the late twentieth, the integration of sensors, cameras, and automated control enabled adaptive signal systems to adjust timing in response to traffic conditions [6]. Emergency vehicle preemption systems have been added to allow first responders to request green signals at intersections. However, they rely on short-range communication such as infra-red and centralized coordination, limiting their effectiveness when the power systems fail [7].

Future Technology

Beacon-X introduces a paradigm shift in how future infrastructure makes decisions, transforming traffic intersections from passive devices into intelligent edge nodes capable of autonomous, adaptive operation. This transformation is enabled by the integration of dual AIs governing four core subsystems: energy, control, sensing, and communications (Figure 2).

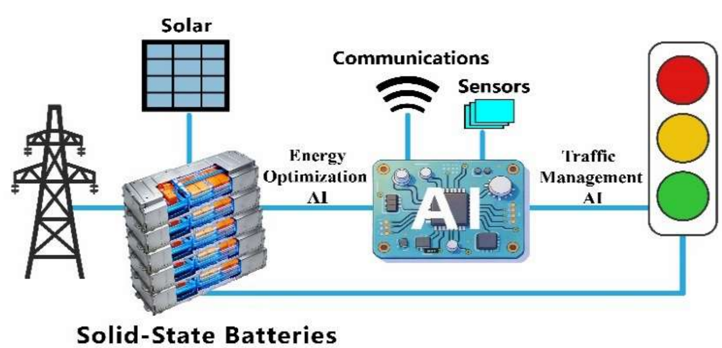

Figure 2. Beacon-X Functional Diagram

Autonomous Energy: Through its Energy Optimization AI, Beacon-X provides uninterrupted, adaptive power using solid-state batteries paired with solar energy harvesting, while continuously monitoring and predicting battery health and readiness.

Solid-state lithium-metal batteries are an emerging technology which replaces liquid electrolytes with solid ionic conductors (Figure 3), representing a structural leap in electrochemistry. Compared with lead-acid storage, solid-state batteries offer order-of-magnitude improvements in performance critical for resilient infrastructure, including a 10× increase in energy density [8] and a 5-10× improvement in cycle life [9]. By eliminating flammable liquid electrolytes, they also offer superior safety and thermal stability, reducing risks of leakage, thermal runaway, and fire that limit lead-acid deployment in outdoor infrastructure [10].

Figure 3. Solid-State Lithium-Metal Battery Structure [11]

Major manufacturers, including Toyota, BMW, and Samsung, have begun pilot production of solid-state batteries, with Toyota announcing initial electric-vehicle shipments with up to a 620-mile driving range by 2028 [12]. While solid-state batteries are expected to play a critical role in energy storage, variability in cycle life and degradation due to interfacial and material heterogeneity remains a challenge for infrastructure deployment [13].

To address this variability and ensure uninterrupted operation, Beacon-X's Energy Optimization AI proactively monitors and predicts battery health, and promptly triggers alerts to municipal traffic authorities when anomalous cells are detected. Rather than relying on static assumptions, it dynamically adapts energy usage to real operating conditions, sustaining energy supply as individual cells age nonuniformly or encounter unexpected conditions.

Solid-state storage is charged by grid and solar under normal conditions and switches to solar-only during outages, while the Energy Optimization AI adapts loads as needed. Solar conversion efficiency is 20-22% now [14] and projected to reach ~30% by 2045 [15].

