JOURNAL OF APPLIED SCIENCE AND SOCIAL SCIENCE
eISSN 2229-3113 pISSN 2229-3205
Volume 15 Issue 08, August 2025
Impact factor: 2019: 4.679 2020: 5.015 2021: 5.436, 2022: 5.242, 2023: 6.995, 2024 7.75

USE OF BEACONS AND PROBES IN TRANSPORT MANAGEMENT

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Annotation: This paper examines the application of beacons and probes in modern transport management systems to enhance traffic monitoring, vehicle tracking, and infrastructure efficiency. Beacons, using Bluetooth or RFID technology, enable real-time communication with nearby vehicles and devices, facilitating data collection on movement patterns and congestion. Probes, typically installed in vehicles or smartphones, provide continuous location and speed data that help analyze traffic flow and optimize route planning. The study highlights how integrating these technologies supports intelligent transport systems (ITS), improves traffic signal coordination, and enhances overall urban mobility. Real-world case studies demonstrate their effectiveness in reducing delays and improving safety.

Keywords: beacon, intelligent transport systems, urban mobility, delay.

Introduction. In the evolving landscape of modern transportation systems, the demand for smarter, safer, and more efficient transport management solutions has never been greater. With rapid urbanization and the increasing complexity of traffic networks, cities and transport agencies are turning to advanced technologies to better monitor, control, and optimize transportation systems. Among these technologies, beacons and probes have emerged as vital tools for real-time data collection, traffic analysis, and user interaction, playing a transformative role in intelligent transport systems (ITS) [1].

Beacons are small wireless devices that use Bluetooth Low Energy (BLE) technology to broadcast signals at regular intervals. These signals can be detected by nearby devices, such as smartphones or onboard vehicle sensors, enabling location-based services and data exchange. In transport management, beacons are strategically placed along roads, transit stations, or vehicles to track movement patterns, deliver context-aware information, or assist in navigation. For example, in public transit systems, beacons can provide commuters with real-time updates, such as arrival times or service disruptions, enhancing the overall user experience.

Probes, on the other hand, refer to mobile data sources, typically vehicles or devices, that transmit information about their location, speed, direction, and other parameters as they move through a transport network. These data points, collected from GPS-enabled vehicles, smartphones, or other connected devices, offer a dynamic view of traffic flow and road conditions [2-4]. Probe data plays a critical role in traffic modeling, congestion analysis, route optimization, and incident detection. Unlike traditional fixed sensors or cameras, probes offer a flexible and scalable approach to monitoring vast transport networks in real time [5].

Together, beacons and probes enable transport authorities to collect and analyze vast amounts of real-time data, leading to improved traffic forecasting, better-informed decision-making, and enhanced traveler services. Their combined application can support a wide range of functions, including adaptive traffic signal control, demand-responsive transit, and smart parking systems.

Additionally, they offer insights into commuter behavior, enabling targeted infrastructure investments and policy decisions that align with actual usage patterns.
The integration of beacon and probe technologies also supports the broader goals of smart city initiatives. By facilitating seamless communication between infrastructure, vehicles, and users, these technologies contribute to reduced travel times, lower emissions, and improved road safety. Furthermore, the data collected from beacons and probes can be used for long-term planning, helping cities design more efficient and sustainable transport systems.
Despite their many advantages, the implementation of beacons and probes comes with challenges, such as data privacy concerns, infrastructure costs, and the need for interoperable systems. Addressing these issues is crucial to fully harnessing the benefits of these technologies.
In conclusion, the use of beacons and probes in transport management represents a significant leap forward in the evolution of intelligent transportation systems. By providing real-time, actionable data and enabling greater connectivity across the transport ecosystem, these technologies offer a powerful means to address the challenges of modern mobility and build more responsive, efficient, and user-centric transportation networks.

