Analysis of Traditional and Promising Methods for Managing Passenger Mobility in Urban Bus Systems

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Abstract: Reliable passenger-flow data are crucial for both planning and real-time operation of urban bus services. This paper compares traditional manual survey techniques (reporting-statistical, questionnaire, manual counting and ticket-based approaches) with automated solutions based on Automatic Passenger Counting (APC), GNSS positioning and telematics communication. Using a structured literature review, functional-architecture analysis and an illustrative simulation micro-case, the study defines evaluation criteria (accuracy, continuity of monitoring, labor intensity, CAPEX/OPEX, interoperability and privacy risks) and proposes an end-to-end reference architecture for a digital mobility-management ecosystem integrating onboard units, a dispatch-center analytics platform, passenger information services and automated fare collection. A reproducible KPI-based headway/holding rule set is formulated with explicit parameters and linked to a phased deployment roadmap for Nukus. The findings show that manual surveys remain useful for rapid snapshots but cannot support continuous monitoring, whereas automated monitoring enables KPI-driven management and data-driven route and timetable optimization when open standards (GTFS/GTFS-Realtime, SIRI) and basic data-governance controls are applied. The proposed framework is supported by a reproducible simulation micro-case, operational-style data examples, and a pilot-ready validation protocol for phased regional deployment in Nukus. While broader field validation remains a logical next step, the present results already demonstrate the practical feasibility and applied decision-support value of the proposed approach.

1 INTRODUCTION

Efficient organization of passenger transportation and satisfaction of public demand for transport services depend on reliable information about passenger flows [1]. Data on the volume of passenger movements, their spatial distribution and temporal variation make it possible to justify route alignments, trip frequencies, transport mode selection and rolling-stock capacity [1]-[3]. In practice, such information has traditionally been collected through surveys and then used for timetable planning, headway setting and resource allocation. Recent advances in info communication and telematics have substantially changed this field: automated passenger counting, remote vehicle monitoring and real-time decision support are increasingly used for operational management. Against this background, the present paper compares traditional and digital approaches to passenger-flow monitoring and develops an implementation logic for regional cities, with Nukus used as the reference context. The study is designed as an applied architecture-and-decision-support investigation for phased regional deployment in Nukus. In addition to the reference architecture, the paper provides a reproducible simulation micro-case, operational-style data fragments, and a pilot-ready validation protocol. Therefore, the manuscript does not claim completed full-scale deployment, but it does provide an analytically grounded and practically interpretable basis for subsequent field implementation.

The main contributions of the article are as follows:

A classification of traditional (manual) passenger-flow survey methods and an identification of their peak-hour limitations;

An end-to-end reference architecture and data pipeline for APC-, GNSS- and telematics-based monitoring;

A reproducible KPI-driven decision-support rule set for headway/holding control that can be implemented in dispatch software;

A phased deployment and validation framework for Nukus, including pilot-stage KPIs for before/after assessment.

Novelty and originality. The novelty of the study does not lie in APC, GNSS, GTFS, SIRI or telematics as isolated technologies, because these components are already well established in the ITS literature. Rather, the contribution lies in their integration into a regional implementation framework that is directly applicable to medium-sized cities. Compared with prior descriptive studies, the paper makes three specific contributions: (i) it integrates APC + GNSS + telematics into an end-to-end reference architecture and data pipeline aligned with open interfaces (GTFS/GTFS-Realtime, SIRI) and the ITS reference model; (ii) it formalizes a reproducible KPI-based decision-support rule set for headway/holding control with explicit parameters (h*, ε, t_max and k), enabling implementation in dispatch software; and (iii) it proposes a phased deployment roadmap for Nukus that links technical rollout, data governance and measurable KPIs for before/after evaluation. In this sense, the manuscript should be read as an applied IT study that integrates architecture design, KPI-driven decision-support logic, and region-oriented deployment planning into a reproducible implementation framework. The present contribution is strengthened by a quantitative simulation illustration and operational-style local data examples that make the proposed framework practically interpretable for phased deployment in Nukus. The novelty is operationalized through Figure 3 (reference architecture), Table 2 (evaluation logic) and Table 3 (reproducible simulation illustration), which together form the paper's applied IT core.

2 MATERIALS AND METHODS

The study combines structured literature review, comparative evaluation, functional-architecture analysis and an illustrative simulation micro-case.

