

An IoT-Based Bus Bunching Prevention Framework Using Real-Time Headway Monitoring and Driver Intervention Mechanisms

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ABSTRACT

Bus bunching is one of the most persistent operational challenges in public transportation systems, causing irregular service intervals, prolonged passenger waiting times, vehicle overcrowding, and reduced service reliability. Existing solutions primarily focus on post-event analysis or complex optimization algorithms that are difficult to deploy in real-world transit environments. This study proposes an Internet of Things (IoT)-based bus bunching prevention framework that integrates real-time vehicle tracking, intelligent headway monitoring, automated driver intervention, and centralized fleet management within a unified architecture. The framework employs ESP32 microcontrollers and GPS modules installed on buses to continuously collect spatial and temporal vehicle data. A centralized web platform processes the data to calculate headways between consecutive buses and identifies potential bunching conditions when predefined thresholds are violated. Upon detection, automated alerts are transmitted to drivers through onboard notification devices and simultaneously displayed on an administrative monitoring dashboard, enabling immediate corrective actions. To evaluate the operational need for such a system, a survey was conducted among public transport users in Malaysia. Results revealed that 70.5% of respondents had experienced bus bunching, while 57.6% reported inconsistent arrival schedules as a major concern. Furthermore, 98.4% supported real-time driver notifications and 96.7% agreed that continuous fleet monitoring would improve service reliability. The findings demonstrate that integrating real-time monitoring with active intervention mechanisms provides a practical and scalable approach to preventing bus bunching and enhancing public transport performance.

INTRODUCTION

Background

Reliable public transportation depends on maintaining consistent service intervals between buses operating along the same route. However, maintaining regular bus headways remains a major challenge in urban transit systems due to traffic congestion, varying passenger demand, road incidents, and operational disruptions. These uncertainties often result in bus bunching, a phenomenon in which two or more buses intended to operate at regular intervals arrive at a stop within a short time of one another. Consequently, passengers experience prolonged waiting times followed by the simultaneous arrival of multiple buses, often causing overcrowding on leading vehicles and underutilization of trailing vehicles. Such operational inefficiencies negatively affect service reliability, passenger satisfaction, fuel consumption, and overall fleet productivity.

Recent advancements in Global Positioning System (GPS), wireless communication technologies, cloud computing, and Internet of Things (IoT) applications have enabled real-time monitoring of vehicle movements. These technologies provide opportunities to move beyond passive vehicle tracking towards

proactive operational control capable of detecting and preventing bus bunching before service disruption becomes severe.

Problem Statement

Although many public transportation operators employ GPS tracking systems to monitor fleet locations, most existing solutions focus primarily on visualization and post-operational analysis. Limited attention has been given to integrating real-time monitoring with immediate intervention mechanisms that support operational decision-making. Current bus transportation management systems often lack continuous headway monitoring, automated detection of potential bus bunching events, real-time driver notification mechanisms, and integrated fleet management capabilities that enable operators to implement timely service recovery actions. Many existing studies primarily focus on GPS-based tracking, post-event analysis, spatial-temporal assessments, or predictive modelling rather than providing integrated real-time operational intervention mechanisms for preventing bus bunching. For example, Shan et al. (2023) and Ganguly and Maitra (2024) concentrated on analysing bus bunching patterns using GPS and clustering techniques, while Khalid et al. (2016) focused on passenger-oriented bus tracking and visualization. Similarly, advanced control methods proposed by Deng et al. (2020), Lizana et al. (2014), and Quek et al. (2021) require more complex operational infrastructures and do not emphasize direct driver notification within a practical low-cost IoT environment. As a result, transit agencies frequently rely on reactive responses after service disruptions have already occurred, leading to irregular bus intervals, increased passenger waiting times, overcrowding, and reduced service reliability. As a result, transport operators frequently respond to bus bunching only after service degradation has already occurred.

Research Objectives

To address these operational limitations, this project establishes the following objectives:

- To establish a real-time GPS-enabled monitoring architecture for public bus operations.
- To develop a headway monitoring mechanism capable of identifying potential bus bunching conditions.
- To implement automated intervention features that provide corrective notifications to drivers and fleet administrators.
- To assess stakeholder acceptance of the proposed bus bunching prevention framework.

Research Contributions

The primary contribution of this research is the development of a four-layer bus bunching prevention framework consisting of real-time vehicle data acquisition, intelligent headway monitoring, active driver intervention and centralized fleet management. Unlike conventional monitoring systems that provide only location visibility, the proposed framework emphasizes operational prevention by enabling immediate responses to emerging bunching conditions.