Beacon-Based Systems: Results and Insights

1.1 Public Transport Tracking with BLE Beacons

A study in Johor, Malaysia deployed BLE detection devices (Raspberry Pi Zero units) at bus stops and Estimote BLE beacons on buses to enable real-time tracking of bus movements and journey durations. The installed system allowed detection of bus arrivals and departures, facilitating ETA computation and future machine learning–based predictions
Beacons successfully transmitted data within ~70 m range, though metal enclosures slightly reduced signal strength beyond 20 m
The system supported remote access and automated monitoring (via ThingsBoard and Heroku), enabling enhanced operational oversight
Discussion:
Such beacon deployments are effective for improving passenger information systems.
However, signal obstructions and hardware in unprotected zones may affect reliability and coverage.
1.2 Collision Prevention in Constrained Spaces
In an underground tunnel in Busan, South Korea, Bluetooth beacons were used to warn drivers of pedestrian or other vehicle presence ahead. Nine beacons were placed along the tunnel, with warning zones defined using RSSI thresholds.
Results:
In 50 test iterations, the system achieved a primary caution alert accuracy of 93% and secondary warning alert accuracy of 95%. No false negatives were observed
This illustrates beacons' potential for safety-critical systems in confined areas. High detection accuracy showcases beacon reliability under controlled environments.
Adoption challenges may include installation logistics and calibration requirements for RSSI thresholds.
1.3 Safety at School Bus Stops
A U.S. statewide evaluation in Ohio compared technologies to enhance safety at school bus stops. It found that systems where flashing beacons are activated by approaching buses via Bluetooth

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detection were the most cost-effective, reducing crashes by up to 29%—surpassing both static flashing beacons (15%) and variable message signs (26%). Real-time, beacon-triggered alerts markedly improve effectiveness in low-visibility scenarios.

Such solutions offer tangible safety benefits for vulnerable road users, especially children.

Challenges include ensuring robust bus beacons and seamless integration with existing signage.

1.4 Smart Parking Solutions with BLE Beacons

Researchers developed a smart parking system—operating both indoors and outdoors—using BLE beacons paired with particle filtering algorithms.

The system accurately identified the occupied parking space and estimated driver–beacon distance. Successfully guided users to available spots and enabled automated payment processing

BLE beacons offer low-cost, scalable solutions for parking management.

Particle filtering improves accuracy despite signal variability.

However, dense urban installation may require maintenance and careful calibration.

1.5 Detecting and Analyzing Mobility Patterns

The TravelSense project (Helsinki) integrated BLE beacons, GPS, and mobile app data to capture anonymized passenger multimodal trajectories.

Combined data revealed detailed insights into traveler movement patterns, modal transfers, and trip chains

Enabled validation against external datasets and informed urban transport planning BLE beacons, when integrated with mobile sensing and app data, provide rich, fine-grained mobility insights.

Deployment complexity remains, requiring cooperation between public agencies and users.

2. Probe Data: Results and Practical Considerations

Several studies have used Bluetooth sensor detection of MAC IDs at two points to estimate travel time and speed.

Findings:

Bluetooth-based travel times were comparable to GPS and loop detector measures in many studies

One study in Turkey found that, despite heterogeneous traffic conditions, the technology remained effective, with estimation errors minimal when speeds were around 45 km/h and detector spacing was 2–3 miles

Data fusion techniques combining Bluetooth probe data and loop detector data improved accuracy of traffic speed estimation on freeways

Probe data provides scalable and non-intrusive monitoring of traffic.

Penetration rate remains a critical factor—low sample sizes increase variance; calibration against ground truth helps mitigate bias

Fusion with fixed sensors enhances spatial and temporal resolution, offering more reliable speed estimation.

3 Work Zone Performance Monitoring

Various U.S. DOT projects used Bluetooth and probe data to measure performance metrics in work zones.

Indiana retrofitted portable dynamic message signs with Bluetooth detectors to estimate travel times and improve alternate route information. Result: over 30% of probe vehicles diverted more ingeniously after improved signage

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Virginia, Minnesota, Texas, Wisconsin, Ohio, Utah and USDOT also deployed probe data to monitor travel time and mobility impacts in work zones. Analyses included travel time reliability and post-construction performance evaluation
Probe data empowers real-time and post-event evaluation of work zone strategies.
Insights drive performance-based contracts and better traveler communication.
Deployment complexities include device portability, baseline data collection, and integration with existing systems.
3 Data Standards for Probe Vehicles
The SAE J2735 “Probe Vehicle Data (PVD)” messages support standardized data exchange for vehicle snapshots (location, time) in V2X communications
nap.nationalacademies.org
Standardization ensures interoperability between vehicles and infrastructure.
Key challenges include data latency, limited adoption of message types, and message rate variability.