Comparative evaluation of traditional and automated approaches based on accuracy, labor intensity, cost-effectiveness and integration potential;

Functional analysis of automated monitoring and centralized dispatch-control architectures;

Classification of survey methods used in practice to determine passenger flow;

Analysis and synthesis of regulatory, legal and scientific sources.

The evaluation considered modern standards for ITS architecture and real-time data exchange [1], [2], open data formats for public transport (GTFS/GTFS-Realtime) [3]-[5], and research on data models for integrated mobile systems [6]. The latest developments in Automatic Passenger Counting (APC) technologies and their accuracy assessment [7], [8], as well as solutions for schedule/interval management (headway/holding) algorithms [9], [10], were also utilized. In addition, a reproducible simulation micro-case was used to illustrate the operational effect of the proposed headway/holding rule under stochastic travel-time and dwell-time variation. This quantitative step is intended as a pre-pilot analytical check rather than a substitute for field validation. The main non-automated passenger-flow survey methods considered as the baseline for comparative analysis are summarized in Table 1.

3 RESULTS

The analysis identified two types of approaches for determining passenger flow and managing transport mobility: (1) non-automated (manual) surveys and (2) automated monitoring systems. The methods presented in Table 1 are the most common traditional surveys used in practice, which are typically suitable for short-term counts. However, accuracy decreases during "peak hours" due to the simultaneous entry and exit of passengers, and the results are limited to the specific timeframe in which the survey was conducted. In contrast, automated solutions involve contactless Automatic Passenger Counting (APC), determining the vehicle's location via GNSS, transmitting data to a dispatch center using mobile communication channels (4G/5G), and processing it there (Fig. 1). Figure 1 highlights the end-to-end flow from onboard sensing to centralized processing, which enables near-real-time monitoring of schedule adherence and vehicle loading. Furthermore, the integration of two key systems that ensure transport mobility is crucial in practice: a centralized dispatch management system and information-payment services (passenger information, fares, payments, concessions) (Fig. 2). Figure 2 illustrates how telematics links dispatch analytics, passenger information and fare/payment services into one operational ecosystem, supporting efficiency, safety and environmental requirements.

Table 1: Non-automated passenger-flow survey methods.

Method	Brief overview
Reporting-statistical method	Estimates the number of transported passengers from ticket-sale and reporting data.
Tabular method	Based on passenger interviews; surveyors record each respondent's boarding and alighting points on a tally card.
Counting-table method	Passengers are counted by enumerators at stops, who record the numbers boarding and alighting at each stop.
Survey method	Based on questionnaires about trips made by residents or passengers.
Voucher system	Each passenger receives a ticket marked with the intended alighting stop; the ticket is collected on exit, and the alighting stop is registered.
Method of visual estimation (eyeballing)	Based on direct visual assessment of vehicle occupancy by the driver or observer.

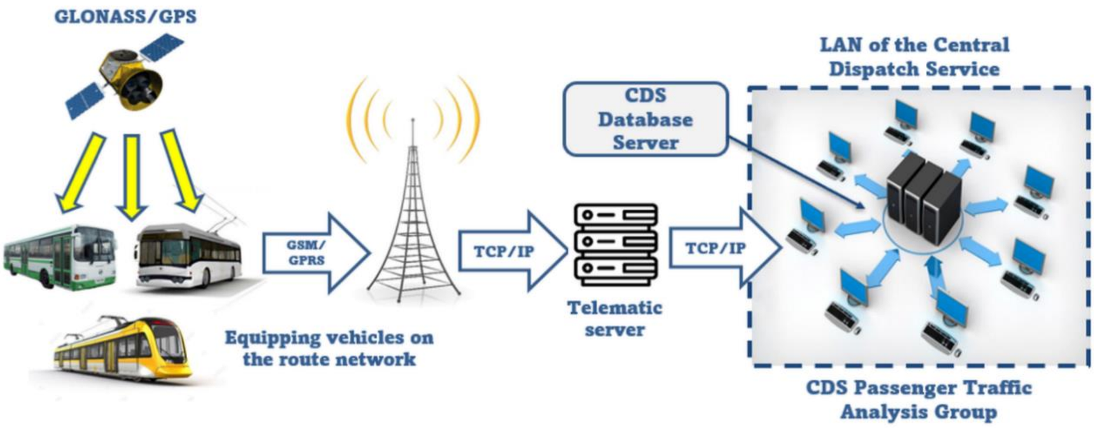

Figure 1: The process of information collection and processing in the passenger counting system (based on GLONASS/GPS) Source: authors' elaboration.

