International Journal of Exact Sciences

ISSN 2966-1153 vol. 3, n. 1, 2026

ARTICLE 1
Acceptance date: 11/03/2026

TOWARDS SMART FARE PRICING: PREDICTIVE ALGORITHMS AND BLOCKCHAIN FOR DYNAMIC PRICE OPTIMIZATION IN PASSENGER TRANSPORT

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Abstract: Dynamic pricing in passenger transport services is undergoing a profound transformation driven by big data, artificial intelligence, and blockchain technology. This article proposes an integrated framework that combines predictive algorithms with blockchain infrastructure to optimize real time pricing strategies, improving both operational efficiency and end-user satisfaction. Using machine learning techniques, specifically time-series models and demand elasticity estimation, a dynamic pricing engine is developed that adjusts fares according to demand fluctuations, user segmentation, and external variables (such as weather, events, and traffic conditions). In parallel, blockchain technology is implemented to ensure transparency, traceability, and automation of fare transactions through smart contracts, reducing fraud and guaranteeing data immutability.

Keywords: dynamic pricing, predictive algorithms, blockchain, transportation systems, smart contracts

INTRODUCTION

In the current context of digital transformation, the passenger transport sector faces significant challenges related to operational efficiency, revenue optimization, and end-user satisfaction. One of the most critical aspects is pricing strategy, which has traditionally been static or rule-based and is increasingly ineffective in the face of demand volatility and growing expectations for personalization (Sharan et al., 2020). In this scenario, dynamic pricing emerges as a viable solution, enabling real time fare adjustments based on contextual variables, consumer behavior patterns, and market conditions.

The application of predictive algorithms based on artificial intelligence (AI) and machine learning has proven to be a powerful tool for demand forecasting and the design of more accurate and adaptive pricing strategies (Zhang & Zhao, 2024). However, this approach raises challenges related to transparency, traceability of algorithmic decisions, and data security, particularly in sensitive sectors such as public transport subject to local and national regulations.

Blockchain technology provides a complementary approach by offering a decentralized, immutable, and auditable environment for managing fare transactions through smart contracts that automate pricing rules and strengthen trust between operators and end users (Saberi et al., 2019). The integration of blockchain with predictive algorithms opens a new paradigm in fare management, with the potential to redefine business rules in passenger mobility.

Despite these advantages, there are few integrated implementations combining both approaches in the passenger transport sector, particularly in urban and interurban contexts. Therefore, this research proposes and validates a hybrid dynamic pricing model that incorporates demand forecasting algorithms and blockchain-based infrastructure, aiming to improve system efficiency, increase revenues, and enhance users' perception of transparency (Maestre et al., 2023).

This article is structured as follows: first, a critical review of the literature on dynamic pricing, predictive algorithms, and blockchain applications in transport is presented. Next, the theoretical framework underpinning the proposed model is outlined.

The methodology section details the technical architecture and validation methods, followed by a real-world case study. Finally, results, discussion, and conclusions are presented, including recommendations for implementation and future research directions.

This study addresses the following research questions:

RQ1: Can predictive demand algorithms significantly improve fare optimization accuracy in urban passenger transport?

RQ2: Does the integration of blockchain based smart contracts enhance transparency and user trust without compromising system performance?

To address these research questions, the study adopts a mixed-methods research design combining quantitative experimental analysis with qualitative analytical inquiry. This design allows both the statistical evaluation of system performance and the contextual interpretation of user and institutional responses. Specifically, the quantitative component addresses RQ1 by evaluating predictive accuracy, revenue performance, and system latency, while the qualitative component addresses RQ2 by analysing user trust, transparency perception, and institutional acceptance. Table 1 and Sections 4.1 and 4.2 report the empirical indicators associated with each research question. This structure ensures methodological traceability from research questions to empirical indicators and observed outcomes.

Literature Review

Pricing in passenger transport has traditionally been governed by municipal regulations, public subsidies, or general fare policies. However, with the advent of digitalization and increased competition, particularly in deregulated or semiregulated markets, dynamic pricing has gained prominence as a mechanism to maximize revenue and respond to fluctuations in demand (Zhang & Zhao, 2024).

Traditional pricing models in passenger transport

Conventional fare systems, widely applied in public and private transport, are typically based on fixed cost structures, zonal pricing, or simple time based segmentation (peak/off-peak). While these models facilitate predictable budget planning, they lack the flexibility to respond efficiently to unexpected demand spikes or emerging mobility patterns (Lu et al., 2024). Moreover, they often ignore price elasticity, leading to inefficiencies and lost revenue opportunities.

Dynamic pricing and predictive algorithms

Recent literature highlights the potential of demand forecasting algorithms as enablers of dynamic pricing systems. Machine learning models, such as neural networks, decision trees, ARIMA models, and XGBoost, have been successfully applied to estimate passenger behavior (Sharan et al., 2020). These approaches capture temporal, seasonal, and contextual patterns more accurately than classical statistical methods.

