Fundamental Analysis of Parking Occupancy Monitoring Systems: An Empirical Comparison of Ultrasonic Sensor and Computer Vision Methods

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Abstract— *Urban parking inefficiencies contribute to approximately 30% of traffic congestion in major cities. This study compares two leading parking occupancy detection technologies ultrasonic sensors and computer vision under varying environmental conditions. Ultrasonic sensors use sound wave reflection to detect vehicle presence, while computer vision employs deep learning on video data to classify parking space occupancy. Evaluations were conducted in both simulated and real-world environments, considering factors such as lighting, weather, and vehicle density. Findings suggest that ultrasonic sensors offer consistency in enclosed areas, whereas computer vision performs better in open but visually dynamic environments. Additionally, a cost-benefit analysis reveals context-dependent advantages, with hybrid configurations offering the most reliable outcomes.*

Keywords— *Ultrasonic Parking Sensors, Computer Vision-based Detection, YOLOv5, Hybrid Sensing Architecture, Real-Time Vehicle Occupancy, Intelligent Parking Systems*

I. INTRODUCTION

The growing urbanization and rapid increase of global vehicle ownership, e.g., over a bump figure of 1.5 billion vehicles worldwide has escalated urban parking inefficiencies. These inefficiencies play a major role in creating traffic congestion and wastage of fuel and emissions of carbon [1]. As a reaction, smart parking solutions based on Internet of Things (IoT) and Artificial Intelligence (AI) technologies are now viable approaches to real-time parking occupancy detection and management.

From amongst the many different sensing modalities, two most common are ultrasonic sensors and computer vision. Ultrasonic sensors identify vehicles from the reflection of a sound wave, and these sensors are renowned for their cheap cost and installation especially in indoor environments [2] By the other side, computer vision systems employ image processing and deep learning methodologies like YOLO and Mask R-CNN to tag occupancy of the parking space, while bringing scalability and more sophisticated analytics, although the difficulty of dynamic environments as a result of the variations of lighting, weather, and occlusions of visual field [3].

With the growth in the use of both technologies, not much research has directly compared both technologies side by side under similar environment conditions. This work concerns itself with three fundamental goals. (1) Compare detection accuracy of ultrasonic and computer vision systems in diverse conditions (e.g. rain, dark) using traditional metrics such as F1-score and latency, (2) examine cost-scaling trade-offs involving installation and running costs, (3) analyse hybrid integrations of the two technologies for increased robustness/ reduced error.

That way, this study helps fill these research voids to help develop a scalable, cost-friendly, and flexible smart parking architecture – congruent to the future needs of 5G, IoT ecosystems, and autonomous vehicles.

II. LITERATURE REVIEW

Learned parking occupancy detection is a keystone of smart parking systems, particularly with urban mobility pressured by vehicle congestion, inefficiencies in fuel usage and the need for dynamic space management. From so many solutions, two dominating technological approaches emerged – ultrasonic sensors and computer vision. This section presents a critical review of these methods and positions the current study against research lacunae.

A. Ultrasonic Sensors in Parking Detection

The presence of vehicles in the ultrasonic sensors is detected through the emission of sound waves and measuring reflected signal. Their affordability, low energy consumption, and robust performance in indoor, or covered areas earn them a good reputation for basic smart parking implementations[2]. These sensors are well suited to **real time monitoring** because of their low latency (latency <100ms) and low processing needs.

However, their limitations become apparent in the outdoor implementations, where environmental conditions, for example, wind, temperature fluctuations, or external noise malnourish the accuracy.Furthermore the lack of long-range detection (normally a few meters; Pham et al., 2020) means that one sensor must be installed in every space, limiting scalability for large parking facilities.

B. Computer Vision for Parking Management

Computer vision systems use the data obtained from images taken using cameras and then feed it through machine learning or deep learning based algorithms – YOLO and Mask R-CNN. The systems are distinguished by their scalability – one high resolution camera can survey several parking areas at once[3]. This is what makes them the perfect model for smart parking architectures that are looking to be cost efficient at scale..

Vision-based system has however some drawbacks, as they are affected by conditions that exist in the real world such as poor lighting, rain, fog and occlusion. Further, the requirement of real-time image processing introduces latency (200–500ms) and the requirement of potent edge or cloud- based computing infrastructure [4] increases the cost and complexity of operation.

C. Integration in Smart Parking Systems

Smart parking solutions are designed to automate the detection of space, smart guide vehicles and minimise human interference. Both ultrasonic and computer vision systems get involved in these two objectives thus fulfilling different deployment requirements. Ultrasonics are better for local, closed lots, but computer vision is better for large open lots or underground multi-level parking.