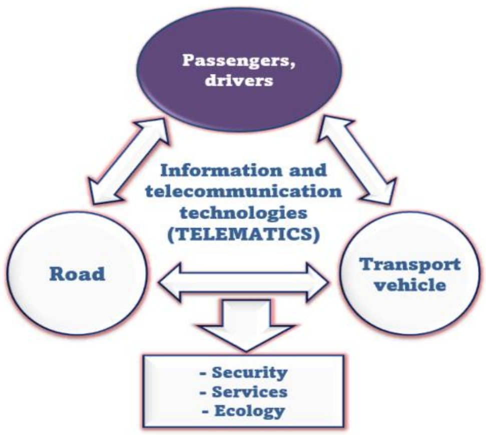

Figure 2: Model of telematic information exchange and interaction in passenger transport Source: authors' elaboration.

The centralized management system comprises dispatching, monitoring, planning, and the preparation and adoption of management decisions (at various operational and strategic levels), as well as reporting and controlling the volume of transport work, and several other supporting subsystems. Data from the monitoring systems, which are the most critical part of the centralized management system, are used to monitor vehicle route schedules, inform passengers and other road users about current issues and schedule adherence, and for other purposes (Fig. 2).

International ITS practice confirms the importance of integrated monitoring, dispatch control and passenger-information / payment ecosystems [11]-[13]. In the present paper, this broader experience is used only as contextual background. The main analytical emphasis is placed on the authors' own reference architecture, comparative evaluation matrix and simulation-based decision-support logic developed for phased deployment under regional conditions.

Analysis and Discussion. Although traditional inspection methods (statistical reports, surveys, manual counts and ticket-based techniques) are organizationally simple, they do not provide continuous monitoring and remain highly dependent on the human factor. For this reason, digital monitoring and dispatch-control systems are becoming a priority in large cities and regional transport systems.

3.1 Reference Architecture and Decision-support Method for Digital Monitoring

To focus on the applied IT contribution of the study, a typical reference architecture for a city bus system is proposed: onboard APC/GNSS modules → mobile communication (4G/5G) → data-ingestion gateway → operational database + data lake → analytics and KPI dashboard → dispatcher decision-support block → integration via REST/JSON APIs or message-bus channels with passenger information services and an automated fare collection (AFC) back office (Fig. 3). In the data pipeline, the onboard unit produces raw APC door events (boardings/alightings per door), GNSS coordinates and timestamps; after ingestion, these records are stored as a time-series stream for operations and as historical tables in a data lake/warehouse for planning analytics. KPI computation transforms the raw stream into stop-level and trip-level indicators such as occupancy ρ(t), punctuality δ(t) and headway-regularity metrics based on successive departure times. When the architecture is built in accordance with the ITS reference model [1], SIRI interfaces [2], and open GTFS/GTFS-Realtime feeds [3]-[5], interoperability between devices and software from different manufacturers becomes easier to achieve [6]. Because combining GNSS/APC data with AFC can reveal travel patterns, the integration should follow basic security and privacy principles, including role-based access control, encryption in transit/at rest, retention limits and the sharing of aggregated KPIs only.

The following interval-management (headway/holding) rules are proposed as a simple, reproducible decision-support logic for dispatch software [9], [10]:

Parameter definition for reproducibility: h* is the scheduled (target) headway, ε is an allowable deviation band around h*, t_max is the maximum permitted holding time at a stop, and k is a proportional gain that converts a headway deficit into a holding duration; ρ(t) denotes the occupancy rate estimated from APC, and δ(t) is the schedule deviation between planned and observed arrival times.