For instance, Sharan et al. (2020) developed an LSTM based approach to forecast urban transport demand, achieving significant improvements over linear models. The inclusion of contextual variables such as major events, weather conditions, or traffic disruptions has also proven critical to prediction quality (Huang et al., 2020).

DOI https://doi.org/10.22533/at.ed.8208312611031

Dynamic pricing systems not only forecast demand but also incorporate price sensitivity models. Studies show that price personalization based on user profiles can maximize revenue without negatively affecting equity, provided transparency and regulation are ensured (Sharan et al., 2020).

Blockchain applications in passenger fare systems

Blockchain technology has gained increasing relevance in passenger transport, not only for its security and decentralization capabilities but also for its applicability to automated fare systems via smart contracts. In multi-stakeholder environments (operators, intermediaries, users, regulators), blockchain offers a trusted infrastructure for recording and verifying transactions without centralized intermediaries (Saberi et al., 2019).

Duan et al. (2023) emphasize that blockchain's traceability and immutability are particularly valuable for resolving fare disputes, auditing real time pricing processes, and strengthening user trust. Additionally, cryptographic tokens enable incentive schemes, passenger loyalty programs, and behavior adjusted dynamic fares, facilitating the transition toward interoperable Mobility as a Service (MaaS) ecosystem (Li et al., 2020).

Towards AI blockchain integration in passenger mobility

While the individual benefits of AI and blockchain are well documented, their combined application in passenger transport remains at an early stage. This synergy enables highly accurate demand prediction while ensuring that resulting fares are applied automatically, securely, and auditable through smart contracts. According to Karger et al. (2021), such hybrid approaches can reduce regulatory friction, lower operational costs, and create more transparent and efficient systems.

In summary, the literature indicates that convergence between predictive algorithms and blockchain technology represents an emerging pathway for innovation in fare strategies, although technical, regulatory, and governance challenges must be addressed for large-scale adoption.

Theoretical and conceptual framework

This article is grounded in three theoretical pillars: the economics of dynamic pricing, demand forecasting algorithms in intelligent environments, and principles of distributed governance enabled by blockchain technology. This framework provides the conceptual foundations for building an integrated model that optimizes fare setting in passenger transport services, considering not only technical efficiency but also transparency and equity in price application.

Dynamic pricing theory in demand sensitive markets

The concept of dynamic pricing originates from microeconomic theory applied to markets characterized by high demand elasticity and limited short-term supply capacity. This approach involves adjusting prices according to changing market conditions in order to maximize expected utility or total revenue (Talluri & van Ryzin, 2004). In the transport sector, dynamic fares have become widespread through platforms such as Uber or Lyft, where prices vary according to local

DOI https://doi.org/10.22533/at.ed.8208312611031

demand, vehicle availability, and external factors such as weather conditions or public events (Burrell, 2016).

In this context, the relationship between price and demand is governed by elasticity models that make it possible to anticipate user sensitivity to fare changes. As suggested by Sharan et al. (2020), dynamically priced fares can be ethically compatible with social efficiency objectives, if principles of equity and transparency are explicitly incorporated into their design and implementation.

Demand forecasting through machine learning algorithms

The integration of predictive algorithms into pricing mechanisms is rooted in cyber-physical systems and artificial intelligence, particularly in their ability to learn complex patterns from large volumes of historical and real time data (Goodfellow et al., 2016). Time-series models such as ARIMA, Prophet, and LSTM neural networks are especially effective in capturing both seasonality and non-linearity in urban mobility data (Hyndman & Athanasopoulos, 2018).

Conceptually, these models rely on supervised regression functions in which independent variables may include not only temporal indicators (hour, day, season, etc.), but also contextual features such as weather conditions, school calendars, public holidays, roadworks, and even sporting or social events (Huang et al., 2020). This perspective aligns with the Mobility as a Service (MaaS) approach, which seeks to integrate supply, demand, and user experience within a unified cognitive architecture (Kamargianni et al., 2016).

Foundations of blockchain technology and smart contracts in passenger mobility

Blockchain technology, as a form of distributed ledger technology (DLT), ensures data immutability, auditability, and decentralization through cryptographic and consensus mechanisms (Jaime, 2019). When applied to transport systems, blockchain enables each transaction to be recorded transparently, tamper-resistantly, and accessibly for all participating stakeholders.

A key component within the blockchain conceptual framework is the use of smart contracts, which allow predefined fare conditions to be executed automatically without human intervention, thereby reducing operational errors and administrative costs (Christidis & Devetsikiotis, 2016). Recent literature highlights that smart contracts can incorporate conditional fares, cancellation penalties, or user loyalty incentives, significantly increasing system flexibility (Saberi et al., 2019).

Conceptual convergence: towards an autonomous and transparent pricing system

The convergence of these three elements gives rise to cognitive and distributed fare systems capable of anticipating demand scenarios, assigning optimal prices in real time, and ensuring that pricing decisions are both auditable and ethically enforceable. This integration is consistent with emerging approaches in explainable artificial intelligence (XAI) and algorithmic governance (Burrell, 2016), which aim not only to optimize decisión making but also to make such decisions understandable and acceptable to users and public regulators.