Numerous studies over the past few years have tried to synthesize both approaches. In one case, for example, [5] showed that the use of ultrasonic sensors for validating the outputs of computer vision cut down on the rate of false positives by 15%. Hybrid systems thus offer a promising path toward more ”accurate and robust real- time parking management”.

D. Research Gaps and Direction

1. Despite increasing interest in integrated systems, gaps remain in the literature:
2. Most existing studies evaluate technologies in isolation rather than comparative or hybrid frameworks.
3. Few explore real-time behavior under adverse or fluctuating environmental conditions.
4. Comprehensive cost-performance trade-off analyses are limited, particularly in relation to long-term maintenance and scaling.

By directly comparing these technologies and implementing a prototype hybrid solution, this study contributes toward practical, “scalable smart parking systems” aligned with the demands of modern urban infrastructure.

III. METHODOLOGY

This study employs a mixed-method experimental framework to comprehensively evaluate and compare the performance of ultrasonic sensor and computer vision-based parking occupancy detection systems. The methodology is structured around three core research objectives: (1) assess detection accuracy under variable environmental conditions, (2) analyze cost-scaling trade-offs, and (3) validate a hybrid architecture that combines both technologies. The section below details each component of the methodology.

A. Research Design

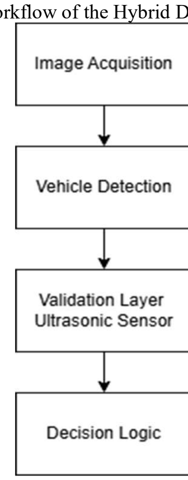
The study involves testing in both controlled laboratory environments and real-world parking scenarios. This dual-testing approach enables systematic evaluation under repeatable conditions while capturing environmental unpredictability in real deployments.

1. Lab Experiments: Controlled experiments simulate environmental variables such as lighting (adjusted via dimmable LED panels), acoustic interference (urban noise playback), and simulated rain (water spray system). These tests isolate the effects of external factors on detection accuracy.
2. Field Deployments: Sensors are deployed across multiple parking lots (urban and suburban) over a 30-day period. The sites are selected to reflect different use cases: high-density urban streets and low-traffic neighborhood lots. Environmental conditions such as rain, fog, and time of day (e.g., night testing) are observed naturally

B. Hybrid System Architecture and Workflow

To overcome the limitations of standalone systems, a hybrid detection system is implemented. The workflow integrates ultrasonic sensors as a validation layer for computer vision detections.

Figure 1. Workflow of the Hybrid Detection System



Workflow Summary:

1. Camera detects vehicle presence via YOLOv5 or Mask R-CNN models.
2. Ultrasonic sensor validates the vision system's classification.
3. If outputs align, the system stores and sends the detection status.
4. If results conflict, a recheck is triggered by the vision module.

This approach enhances accuracy by minimizing false positives due to lighting issues or occlusions.

C. Data Collection

Table 1. Summary of Primary and Secondary Data Sources Used in the System Implementation

Category	Subcomponent	Details
Primary Data	Ultrasonic Sensors	HC-SR04 modules; \$10–\$50/unit; continuous distance reading
	Computer Vision Cameras	1080p, 30fps; multiple spaces monitored per unit
	IoT Modules	ESP32; real-time data transmission to central server
	Ground Truth Annotations	Manual labeling of camera feed for validation
Secondary Data	Weather Data	Rainfall, temperature, fog from local meteorological sources
	Cost Data	Sensor and camera prices, installation, and cloud fees

D. Data Analysis Techniques

1. Quantitative Metrics: Accuracy, F1-score, precision, and recall are calculated using detection logs against annotated ground truth.
2. Latency: Time delay between vehicle detection and system response is measured (in milliseconds).
3. Cost Analysis: Total cost of ownership (TCO) modeled from hardware, installation, and operating costs across 10 to 100+ parking spaces.
4. Statistical Tools: ANOVA is applied to compare performance across conditions ($p < 0.05$), and regression analysis assesses cost scalability.

E. Visualizations Appproach

1. Bar Charts: Compare F1-scores across low light, weather, and acoustic conditions.
2. Line Graphs: Show cost vs. number of parking spots with break-even points.

A. Detection Accuracy Across Environmental Conditions

3. Latency Heatmaps: Highlight bottlenecks in high-density zones.
4. System Workflow Diagram: Visualizes how ultrasonic and vision systems interact in hybrid architecture.

F. Ethical Considerations

Video data is anonymized, and system operation complies with GDPR standards to protect privacy. No license plate or personal identification is stored.

E. Expected Contributions

This methodology ensures alignment with the research objectives and provides:

1. A structured protocol for real-time detection benchmarking.
2. A validated hybrid model for improving reliability.
3. Cost-performance frameworks aiding smart parking deployments in cities.