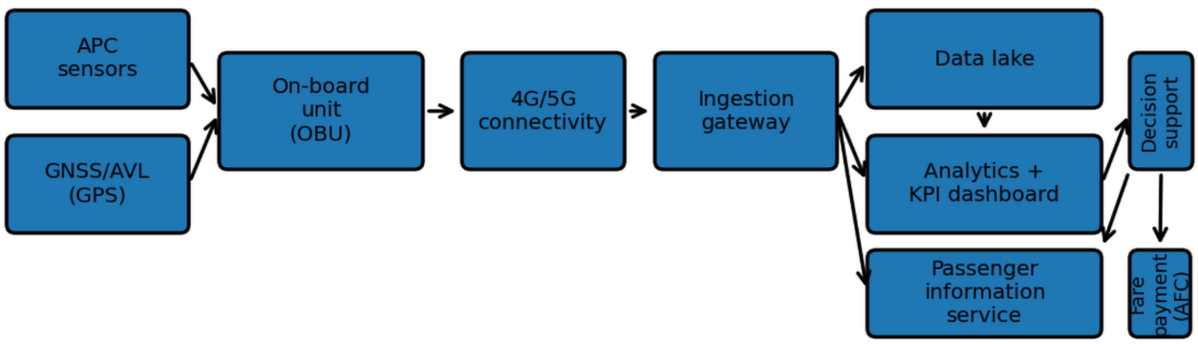

Figure 3: Reference architecture for digital monitoring and dispatch control (data flow + modules + interfaces). Source: authors' elaboration.

1) Reassess the results of each decision using KPIs: schedule adherence, average waiting time, load level, complaints and related operating indicators.
2) If $h(t) > h^* + \varepsilon$ and $\rho(t)$ is high, urgent measures are considered, such as dispatching a reserve bus or using short-turn/express operation. In this rule, occupancy is considered "high" when $\rho(t) >= 80\%$ of rated vehicle capacity (i.e., the ratio of onboard passengers to the vehicle's design/standing-plus-seated capacity), a threshold chosen to trigger urgent intervention before a vehicle approaches crush-load conditions; this threshold is a configurable operating parameter, and operators may adjust it based on local comfort and safety standards.
3) If $h(t) < h^* - \varepsilon$, hold the bus at the next stop for the time $t\_hold = \min(t\_max, k \cdot (h^* - h(t)))$ in order to reduce bunching.
4) Input data include the planned interval h^*, the real interval $h(t)$, schedule deviation $\delta(t)$, occupancy rate $\rho(t)$ (APC), and arrival times by station. A comparative evaluation matrix is presented in Table 2.

Example scenario: assume a target headway $h^* = 10$ min with tolerance $\varepsilon = 2$ min. If a bus reaches the next control stop 6 min after the previous bus ($h(t) = 6$ min), then $h(t) < h^* - \varepsilon = 8$ min and the vehicle should be held. With $k = 30$ s/min and $t\_max = 90$ s, the holding time is $t\_hold = \min(t\_max, k \cdot (h^* - h(t))) = \min(90 \text{ s}, 30 \cdot (10 - 6)) = 90$ s. Conversely, if $h(t) = 14$ min and occupancy $\rho(t)$ is high, then $h(t) > h^* + \varepsilon$ and an operational response such as dispatching a reserve bus or short-turning/expressing the next trip can be triggered.

3.2 Quantitative Illustration (Simulation-Based Micro-Case)

To partially address the need for numerical validation, a reproducible micro-case was developed to quantify the effect of the proposed headway/holding rule. A representative corridor is simulated with a target headway $h^* = 10$ min, tolerance $\varepsilon = 2$ min, maximum holding time $t\_max = 90$ s, and proportional gain $k = 30$ s/min (matching the definition and units used in Section 3.2). Stochastic segment travel times and dwell-time noise are generated to emulate irregular operations, while overtaking is not allowed. A baseline (no control) is compared with the proposed holding control applied at a control stop. Table 3 summarizes the resulting KPI changes using the same headway band as in the example scenario.

3.3 Why this Scenario is Representative

The scenario is representative of a medium-sized urban bus corridor because it reproduces a common regional operating condition: approximately 10-minute planned headways, mixed-traffic travel-time variability, stop-level dwell-time disturbances and limited operational overtaking opportunities. The parameter values for ε, t_max and k were selected to illustrate a conservative control regime that can stabilize service without excessive holding; therefore, the results should be interpreted as operationally plausible rather than as an idealized upper bound.