RELATED WORKS

Real-Time Vehicle Tracking Technologies

GPS-based tracking technologies form the foundation of modern public transportation monitoring systems. Previous studies have demonstrated the effectiveness of GPS data in analysing vehicle trajectories, service reliability, and route performance. Shan et al. (2023) utilized GPS trajectory data to analyse spatiotemporal bus movements and identify the propagation of bus bunching along urban routes, while Kathuria et al. (2020) employed GPS data to evaluate travel-time variability and service reliability in a Bus Rapid Transit (BRT) system. Similarly, Khalid et al. (2016) developed a GPS-enabled bus tracking system that improved passenger access to real-time vehicle location information. However, many of these implementations primarily support visualization, performance evaluation, or historical analysis rather than active operational

control. Although GPS technologies successfully identify movement patterns and service disruptions, their role in preventing bus bunching remains limited when not integrated with intervention mechanisms.

Bus Bunching Detection Approaches

Several studies have focused on identifying bus bunching by utilizing spatial-temporal analysis, clustering techniques, statistical models, and trajectory mining methods. Ganguly and Maitra (2024) applied ST-DBSCAN density clustering, k-means++, and a propagation ratio metric to identify critical bunching locations and analyse the spread of bus bunching across urban routes. Similarly, Shan et al. (2023) demonstrated how empirical GPS trajectory data could reveal the formation and progression of bus bunching events. To support operational incident awareness, Goncu and Sahin (2023) developed a GPS-based incident detection algorithm capable of detecting disruptions in a Bus Rapid Transit system with high accuracy and low false-alarm rates. While these approaches are effective in identifying bunching patterns and operational anomalies, they generally function as analytical tools for system evaluation rather than real-time decision-support systems. Consequently, they do not provide immediate corrective actions once a bunching event is detected

Bus Bunching Control and Intervention Strategies

To address service irregularities, researchers have proposed various control strategies including dynamic speed adjustment, holding control, adaptive scheduling, and predictive optimization. Deng et al. (2020) developed a real-time speed control algorithm that dynamically adjusts bus speeds according to roadway conditions and intersection delays, resulting in improved headway regularity. Lizana et al. (2014) proposed a rolling horizon predictive model to regulate bus holding times at designated stops, while Quek et al. (2021) investigated dynamic holding and speed adjustment strategies through agent-based simulation to reduce passenger waiting times. More recently, Yue and Liangliang (2024) introduced an adaptive scheduling model that continuously recalibrates dispatching schedules based on live GPS information. Although these approaches have demonstrated effectiveness in reducing headway variance and improving operational efficiency, many require sophisticated computational models, extensive infrastructure, or centralized optimization platforms that may be difficult to deploy in resource-constrained transit environments.

Table I summarizes key literature approaches, highlighting tracking hardware, real-time capability, methods, and features.

Table I. Comparison of Existing Bus Bunching Prevention Approaches

Author(s) & Year	GPS Used	Hardware Device	Real-Time	Method / Algorithm	Key Features
Shan et al. (2023)	Yes	GPS Receiver	No	Spatial-temporal analysis	Visualizes bunching propagation via ArcGIS
Ganguly & Maitra (2024)	Yes	GPS Receiver	No	ST-DBSCAN, K-means++, Propagation Ratio	Identifies critical stop clusters and propagation
Deng et al. (2020)	Yes	GPS, Vehicle Sensor	Yes	Speed control algorithm	Adapts speed dynamically to traffic conditions
Moodi et al. (2023)	Yes	GPS Receiver	No	Gradient Boosting Regression	Predicts service instability using machine learning
Lizana et al. (2014)	Yes	GPS, Central Controller	Yes	Rolling Horizon Predictive Model	Controls vehicle holding times at stops dynamically

Quek et al. (2021)	Yes	Onboard Unit (AVL + GPS)	Yes	Dynamic holding & speed adjustment	Agent-based simulation for active intervention
Yue & Liangliang (2024)	Yes	GPS Controller	Yes	Adaptive scheduling algorithm	Real-time tracking and schedule recalibration
Kathuria et al. (2020)	Yes	GPS Receiver	No	Linear regression, K-means, WDI	BRT travel-time reliability classification
Goncu & Sahin (2023)	Yes	GPS / Embedded System	Yes	Incident detection algorithm	High detection accuracy (100%) in BRT corridors
Khalid et al. (2016)	Yes	Android Smartphone	Yes	Mobile internet location streaming	Low-cost tracking for university campus transit