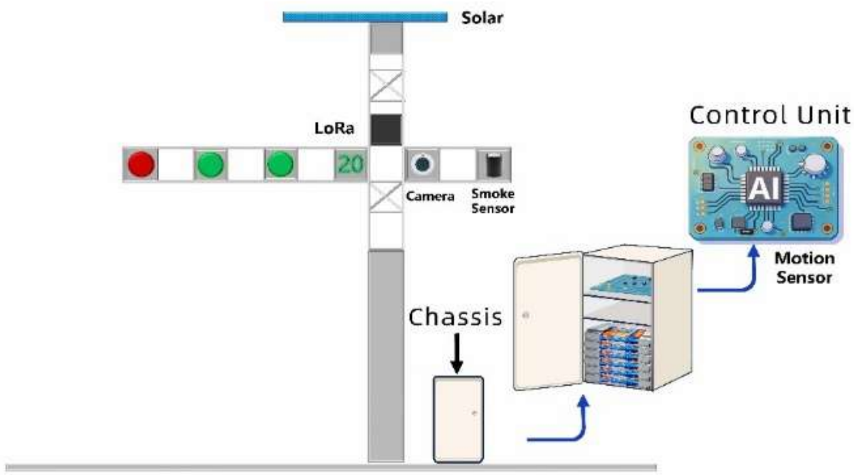

Figure 4. Beacon-X System Design

Multi-Modal Sensing: Beacon-X integrates motion sensors, smoke sensors, and high-definition cameras to detect hazardous conditions and traffic flow (Figure 4). Environmental states are identified through threshold- and pattern-based analysis, with motion sensors triggering alerts during earthquakes and smoke sensors detecting wildfire conditions. Filtered sensor data and real-time video analysis enable congestion inference, emergency vehicle detection, and prioritized control during rescue operations.

Control Unit: The control unit supports edge computing for AI, adaptive signaling, multimodal sensing, and communications. As edge capabilities matures, it enables real-time hazard detection, traffic buildup prediction, and dynamic prioritization of evacuation and emergency vehicles. On-device AI performs two core functions: energy optimization, as detailed in *Autonomous Energy* section, and traffic management. The Traffic Management AI enables intersections to make local decisions without relying on central servers. By fusing sensor inputs with real-time vehicle detection, adaptive timing, and cooperative coordination among neighboring nodes, Beacon-X establishes dynamic green corridors for evacuation and rescue while reducing latency, improving robustness, and eliminating single points of failure.

Resilient Communications: To minimize bandwidth and energy consumption, Beacon-X leverages existing low-power, low-cost Long Range (LoRa) communication to enable resilient, low-latency coordination among neighboring intersections and with traffic control centers (Figure 5). This supports reliable exchange of status information and coordinated control during emergencies. By enabling decentralized cooperation, LoRa provides a scalable communication foundation for Beacon-X's autonomous, resilient architecture.

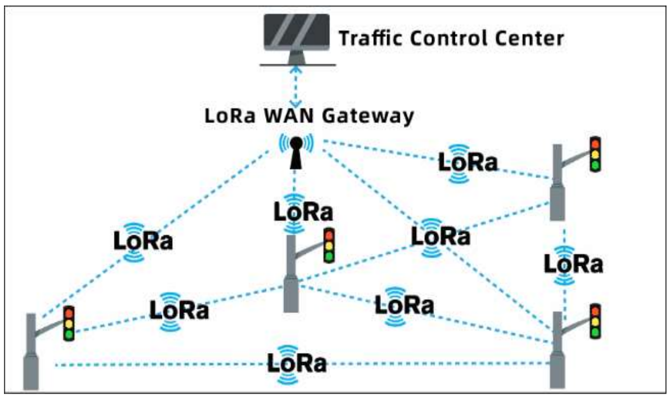

Figure 5. Beacon-X Network Communications

Breakthroughs

Unlike smart city plans which depend on grid power and centralized intelligence with passive backups, Beacon-X delivers a first-of-its-kind architecture with two breakthroughs to enable autonomous, adaptive operation directly at traffic intersections.

Breakthrough I: Edge-Based Energy Optimization AI

Beacon-X pioneers a foundational breakthrough by developing an edge-based Energy Optimization AI that autonomously manages solid-state solar-integrated energy storage. On-device AI continuously analyzes critical measurements such as voltage, current, impedance, and temperature to infer battery state, predict available energy under degradation and environmental uncertainty, and optimize power allocation across intersection subsystems. During extended outages, the Energy Optimization AI prioritizes critical functions, such as emergency signaling and rescue prioritization, while gracefully scaling nonessential loads. This transforms energy storage into an adaptive, self-optimizing lifeline capable of long-duration autonomous operation under extreme conditions. Through remote management, traffic engineers gain real-time visibility into energy availability, enabling proactive maintenance to prevent failures.

This closed-loop architecture marks a fundamental shift toward energy reliability beyond the limits of current backup systems. The Energy Optimization AI is chemistry-agnostic and designed to generalize across storage technologies, with solid-state batteries representing a forward-compatible implementation.

Breakthrough II: Edge-Based Traffic Management AI

Building on the energy reliability established by Breakthrough I, Beacon-X advances to its second breakthrough: edge-based Traffic Management AI. Based on real-time sensor inputs, the Traffic Management AI optimizes signal timing during normal operation and rapidly transitions to crisis-specific control during disasters. When in emergency, it dynamically prioritizes evacuation flow and emergency vehicle movement while reallocating computation and energy toward life-safety functions.