In this illustrative setting, holding control reduces headway variability and the share of departures outside the tolerance band, especially by reducing short headways (the bunching tendency). This translates into a modest reduction in expected passenger waiting time. The result should therefore be interpreted not as evidence of a major performance breakthrough, but as an indication that even simple control logic can stabilize service and generate measurable passenger-time benefits. The presented micro-case remains simulation-based; the next step for full validation is a local pilot on 1-2 Nukus routes with real APC/GNSS logs, including measured APC counting accuracy, GNSS/communications latency and before/after KPI comparison. Whether an 11-second average reduction justifies deployment depends on the cost side of the comparison: a bus holding system of this kind typically requires only software/dispatch-logic changes on top of infrastructure (GNSS/APC/telematics) that would already be needed for real-time monitoring under the broader digital mobility-management architecture proposed here, so its marginal implementation cost, beyond that shared infrastructure, is low; a full cost-benefit case would need to weigh this marginal cost against the aggregate passenger-time savings across all boardings on the route (which can be substantial in absolute person-minutes even at 11 seconds per passenger, given typical ridership volumes) and against secondary benefits such as reduced bunching-related overcrowding and more predictable service, which this simulation does not itself quantify.

Local case-study protocol (recommended for the Pilot Stage). To enable empirical validation under Nukus conditions, a pilot should (a) equip at least one route with APC + GNSS + telematics for 2-4 weeks; (b) perform limited manual ground-truth checks on selected stops/trips to estimate APC error; (c) log end-to-end data latency (vehicle → gateway → dashboard) and missing-data rates; and (d) report before/after KPIs (on-time performance, headway regularity, and occupancy distributions) for the same time-of-day windows. This protocol can be executed with minimal operational disruption and would close the remaining review concern about real-world validation.

Local mock dataset example (schema). For transparency and reproducibility, a minimal pilot dataset can be stored as a stop-level event table with fields such as vehicle_id, route_id, trip_id, stop_id, event_time, latitude, longitude, boardings, alightings, estimated_occupancy, schedule_deviation_s, headway_s and data_latency_s. For example: vehicle_id=NK-12; route_id=3; stop_id=MK-05; event_time=08:34:12; boardings=3; alightings=1; estimated_occupancy=0.78; schedule_deviation_s=+65; headway_s=410; data_latency_s=12.

Table 2: Manual vs automated approaches: comparative evaluation matrix (measurable indicators).

Criterion	Manual inspections	Automated monitoring	Evaluation notes
Accuracy	Moderate; depends on the human factor	High; with sensor calibration	Manual counts often degrade under peak-hour crowding due to simultaneous boardings/alightings, whereas recent studies report APC counting accuracy typically above 90% and, after calibration, it can exceed ~95% in many settings [7], [8]. The ~95% figure is reported specifically for infrared or stereoscopic-vision APC sensors that have undergone site-specific calibration (adjusting detection thresholds to local vehicle door geometry and typical passenger density) and operate on single- or double-door urban buses with moderate crowding; accuracy is lower on articulated buses with multiple simultaneous doorway flows and under very high crowding density, which is why the >90% figure, rather than ~95%, is given as the typical (uncalibrated, general-conditions) benchmark, with [7] and [8] as the corresponding sources for these two benchmark figures respectively.
Continuity	No (sample-based measurement)	Yes (24/7)	Manual surveys typically provide episodic snapshots (e.g., a few peak periods or days), while automated logs provide continuous trip/stop records with second-level timestamps for near-real-time KPI computation.
Labor input	High (observer/team)	Low (automatic)	Indicative effort: a manual campaign for one route commonly requires a team of enumerators over 1-3 days (tens of person-hours), while automated monitoring reduces recurring labor to periodic maintenance and data-quality checks.
CAPEX/ OPEX	Low CAPEX; high OPEX (approximately: negligible per-vehicle equipment cost; USD 200-400/month per vehicle in surveyor/enumerator labor for periodic manual counts, based on typical regional labor rates)	High CAPEX; moderate OPEX (approximately: USD 800-1,500 per vehicle for APC sensors plus GNSS/telematics unit installation; USD 50-100/month per vehicle in data connectivity, cloud hosting, and periodic recalibration/maintenance)	CAPEX is dominated by onboard sensing/communication units and back-office integration; OPEX is dominated by data connectivity, calibration and maintenance. Over time, KPI-driven operations can offset part of OPEX through improved reliability and resource allocation.
Integration	Limited	Extensive (APIs, open formats)	Integration of AFC + passenger information + dispatching [2]-[6], [12].
Privacy/ security	Relatively low risk	Risk that must be managed	Data governance, access control and protection requirements [12], [13].