Research Gap

A review of the literature indicates that existing studies generally focus on one of three areas: (i) tracking and visualization, such as GPS-based fleet monitoring systems developed by Khalid et al. (2016) and trajectory analysis frameworks proposed by Shan et al. (2023); (ii) bunching detection through clustering and statistical analysis methods, as demonstrated by Ganguly and Maitra (2024) and Goncu and Sahin (2023); and (iii) scheduling optimization and operational control mechanisms, including the speed control, holding, and adaptive scheduling approaches proposed by Deng et al. (2020), Lizana et al. (2014), Quek et al. (2021), and Yue and Liangliang (2024). Despite the significant contributions of these studies, few integrate all three functions within a unified operational framework that combines real-time monitoring, automated detection, driver intervention, and administrative oversight. Furthermore, previous studies have largely focused on offline analytics, simulation-based evaluations, or centralized optimization models, with limited attention given to practical low-cost IoT architectures that support direct driver feedback and real-time operational response.

To address this gap, the present study proposes an IoT-based Bus Bunching Prevention Framework that integrates GPS-enabled monitoring, automated headway analysis, real-time driver notification mechanisms, and centralized fleet management into a single operational platform. By combining continuous vehicle tracking with active intervention capabilities, the proposed framework extends beyond passive monitoring and supports proactive bus bunching prevention in public transportation systems. Table II details the research gaps derived from the literature.

Table II. Research Gap Analysis

Title / Reference	System Focus	Identified Limitations	Proposed System Solution
Shan et al. (2023)	Post-incident GPS evaluation	Offline analysis; no driver interaction	Real-time monitoring with active driver alerts
Ganguly & Maitra (2024)	Spatial density clustering	Lack of live operational control tools	Automated headway threshold detection
Deng et al. (2020)	Dynamic speed control	High computational complexity	Direct driver notification and response tracking
Moodi et al. (2023)	ML reliability prediction	Requires extensive post-processing	Lightweight IoT-based dashboard architecture
Khalid et al. (2016)	Mobile tracking app	Passenger visualization only; no headway alerts	Integrated driver buzzer & push-button acknowledgment

Existing research concentrates largely on offline data analytics, mathematical simulations, or complex control algorithms that lack direct driver feedback loops. Few systems combine continuous GPS positioning, automated distance/time threshold detection, physical driver alerts, acknowledgment mechanisms, and administrative web visualization in a unified, cost-effective platform.

METHOD

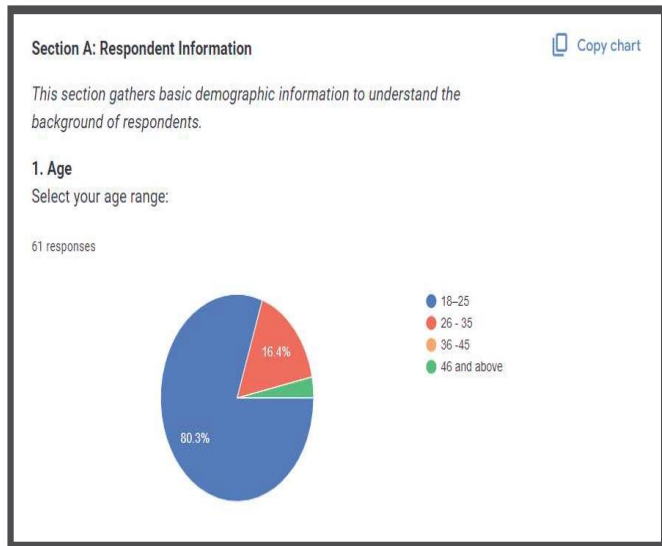


Figure 1 : Age distribution of respondents

To validate the operational need and user acceptance of the proposed Bus Bunching Prevention Framework, a quantitative survey was conducted among public transportation users across several states in Malaysia, with a primary focus on Melaka and Selangor. The survey instrument was designed to collect information on four key aspects: respondent demographics, public bus usage patterns, experiences related to bus bunching incidents, and perceptions toward the proposed IoT-based monitoring and intervention system. The questionnaire included both multiple-choice and Likert-scale questions to assess the prevalence of bus bunching issues and the level of support for potential technological solutions.