Further, the Traffic Management AI enables edge-based collaboration, allowing intersections to share learning information without central control. Instead of large volumes of raw data, intersections exchange only critical information, such as real-time alerts, emergency prioritization, and compact model updates to save bandwidth. This enhances resilience and enables intelligence to adapt to location-specific traffic behavior and disaster patterns.

Edge-to-edge coordination is facilitated by LoRa, allowing neighboring intersections to synchronize responses while remaining fully autonomous if isolated. Through continuously evaluating outcomes such as evacuation throughput, clearance time, and battery health, Beacon-X propagates refined control strategies across the network, ensuring resilience and self-healing traffic management even if central systems fail or individual nodes degrade.

Design Process

In the wake of the 2025 Los Angeles wildfires, we watched entire neighborhoods burn over three harrowing weeks. Worried about our family members being trapped in the wildfires, we set out to reimagine large-scale evacuations and rescues, seeding the idea of Beacon-X.

To design infrastructure for the next twenty years, we conducted in-depth requirements analysis to examine current system constraints, most notably reliance on grid power and centralized control, and converging trends including climate-driven disasters and advances in energy storage and edge computing. Consultation with first responders at Fire Station 14 in San Jose, California, further highlighted that responder risk is greatest during transit rather than at the scene. Together, these requirements led to a future-ready architecture that enables autonomous, resilient operation to sustain equitable life-safety coverage while minimizing adoption barriers.

Through design iterations, we explored design trade-offs and discarded a few concepts:

1. Centralized traffic network architecture: An initial concept relied on centralized emergency traffic control to override signals during disasters. Although this approach enabled coordinated response, it was ultimately rejected due to its dependence on grid power, centralized

communications, and decision-making, which undermines continuous operation under system-wide failures.

2. Lithium-ion-Solar energy storage: We evaluated different types of lithium-ion batteries for energy storage and remained concerned over the issues of flammable liquid electrolytes and accelerated degradation under high temperatures, which occur often during disasters. Their safety risks, maintenance burden, and limited suitability for unattended, life-critical infrastructure led us to pursue solid-state battery technology instead.

3. Infrared for Emergency Vehicle Preemption: We initially evaluated retaining infrared communication for emergency vehicle preemption; however, its reliance on unobstructed line-of-sight and limited operating range rendered it unsuitable for reliable operation during disasters. Beacon-X instead adopts LoRa for resilient, long-range communication, enabling emergency vehicles to notify intersections and cascade alerts across downstream nodes along their routes.

Our selected design was guided by a forward-looking assessment of technologies expected to mature into scalable, cost-effective solutions over the next two decades. Solid-state solar-integrated storage was selected for superior energy density, extended service life, intrinsic safety, and favorable long-term cost trajectory as production scales. To avoid the horrendous situation of fire hydrants containing no water during the LA wildfires, we specifically designed an Energy Optimization AI to continuously assess battery health and prevent silent failures. With this in place, a Traffic Management AI enables adaptive, collaborative edge-based computation instead of static rule sets, while sensing and communication subsystems employ modular, upgradeable, low-power networking to ensure resilient operation.

To validate this approach, we developed a proof-of-concept prototype:

Using commercially available components, we built a hardware prototype centered on a Raspberry Pi 5 microcontroller. Despite current hardware constraints, the system demonstrated core feasibility by autonomously activating traffic signals under sensor-triggered disaster simulations. Based on commercial pricing of off-the-shelf components, the cost of the prototype hardware was under $900, indicating feasibility and strong potential for future price reduction.