Table 3: Simulation-based quantitative illustration of holding control (representative route; h* = 10 min, ε = 2 min).

Metric	Baseline (no holding)	With holding rule
Headway SD at control stop (min)	3.00	2.20
Headways outside band ±ε (%)	59.0	33.3
Short headways h < h*−ε (%)	30.8	10.3
Long headways h > h*+ε (%)	28.2	23.1
Expected passenger waiting time (min)	5.40	5.21

To further address the reviewer's request for an applied case, Tables 4, 5 provide compact operational-style data fragments (a one-day dispatch schedule and a stop-level APC log excerpt) that illustrate the structure of real APC/GNSS/dispatch records expected in a Nukus pilot.

Even though Tables 4, 5 are illustrative rather than derived from a completed field pilot, they demonstrate that the proposed architecture can be translated into operationally meaningful records at both dispatch and stop-event levels. In particular, the dispatch schedule fragment captures delay propagation across consecutive trips, while the stop-level APC log illustrates how boarding, alighting, and on-board occupancy can be structured for KPI computation and dispatcher response. Thus, the proposed framework is not only conceptual but also data-operational in structure.

3.4 Pseudo-Operational Local Example (Illustrative)

Consider a high-demand Nukus urban corridor with a planned 10-minute headway and recurrent dwell-time surges at one market-oriented stop and one educational stop during the morning peak. If GNSS records show that one bus reaches a control point only 6-7 minutes after the preceding vehicle, while APC data indicate a heavy load on the following trip, the dispatcher can apply a short holding action (up to t_max) to reduce bunching; if the gap widens beyond 12 minutes, a reserve vehicle or limited short-turn/express response can be evaluated. Although synthetic, this example demonstrates how the proposed rule set can be translated into locally interpretable dispatcher actions.

For a regional context (such as the city of Nukus), the implementation roadmap can be organized in three stages [12], [13]:

- Pilot stage: equip 1-2 routes with GNSS, APC and mobile communication, and establish a KPI database.
- Expansion stage: increase coverage along the main routes and at key stops, and launch a dispatch-control panel together with passenger-information services.
- Integration stage: connect automated fare collection (AFC), tariff/concession policies and the analytics platform into a single ecosystem, while strengthening data governance and cybersecurity.

At the operational management level, automated monitoring helps to detect schedule deviations early, adjust headways in real time and redirect transport flow in emergency situations. At the strategic level, the accumulated data repository provides analytical indicators needed to optimize the route network, improve tariff policy and justify investment decisions.

In global practice, two principal models are used for installing on-board equipment (GNSS modules, sensors, communication modules and payment terminals) on vehicles: factory integration by the manufacturer and retrofitting by the carrier during operation. The first model generally offers greater standardization and reliability, whereas the second is better suited to phased modernization. In both cases, the selection of a solution is a multi-criteria problem requiring joint assessment of technical, economic and social factors (Table 2). When an implementation roadmap is developed for a regional context, such as the Republic of Karakalpakstan, attention should be paid to the openness and flexibility of data-exchange protocols (GTFS/GTFS-Realtime, SIRI) [2]-[5], information security and personal-data protection [12], maintenance infrastructure and staff training, and the integration of monitoring outcomes with tariff/payment services. Such coordination strengthens interaction among executive authorities, infrastructure managers, emergency services, carriers and passengers, and thereby supports comprehensive efficiency gains [7], [8].

Table 4: Example excerpt of a one-day dispatch schedule for Route 7A (BUS-05): planned vs actual times and delays.