Responses were collected from individuals with varying transportation usage frequencies and occupational backgrounds to ensure a broad representation of public transport users. The collected data were subsequently analyzed using descriptive statistics, including frequencies and percentages, to identify common operational challenges faced by commuters and evaluate stakeholder acceptance of real-time monitoring, driver notification, and fleet management functionalities. The survey findings were then used to inform the design requirements and validate the practical relevance of the proposed bus bunching prevention framework.

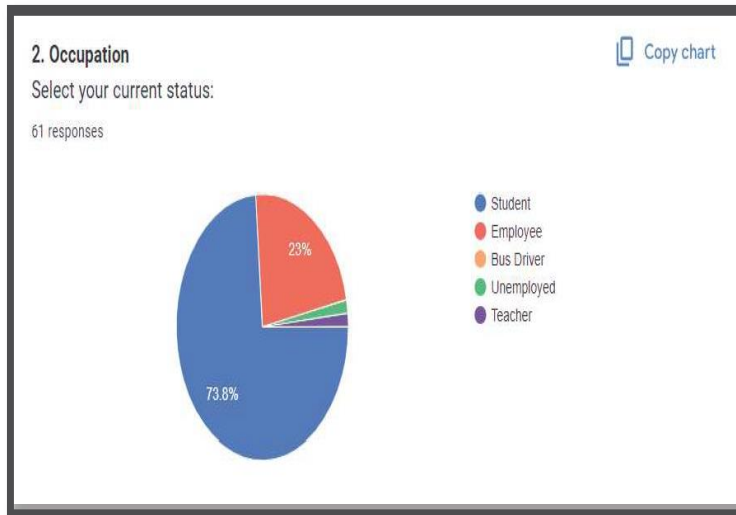
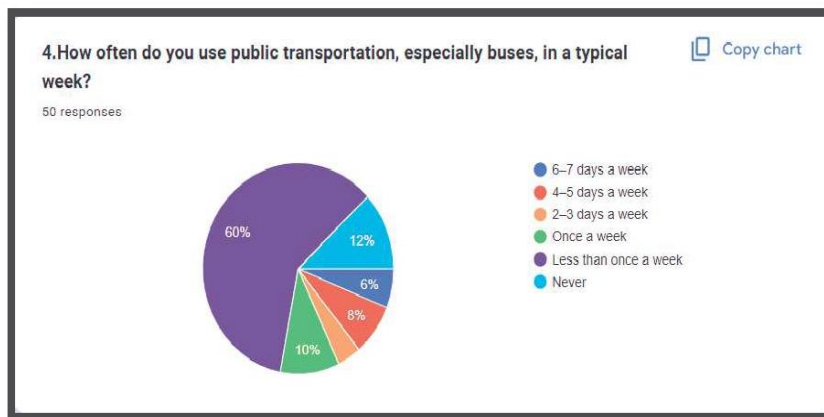


Figure 2 : Occupation status of respondents

Survey responses provided insights into commuter behavior. A total of 80.3% of respondents were aged between 18 and 25 years, with 73.8% identifying as students. Geographic representation concentrated primarily in Melaka and Selangor. Regarding public transit frequency, 60% of respondents reported using public buses less than once per week, while a small proportion relied on buses daily. Primary motivations for bus usage included cost savings and commuting to educational institutions or workplaces. Notably, 44% of respondents reported average one-way trip durations exceeding 1 hour, underscoring the critical need for



punctual scheduling and minimized transit delays.