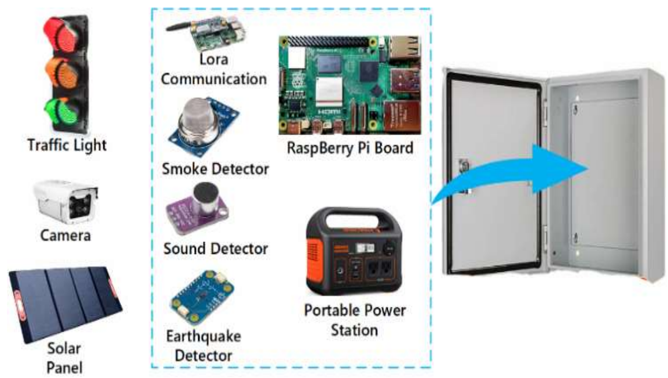

Figure 6. Beacon-X Hardware Prototype Components

For software validation, we developed machine-learning frameworks to demonstrate the feasibility of our two breakthroughs. For the Energy Optimization AI, we chose lithium-ion cells as a surrogate for solid-state batteries for system evaluation. Using Python, we trained fourteen machine-learning models with in-house battery data collected from 400 charge–discharge cycles at an 8:2 train-test split, and selected XGBoost for its optimal balance of accuracy, stability, and computational efficiency. With consistent ≤5% error in state-of-charge estimation, the trained XGBoost framework validated accurate, real-time inference of battery health and electrochemical state, demonstrating the feasibility of an Energy Optimization AI that supports infrastructure autonomy and resilience. For the Traffic Management AI, we used the YOLO algorithm to perform stable, single-pass real-time vehicle detection, demonstrating the viability of autonomous traffic analysis and decision-making at the intersection level.

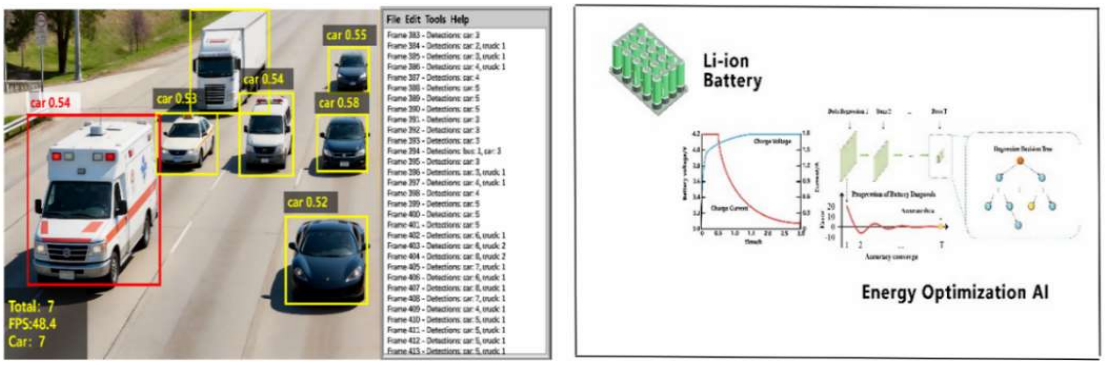

Figure 7. Beacon-X Software Prototype for Traffic Management and Battery Management

Despite technology and component limitations, our prototype provides system-level validation of Beacon-X's highly integrated architecture, confirming the core design principles and autonomous control strategies. These results establish a credible pathway toward the next-generation infrastructure as new energy storage, edge computing, and communications mature.

Our design received positive validation from the City of Santa Clara Traffic Engineering Division. Their feedback affirmed the value of uninterrupted power supported by remote battery monitoring for maintaining reliable traffic operations.

Our design process combined requirements analysis, design iterations, design prototype, and stakeholder input to shape Beacon-X's final design. By validating core design decisions against real-world constraints and stakeholder input, this process confirms both the feasibility and practical relevance of the proposed architecture.

Consequences

By enabling autonomous operation during infrastructure failures, Beacon-X enhances rescue efficiency when disasters strike. Preserving coordinated signal control under extreme conditions reduces evacuation delays and directly improves human survival rates during crises.

With energy autonomy and system adaptivity embedded at intersections, Beacon-X reduces dependence on centralized traffic management and grid power. This decentralization enables more equitable life-safety coverage across rural and underserved communities, reducing disparities associated with centralized infrastructure deployment.

Beacon-X also offers important environmental benefits. Reduced intersection idle time can lower fuel consumption and carbon dioxide emissions, while faster emergency response during wildfires can help contain fire spread, reducing air pollution and long-term damage to soil and surrounding ecosystems.

Economically, Beacon-X presents a challenge in higher upfront investment. Lead-acid batteries currently cost $150–$300 per kWh [16], while solid-state batteries at approximately $400 per kWh [17]. However, as manufacturing scales, solid-state costs are projected to reach ~$140 per kWh by 2046 [18]. With longer service lifetimes and reduced maintenance demands, total cost of ownership is expected to be lower over time [19]. More profoundly, the protection of human lives, homes, communities, and memories far outweigh any initial cost.

Beacon-X inaugurates a new class of infrastructure in which centralized control and passive backup are replaced by edge-based autonomy and adaptivity through its breakthroughs. By bridging technological advancement with public safety, Beacon-X seeks to bring hope to every intersection of life.

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