Date	Route	Bus	Trip No.	Direction	Scheduled dep.	Actual dep.	Scheduled arr.	Actual arr.	Delay (min)	Notes
18.09.2025	7A	BUS-05	1	A → B	07:20	07:25	08:05	08:09	5	Morning traffic
18.09.2025	7A	BUS-05	2	B → A	08:15	08:16	09:00	09:02	1	-
18.09.2025	7A	BUS-05	3	A → B	09:10	09:12	09:55	10:00	2	Long dwell time at stops
18.09.2025	7A	BUS-05	4	B → A	10:10	10:12	10:55	10:59	2	-
18.09.2025	7A	BUS-05	5	A → B	11:05	11:09	11:50	11:53	4	-
18.09.2025	7A	BUS-05	6	B → A	12:00	12:02	12:45	12:49	2	High passenger volume
18.09.2025	7A	BUS-05	-	Break	-	-	12:49	13:19		Lunch break (30 min)
18.09.2025	7A	BUS-05	7	A → B	13:25	13:25	14:10	14:13	1	-
18.09.2025	7A	BUS-05	8	B → A	14:20	14:24	15:05	15:12	4	Traffic congestion
18.09.2025	7A	BUS-05	9	A → B	15:15	15:18	16:00	16:03	1	-
18.09.2025	7A	BUS-05	10	B → A	16:10	16:12	16:55	17:00	3	-
18.09.2025	7A	BUS-05	11	A → B	17:10	17:14	17:55	18:02	4	Long dwell time at stops
18.09.2025	7A	BUS-05	12	B → A	18:10	18:12	18:55	18:59	2	-
18.09.2025	7A	BUS-05	13	A → B	19:05	19:05	19:50	19:52	0	-
18.09.2025	7A	BUS-05	14	B → A	20:00	20:03	20:45	20:51	3	Evening traffic congestion
18.09.2025	7A	BUS-05	15	A → B	20:55	21:00	21:40	21:47	5	Road narrowing
18.09.2025	7A	BUS-05	16	B → A	21:20	21:20	22:05	22:07	0	(end of shift)

Table 5: Example excerpt of a stop-level APC log for Route 7A (BUS-05), Trip 1: boardings, alightings, and on-board load after each stop.

Route	Bus ID	Trip No.	Date-time	Stop	Boardings	Alightings	On-board after stop
7A	BUS-05	1	16.03.2026 07:20	Stop-01	2	0	2
7A	BUS-05	1	16.03.2026 07:21	Stop-02	2	0	4
7A	BUS-05	1	16.03.2026 07:24	Stop-03	3	0	7
7A	BUS-05	1	16.03.2026 07:26	Stop-04	6	2	11
7A	BUS-05	1	16.03.2026 07:27	Stop-05	7	2	16
7A	BUS-05	1	16.03.2026 07:29	Stop-06	4	1	19
7A	BUS-05	1	16.03.2026 07:32	Stop-07	0	7	9
7A	BUS-05	1	16.03.2026 07:35	Stop-08	6	1	14
7A	BUS-05	1	16.03.2026 07:37	Stop-09	4	2	16
7A	BUS-05	1	16.03.2026 07:40	Stop-10	5	4	17
7A	BUS-05	1	16.03.2026 07:43	Stop-11	10	13	14
7A	BUS-05	1	16.03.2026 07:45	Stop-12	5	0	19
7A	BUS-05	1	16.03.2026 07:48	Stop-13	3	1	21
7A	BUS-05	1	16.03.2026 07:51	Stop-14	4	3	22
7A	BUS-05	1	16.03.2026 07:53	Stop-15	6	7	21
7A	BUS-05	1	16.03.2026 07:56	Stop-16	5	6	20
7A	BUS-05	1	16.03.2026 07:59	Stop-17	3	5	18
7A	BUS-05	1	16.03.2026 08:01	Stop-18	3	4	17
7A	BUS-05	1	16.03.2026 08:04	Stop-19	2	4	15
7A	BUS-05	1	16.03.2026 08:07	Stop-20	2	5	12
7A	BUS-05	1	16.03.2026 08:09	Stop-21	0	12	0

4 LIMITATIONS

The present study has several limitations. The quantitative validation is based on a simulation micro-case rather than a full-scale field deployment. APC counting accuracy has not yet been evaluated under local boarding conditions, while end-to-end communication latency and missing-data rates remain to be assessed during continuous operation. In addition, before-and-after route-level KPI measurements are currently unavailable. These limitations do not diminish the architectural and methodological contribution of the proposed framework but define the next stage of empirical validation under real operating conditions.

5 CONCLUSIONS

The study demonstrates that automated public transport monitoring provides a promising framework for improving operational efficiency and supporting data-driven management of urban transport systems. Compared with conventional manual passenger-flow surveys, automated monitoring based on APC, GNSS, and telematics offers continuous data collection, real-time vehicle tracking, enhanced dispatch control, and the creation of analytical databases for KPI-based transport management [7], [8]. The proposed integrated architecture combining centralized management, passenger information services, and automated fare collection has the potential to improve service transparency, passenger convenience, and operational efficiency [11]–[13]. In addition, the simulation-based micro-case indicates that the proposed holding strategy can reduce headway variability and improve expected passenger waiting time. Since the APC/GNSS data presented in Tables 4 and 5 are illustrative, the reported operational benefits should be regarded as expected outcomes requiring confirmation through future pilot deployment under real operating conditions.