Figure 3 : Frequency of public bus usage per week

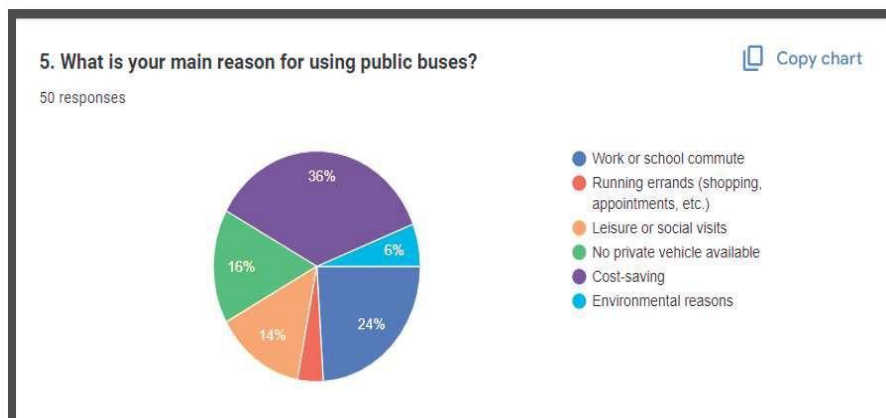


Figure 4 : Main reasons for using public buses

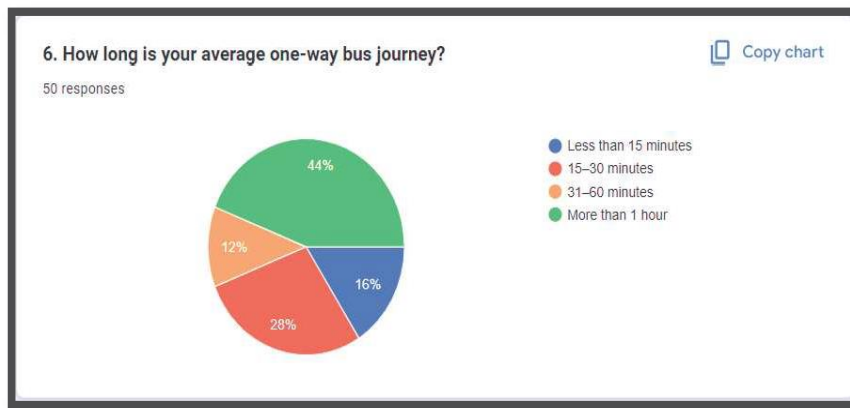


Figure 5 -Respondents' average one way bus journey duration

RESULTS AND DISCUSSION

Validation of the Need for Bus Bunching Prevention Technology

Survey findings indicate that bus bunching remains a significant issue among public transport users. A total of 70.5% of respondents reported experiencing situations where multiple buses arrived simultaneously, confirming that service irregularity is a common operational challenge. Additionally, 57.6% identified inconsistent bus schedules as the primary service issue, followed by excessive waiting times (47.5%), overcrowding (45.8%), and congestion at bus stops (44.1%). These findings demonstrate a clear need for technology-driven preventive mechanisms capable of maintaining consistent service intervals.