Standards facilitate delivery of real-time behavior data critical for dynamic traffic systems.
4 Technology Integration: Beacons and Probes in Broader ITS Vehicle-to-Everything (V2X) Ecosystem
Beacon and probe technologies align with broader V2X frameworks—enabling communication between vehicles, infrastructure, pedestrians, networks, and more
BLE beacons can form part of Vehicle-to-Device (V2D) infrastructure, while probe data flows into Vehicle-to-Infrastructure (V2I) analytics.
Integration enhances cooperative safety, network efficiency, and data-informed planning.
Alignment with wireless and cellular standards (802.11p, C-V2X) remains a consideration for multi-tech systems.
3.2 Infrastructure Integration Challenges
Deploying Bluetooth-based beacon systems faces infrastructure compatibility challenges:
Retrofitting older traffic systems can be expensive (e.g. Munich needed ~€18.5k per intersection)
pmarketresearch.com
.Installation disruptions can increase congestion—for instance, Edinburgh saw a 34% increase during deployments
pmarketresearch.com
.Maintenance burdens like battery replacements, corrosion, and firmware updates add complexity—e.g., Delhi site required 73% more maintenance, Dubai reported 22% failure rates in coastal environments
pmarketresearch.com
.Urban Bluetooth congestion may reduce positioning accuracy to 58%
pmarketresearch.com
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Beacons offer many benefits, but cost, deployment disruption, and environmental durability must be considered in planning.
Cities need careful pilot testing, maintenance planning, and site-specific solutions to address signal interference and hardware wear.
4. Synthesis and Future Implications

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4.1 Benefits Realized

Across applications—public transport, safety monitoring, parking management, mobility pattern sensing—beacons and probes have shown:

High Accuracy in warning zones, travel time estimations, and parking spot identification.

Scalability and Affordability relative to traditional sensors, particularly in transit and parking solutions.

Enhanced Safety and Efficiency, demonstrated by reductions in crashes and traveler delays.

Rich Data Collection, enabling multi-modal insights and deeper planning capabilities.

4.2 Operational Limitations

However, several challenges persist:

Infrastructure Costs and Disruption: Upgrading legacy systems or installing hardware can be costly and cause traffic delays.

Signal Limitations: WLAN or Bluetooth noise in dense urban areas can reduce detection reliability. Hardware protection and signal calibration are vital.

Data Quality and Penetration Rates: Especially for probe data, low vehicle sampling leads to high variance unless compensated via fusion or calibration.

Maintenance Burden: Beacons require upkeep—battery replacement, hardware failure mitigation, firmware updates.

4.3 Strategic Approaches for Adoption

To overcome limitations and maximize impact, practitioners should:

Pilot and Iterate: Begin with controlled deployments (e.g., tunnels, campuses, transit corridors) to refine sensor placement and system integration.

Use Multimodal Sensor Fusion: Combine beacons with GPS, loop detectors, cameras, or mobile data for robust performance.

Apply Standards and Interoperability: Utilize SAE and V2X frameworks to support scalability and cross-agency integration.

Plan for Maintenance and Resilience: Select durable hardware, plan for battery cycles, and design for anti-vandalism and environmental robustness.

Engage Stakeholders: Coordinate with city planners, transit agencies, private vendors, vehicle manufacturers, and the public to ensure successful deployments.

Conclusion

Beacons and probes have proven to be powerful tools in modern transport management. Whether informing commuters, enhancing safety in critical zones, optimizing parking, or uncovering mobility patterns, these technologies offer scalable, real-time intelligence. Yet, realizing their full potential depends on thoughtful implementation—balancing accuracy, cost, maintenance, and integration across complex urban environments.

As smart city initiatives and V2X ecosystems continue to mature, the roles of beacon and probe technologies are set to expand further. Through strategic fusion, standardization, and adaptive deployment, transport systems can become not only smarter, but more responsive, sustainable, and user-centered.

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