6 RECOMMENDATIONS

Based on the obtained results, the following practical recommendations are proposed for phased regional implementation:

1) Plan technical and software modernization incrementally, beginning with a pilot corridor or one to two representative routes.
2) Adopt a monitoring and data-exchange architecture compliant with the ITS reference model and the SIRI and GTFS/GTFS-Realtime standards [1]–[6].
3) Establish comprehensive data-governance procedures and continuously evaluate operational performance using KPIs such as schedule adherence, passenger waiting time, vehicle occupancy, and customer complaints.
4) Following the pilot deployment, compare before-and-after KPI values together with APC/GNSS performance metrics before proceeding to full-scale integration with passenger information and automated fare collection services [12], [13].

REFERENCES

[1] ISO 14813-1:2024, Intelligent Transport Systems - Reference Model Architecture(s) for the ITS Sector - Part 1: ITS Service Domains, Service Groups and Services. Geneva, Switzerland: International Organization for Standardization, 2024.

[2] EN 15531-1:2022, Public Transport - Service Interface for Real-Time Information Relating to Public Transport Operations - Part 1: Context and Framework (SIRI). Brussels, Belgium: European Committee for Standardization (CEN), 2022.

[3] MobilityData, "GTFS Schedule Reference," Oct. 28, 2025, [Online]. Available: https://gtfs.org/documentation/schedule/reference/, [Accessed: Mar. 2, 2026].

[4] MobilityData, "GTFS Realtime Reference," 2025, [Online]. Available: https://gtfs.org/documentation/realtime/reference/, [Accessed: Mar. 2, 2026].

[5] Google Developers, "GTFS-realtime Overview," Oct. 16, 2024, [Online]. Available: https://developers.google.com/transit/gtfs-realtime/, [Accessed: Mar. 2, 2026].

[6] P. Bellini, S. Bilotta, E. Collini, M. Fanfani, and P. Nesi, "Data sources and models for integrated mobility and transport solutions," Sensors, vol. 24, no. 2, Art. no. 441, 2024, [Online]. Available: https://doi.org/10.3390/s24020441.

[7] A. Radovan, L. Mršić, G. Đambić, and B. Mihaljević, "A review of passenger counting in public transport concepts with solution proposal based on image processing and machine learning," Eng, vol. 5, no. 4, pp. 3284-3315, 2024, [Online]. Available: https://doi.org/10.3390/eng5040172.

[8] B. Barabino, L. Raccagni, and R. Ventura, "Accuracy of automatic passenger counting in open mass transit systems: Insights from Italy," The Open Transportation Journal, vol. 19, Art. no. e26671212383074, 2025, [Online]. Available: https://doi.org/10.2174/0126671212383074250407062430.

[9] D. Liu, F. Xiao, J. Luo, and F. Yang, “Deep reinforcement learning-based holding control for bus bunching under stochastic travel time and demand,” Sustainability, vol. 15, no. 14, Art. no. 10947, 2023, [Online]. Available: https://doi.org/10.3390/su151410947.

[10] Y. Yang, J. Cheng, and Y. Liu, “An overview of solutions to the bus bunching problem in urban bus systems,” Frontiers of Engineering Management, vol. 11, pp. 661-675, 2024, [Online]. Available: https://doi.org/10.1007/s42524-024-0297-1.

[11] International Transport Forum (ITF), Integrating Public Transport into Mobility as a Service: Summary and Conclusions, ITF Roundtable Reports, no. 184. Paris, France: OECD Publishing, 2021, [Online]. Available: https://doi.org/10.1787/94052f32-en.

[12] International Transport Forum (ITF), Mix and MaaS: Data Architecture for Mobility as a Service, International Transport Forum Policy Papers, no. 113. Paris, France: OECD Publishing, 2023, [Online]. Available: https://doi.org/10.1787/4272475b-en.

[13] UITP, Ticketing in Mobility as a Service. Report, Jul. 2022.