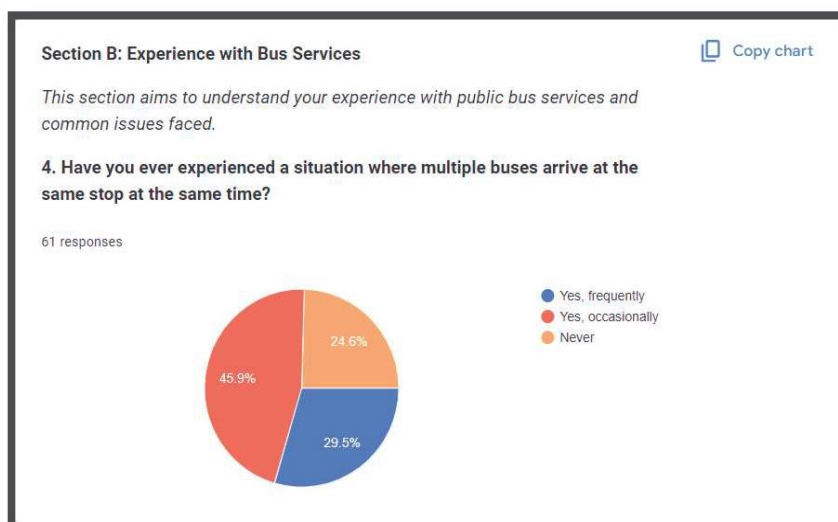


Figure 6: Occurrence of bus bunching experienced by respondents

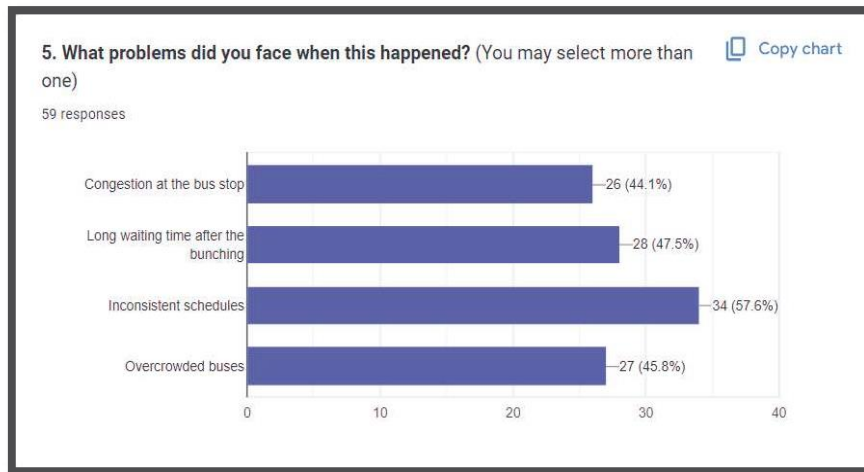


Figure 7: Issues faced due to bus bunching

Acceptance of Real-Time Intervention Technologies

The survey also evaluated public acceptance of various technological intervention mechanisms. Results indicated that 98.4% of respondents supported driver notification features that provide alerts when buses are operating too closely to one another. Meanwhile, 96.7% agreed that real-time administrative fleet monitoring would improve public transport operations, and 95.1% supported the use of both automated and manual intervention mechanisms. These findings validate the importance of integrating monitoring and intervention functions within a single framework.

Proposed Bus Bunching Prevention Framework

Based on the findings of the literature review and stakeholder requirements analysis, this study proposes a comprehensive IoT-based Bus Bunching Prevention Framework designed to support proactive public transportation management. The framework integrates real-time vehicle tracking, intelligent headway monitoring, automated driver intervention, and centralized fleet management within a unified operational platform. Unlike conventional fleet monitoring systems that primarily provide location visualization and post-event analysis, the proposed framework emphasizes operational prevention by enabling continuous monitoring, early detection of service irregularities, and timely response mechanisms that can minimize the occurrence of bus bunching before major service disruptions arise.

The proposed framework consists of four interconnected operational layers that work collaboratively to maintain regular bus headways and improve service reliability. The first layer, known as the Real-Time Data Acquisition Layer, is responsible for continuously collecting operational data from buses in service. Each bus is equipped with a GPS module connected to an ESP32 microcontroller that captures and transmits real-time information, including vehicle location, speed, route position, and timestamp data. Through wireless communication networks, this information is sent to a centralized web-based platform for processing and analysis. Continuous data acquisition ensures that fleet movements can be monitored accurately and provides the foundation for real-time decision-making throughout the system.

The second layer, referred to as the Intelligent Headway Monitoring Layer, serves as the analytical engine of the framework. After receiving data from multiple buses operating along the same route, the system continuously calculates temporal and spatial headways between consecutive vehicles. These headways are compared against predefined operational thresholds established by transport operators. When the distance or time interval between buses falls below the acceptable threshold, indicating a potential bus bunching condition, the system automatically identifies the anomaly and generates an intervention alert. This continuous monitoring process enables transportation operators to detect service irregularities at an early

stage, thereby preventing the progressive formation of bus bunching events that can lead to passenger delays, overcrowding, and reduced fleet efficiency.

The third layer, known as the Active Driver Intervention Layer, facilitates immediate corrective action once a potential bus bunching condition has been detected. When the monitoring system identifies buses operating too closely together, automated alerts are transmitted to onboard notification devices such as buzzers or visual indicators installed within the bus. These notifications inform drivers that their vehicles are approaching a critical headway condition and prompt them to take corrective measures, such as adjusting speed or increasing spacing from the preceding vehicle. In addition, the framework incorporates a driver acknowledgment mechanism through a push-button interface, allowing drivers to confirm receipt of notifications and enabling the system to record intervention responses. This direct communication channel supports rapid operational adjustments and strengthens the effectiveness of real-time control strategies.

The fourth layer, the Fleet Management Layer, provides transportation administrators with a centralized platform for monitoring and coordinating fleet operations. Through a web-based dashboard, operators can visualize bus locations in real time, observe current headway conditions, monitor active alerts, and evaluate the operational status of individual vehicles. The dashboard also supports decision-making by providing administrators with timely information needed to implement dispatching strategies, coordinate service recovery actions, and respond to emerging operational issues. By combining automated system intelligence with human supervisory control, the framework creates a comprehensive fleet management environment capable of maintaining service consistency and improving overall transportation performance.