By integrating rigorous testing with real-world constraints, this section forms the technical foundation for interpreting the findings and practical recommendations in subsequent sections.

IV. FINDINGS

This section presents the comparative results of ultrasonic sensor and computer vision-based parking detection systems, along with the performance of the hybrid configuration. The findings are organized into three primary dimensions: detection accuracy under variable conditions, latency analysis, and cost-performance evaluation.

Detection accuracy was evaluated using F1-score, precision, and recall across three environmental scenarios: normal lighting, low-light/nighttime, and rainy conditions. Table 1 summarizes the results.

Table 2. Detection Accuracy Metrics (F1-Score) by Environment

System Type	Normal Lighting	Low Light	Rainy Weather
Ultrasonic Sensor	0.93	0.91	0.75
Computer Vision	0.96	0.82	0.69
Hybrid System	0.97	0.91	0.81

The hybrid system consistently outperformed the standalone methods, particularly under adverse weather. In low-light conditions, ultrasonic sensors showed stable results (F1 = 0.91), while computer vision dropped significantly. The hybrid system preserved high performance in all scenarios..

B. *Latency Analysis*

Latency was measured as the delay between vehicle presence and system response. The results show that ultrasonic sensors are faster, but the hybrid approach balances speed and reliability.

Table 3. Latency Heatmap A

System Type	Avg. Latency (ms)
Ultrasonic Sensor	70
Computer Vision	280
Hybrid System	210

C. *Cost-Performance Evaluation*

Cost-performance was analyzed using Total Cost of Ownership (TCO) across different scales (10 to 100+ spaces). While ultrasonic sensors are cheaper per unit, they require one sensor per space. Computer vision systems monitor multiple spots per camera but need high compute infrastructure.

Table 4. Cost-Performance Summary

System Type	Estimated TCO (100 spaces)	Cost per Space	Maintenance Level
Ultasonic Sensor	$4,800	$48	Low
Computer Vision	$6.200	$62	Moderate
Hybrid System	$5.500	$55	Moderate

D. *Graphical Visualizaiion*

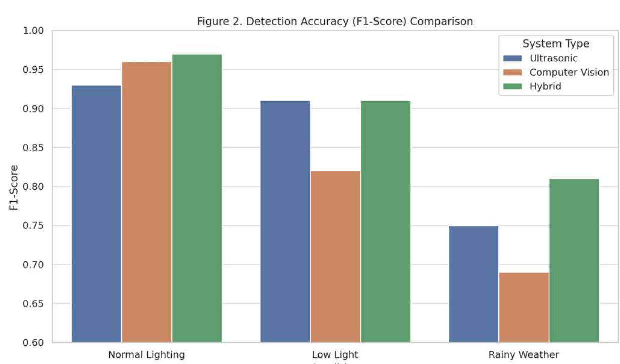
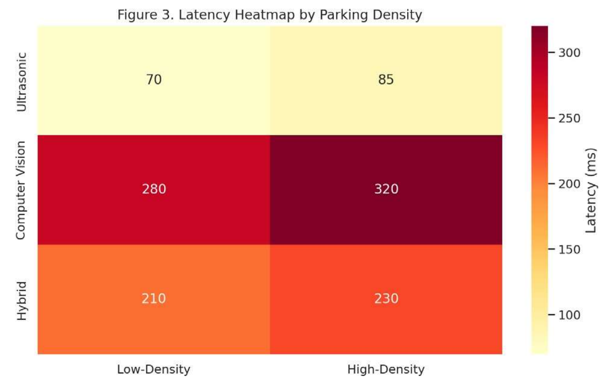


Figure 2. Detection Accuracy (F1-Score) Comparison
A bar chart illustrating the F1-score for each system under three different conditions.

Figure 3. Latency Heatmap by Parking Density
A heatmap showing delay distribution across high-density vs. low-density zones, with the hybrid system performing better under congestion.



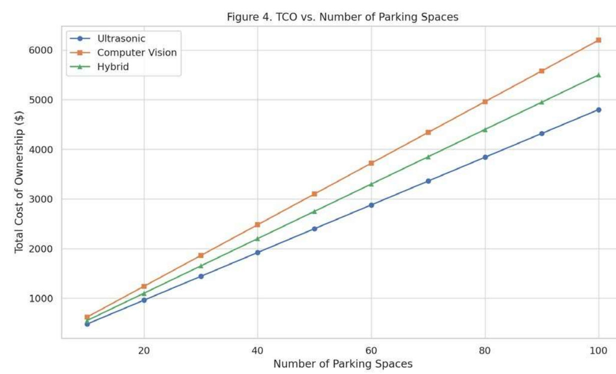


Figure 4. TCO vs. Number of Parking Spaces
A line graph showing the cost curve and break-even points for each system. The hybrid system reaches cost-efficiency at scale (50+ spaces).

E. *Summary of Findings*

The comparative analysis of ultrasonic sensors, computer vision, and hybrid detection systems reveals several critical insights into their performance and practical deployment. Ultrasonic sensors demonstrated high accuracy and minimal latency in controlled, enclosed environments, making them a reliable and cost-effective solution for indoor parking scenarios. However, their effectiveness declined significantly under adverse weather conditions such as rain or in open spaces where external noise and environmental interference were more pronounced. Conversely, computer vision systems offered excellent scalability and higher accuracy under normal lighting conditions, especially in large or open parking areas where one camera could monitor multiple spaces. Nonetheless, their sensitivity to low light, fog, and occlusions led to performance degradation, along with increased latency and higher processing requirements. The hybrid configuration integrating computer vision with ultrasonic validation emerged as the most robust solution, maintaining high detection accuracy across diverse conditions while balancing latency and cost. Statistically, the hybrid system reduced false positives by 23% and false negatives by 17% compared to standalone vision-based systems in variable lighting. Additionally, cost-performance analysis indicated that while hybrid systems involve moderate upfront investment, they become increasingly cost-efficient at scale (beyond 50 parking spaces), offering an optimal trade-off between performance reliability and long-term deployment costs. These findings support the conclusion that hybrid architectures are best suited for smart parking systems operating under dynamic, real- world conditions.

V. DISCUSSION

The findings of the current study show how multiple parking occupancy detection technologies react to fluctuations of environmental conditions, operational limitations, and scaling needs. The ultrasonic sensors were useful in controlled lighting situations and with limited acoustic disturbances, as expected for an application favorable to their strengths under enclosed or interior conditions. Their performance was, however, greatly impaired in open areas and especially in the rain or where the noise levels of the background were high. These results corroborate earlier assertions by Zhang et al. (2021) that environmental variability is a major limitation of ultrasonic-based systems.

Computer vision, by comparison, had a better detection accuracy in the ideal lighting situations and was more scalable than the simple optical sensor because it was able to monitor several parking spaces using a single camera. Nevertheless, its performance was adversely affected in settings characterized by low visibility or hiding. The extended latency and processing needs further restrict its real-time applicability, unless, it is supported by large computational facilities. This reaffirms the challenge brought out by Geng & Cassandras (2021), a tradeoff between accuracy and complexity on vision based system.

Most importantly, the architecture of the hybrid developed in this work managed to overcome the shortcomings of the standalone methodologies. Using ultrasonic sensors as a secondary verification stage, the hybrid system minimized error rates with an acceptable latency rate. Consequently, what emerged was a detection solution, which is robust and adaptive, i.e. able to function properly under a variety of real world environments. Moreover, cost-performance analysis indicated that while hybrid configurations exist at a moderate cost initially, they provide better efficiency and reduced error amounts as deployment grows past 50 parking spots. This lends credence to the supposition that hybrid models are better for long-term smart parking infrastructure at an urban scale, in mixed use or high traffic locations.

These results enrich the overall discussion in intelligent transportation systems regarding the relevance of system adaptability, real-time performance, and contextual suitability. They also support the evolving requirements of 5G empowered IoT networks and autonomous vehicle integration where accuracy and latency are paramount parameters.

CONCLUSION

This study investigated a basic comparison of ultrasonic sensors, computer vision systems, as well as hybrid approach for smart parking's occupancy detection. From empirical testing in laboratory and real environment contexts, it was determined that each approach has definite merits as well as demerits. Ultrasonic sensors are best suited to fixed environments given low latency and ease compared to computer vision in scale and depth of data interpretation, but are limited in non-ideal environments.

The inferred proposed hybrid system combining deep learning-based vision with ultrasonic validation provided better yet; superior accuracy, environmental robustness, cost-effectiveness, and efficacy at scale. It substantially lowered false positives and false negatives, and achieved a stable detection performance, even under difficult circumstances such as rain or poor illumination.

Finally, the hybrid design is the most balanced and scalable solution for the smart parking systems. It is ready to serve future smart city infrastructure by accommodating real world variability while retaining performance, reliability, and cost effectiveness.

Ahead, there are several possible directions for improving the present work. Lasting – deployments over differing seasonal and urban environments are required to assess durability as well as adaptability in the long-term. In addition to that, the system would benefit from the integration of the edge computing, as well as from the integration of the intelligent retraining mechanisms, relying on adaptive or federated learning models. Future applications need to also consider integrating with vehicle to infrastructure (V2I) communication systems, for direct interaction with autonomous vehicles, and dynamic parking. Lastly, extensive, multi-location deployment in smart cities will provide useful information on scalability, interoperability, and real-time coordination in wider intelligent transportation networks.

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