The interaction among the GPS modules, buses, alert mechanisms, and administrative dashboard is illustrated in the context diagram of the proposed framework. The GPS subsystem continuously provides location and speed information to the monitoring platform via the ESP32 controller, enabling accurate vehicle tracking and headway analysis. Once a potential bus bunching event is detected, the system simultaneously generates driver alerts and administrative notifications, ensuring that both operational personnel and transportation managers are informed in real time. This integrated communication architecture promotes faster responses to service disruptions and facilitates coordinated intervention across multiple levels of fleet operations. Overall, the proposed Bus Bunching Prevention Framework transforms traditional fleet monitoring from a passive tracking mechanism into an intelligent and proactive operational control system. By combining continuous data acquisition, automated headway analysis, immediate driver intervention, and centralized fleet supervision, the framework provides a practical, scalable, and cost-effective solution for mitigating bus bunching in public transportation systems. The integration of these capabilities has the potential to improve schedule adherence, reduce passenger waiting times, minimize vehicle overcrowding, enhance resource utilization, and ultimately increase the reliability and efficiency of public transport services. Furthermore, the framework establishes a foundation for future integration with predictive analytics, artificial intelligence, and smart city transportation infrastructures to support more advanced and adaptive transit management strategies

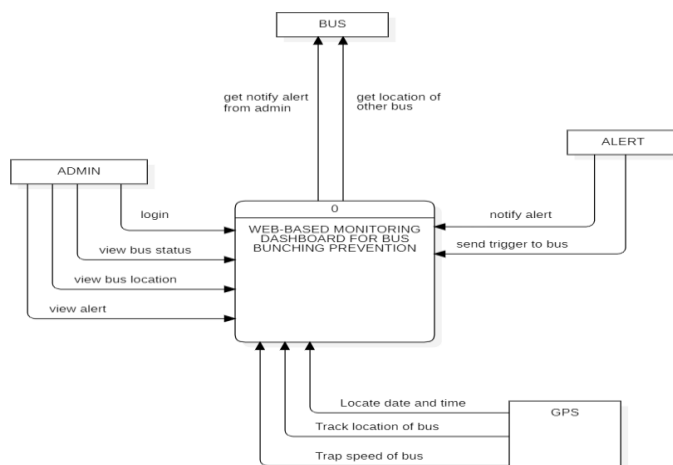


Figure 8: Context Diagram for Proposed Prevention Framework

The context diagram illustrates the overall interaction including the GPS module, bus, and administrator. The GPS module provides real-time location and speed data to the system via the ESP32 microcontroller, allowing accurate tracking of each bus. When two buses are detected to be too close, the system triggers an alert through a buzzer installed in the bus. The bus driver can respond by pressing a push button, which updates the alert status in the system. Meanwhile, the administrator uses a web-based dashboard to monitor live bus data, manage alerts, and ensure proper bus spacing. This interaction ensures effective communication between hardware and software components, enabling timely responses to prevent bus bunching.

Acceptance of Proposed Monitoring System

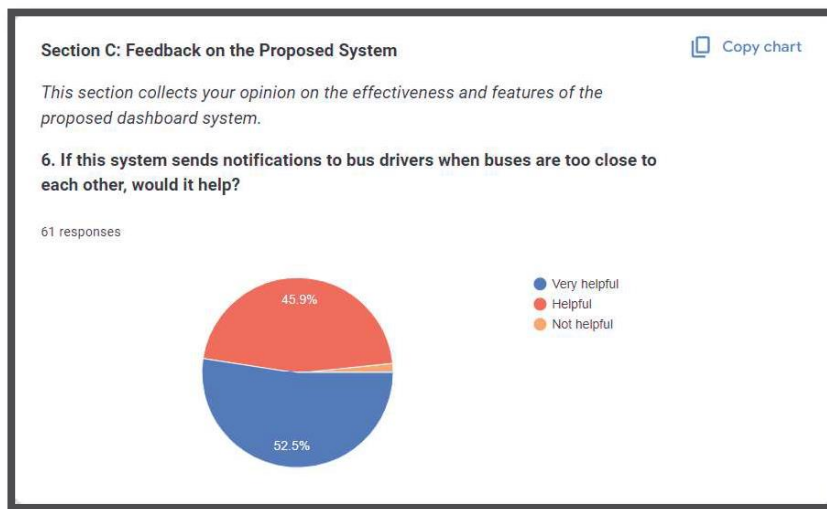


Figure 9: Respondents' opinion on driver notifications

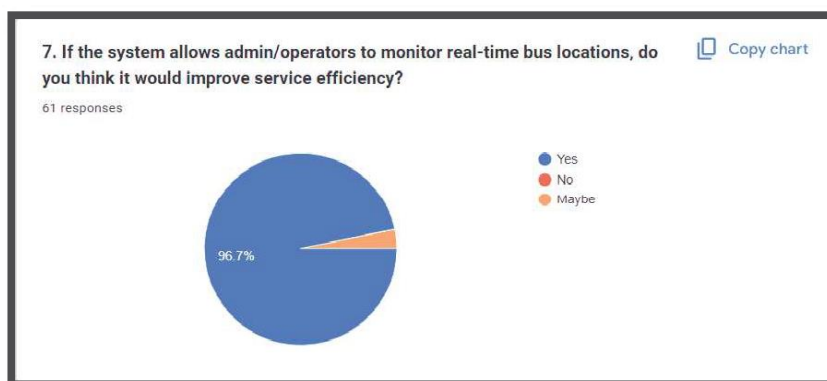


Figure 9: Respondents' view on admin real-time bus monitoring

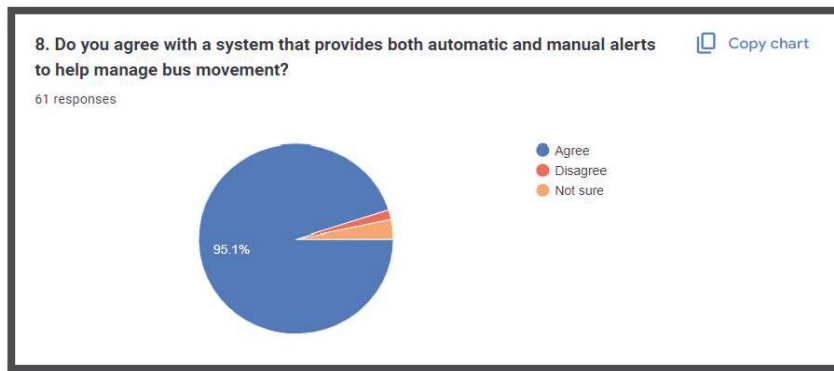


Figure 10 : Agreement with alert features in the system

Public feedback regarding the proposed IoT dashboard features was overwhelmingly positive:

- **Driver Notifications:** 98.4% of respondents agreed that sending real-time alerts to drivers when vehicles are operating too close to one another would improve service.
- **Administrative Real-Time Tracking:** 96.7% agreed that continuous fleet monitoring by transit managers would enhance overall operational efficiency.
- **Dual Alert System:** 95.1% supported incorporating both automated threshold alerts and manual dispatch overrides within the system.

Participants also suggested integrating public-facing GPS tracking links, mobile application access, and estimated time of arrival (ETA) displays at bus stops.

CONCLUSION

This study proposed an IoT-based Bus Bunching Prevention Framework that integrates real-time vehicle tracking, intelligent headway monitoring, automated driver intervention, and centralized fleet management to address one of the most persistent challenges in public transportation operations. The framework was developed to overcome the limitations of existing bus monitoring solutions, which primarily focus on vehicle tracking, post-event analysis, or complex optimization techniques rather than providing proactive operational interventions. By utilizing GPS-enabled ESP32 devices and a centralized monitoring platform, the proposed system enables continuous observation of bus movements, automatic detection of potential bus bunching events, and immediate notification to both drivers and fleet administrators, thereby supporting timely corrective actions.

The findings from the stakeholder survey further validated the relevance and necessity of the proposed framework. A substantial proportion of respondents (70.5%) reported experiencing bus bunching incidents, while inconsistent schedules, long waiting times, overcrowding, and congestion at bus stops were identified as major concerns among public transport users. These results clearly indicate that service reliability remains a critical issue requiring effective technological solutions. Moreover, the overwhelming support for real-time driver notifications (98.4%), administrative fleet monitoring (96.7%), and integrated alert mechanisms (95.1%) demonstrates strong user acceptance of proactive monitoring and intervention technologies.

Overall, the proposed framework contributes a practical, scalable, and cost-effective solution for improving bus service regularity and minimizing the operational impacts of bus bunching. By transforming conventional fleet monitoring from a passive tracking tool into an active decision-support mechanism, the framework has the potential to enhance schedule adherence, reduce passenger waiting times, improve resource utilization, and increase overall public transport reliability. Future work may focus on developing a full prototype implementation, conducting field trials with public transport operators, and integrating predictive analytics and artificial intelligence techniques to further improve intervention effectiveness and system performance.

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