This theoretical framework underpins the architecture proposed in this article, in which a machine learning based pricing engine is connected to a blockchain layer that applies fares through auditable smart contracts. Accordingly, the proposed model seeks not only to maximize revenues, but also to strengthen end-user trust and enhance system-wide traceability.

METHODOLOGY

This article adopts a mixed method, quasi experimental research design (quantitative experimental and qualitative analytical) with the objective of designing, implementing, and validating a dynamic fare pricing model based on demand forecasting algorithms integrated with blockchain technology. The methodology is structured into four main phases: (i) data collection and preprocessing, (ii) development of the predictive model, (iii) implementation of the smart contract system, and (iv) experimental validation through a pilot study in a real urban transport environment.

Data collection and preprocessing

Historical data were collected over a 12 month period from a mid-sized urban public transport operator located in a Latin American city. The dataset included:

- Passenger ticket validation records (timestamp, route, station, and anonymized user ID).
- External variables: weather conditions (temperature and precipitation), special events, and traffic congestion indicators.
- Socioeconomic and demographic indicators by origin to destination zone.

All data were anonymized in compliance with the General Data Protection Regulation (GDPR) and processed using data cleaning techniques, missing value imputation, and z-score normalization prior to model development (Kotsiantis et al., 2006).

Although the dataset corresponds to a single midsized Latin American city, its operational characteristics, demand volatility, and fare structure are representative of many urban bus systems in emerging metropolitan contexts. Therefore, while the findings should not be interpreted as universally generalizable, they provide strong analytical transferability to comparable urban public transport systems operating under similar demand volatility and regulatory constraints. This approach follows established practices in applied transport research, where controlled pilot studies are used to balance realism and analytical rigor.

Predictive model design

A supervised learning approach based on Long Short Term Memory (LSTM) networks was employed due to their ability to model time series with long-term dependencies (Hochreiter & Schmidhuber, 1997). The model was trained to predict hourly passenger demand (number of validations per route and time slot) by route using a training set (70%) and a validation set (30%) with cross validation. Evaluation metrics included root mean square error (RMSE), mean absolute error (MAE), and the coefficient of determination (R^2). Model hyperparameters were optimized using Bayesian optimization over the validation set to balance predictive accuracy and model generalization. This approach was selected to prevent overfitting and to ensure robustness under non-stationary demand conditions.

In addition, price demand elasticity models were integrated using logistic regression to estimate fare sensitivity across user segments, considering estimated income levels, usage frequency, and travel purposes (Train, 2009). These elasticity estimates directly inform the fare optimization process evaluated under RQ1.

Implementation of the blockchain layer and smart contracts

The system was implemented on a permissioned blockchain based on Hyperledger Fabric, selected for its flexibility, scalability, and modular governance architecture (Androulaki et al., 2018). Smart contracts were developed in the Go programming language and deployed across nodes validated by the transport operator and a regulatory authority. Unlike centralized databases, the blockchain layer ensures tamper resistance and multistakeholder auditability, which are critical requirements in regulated public transport environments. This design choice responds not only to technical considerations but also to governance requirements in public transport systems, where transparency, auditability, and institutional trust are critical. The impact of this layer is empirically assessed through fraud reduction, transaction latency, and perceived transparency indicators.

Smart contract functionalities include:

- Automatic registration and validation of issued fares.
- Application of fare rules based on demand-related parameters.
- Automated auditing by third parties (users and regulators).
- End to end traceability and immutability of each transaction.

System latency and real time responsiveness were evaluated, ensuring that fare issuance and validation during demand peaks complied with real time operational requirements (<400 ms).

Empirical validation in a real world environment

A quasi experimental design was implemented over a six week period on three high demand transport routes. A control group operating under a traditional fixed fare scheme and an experimental group using dynamic pricing supported by blockchain technology were established. Statistical significance was assessed at a confidence level of $\alpha = 0.05$. The following indicators were measured:

- Improvement in demand prediction accuracy (ΔR^2).
- Variation in average daily revenue (%).
- Level of user acceptance and trust (measured through post use surveys).
- System response times.

Results were analysed using statistical tests (Student's t-test and ANOVA) to assess the significance of observed differences between both groups. In addition, semi structured interviews were conducted with system managers, frequent users, and regulatory authorities to explore perceived barriers and facilitators to adoption. A total of 12 semi structured interviews were conducted using purposive sampling to capture

DOI https://doi.org/10.22533/at.ed.8208312611031

operational, user, and regulatory perspectives. Interviews were analysed using thematic coding to identify recurring patterns related to adoption barriers, trust formation, and regulatory concerns. Routes were selected to ensure comparable demand levels and operational conditions between control and experimental groups.

Ethical and regulatory considerations

The research was reviewed and approved by a university ethics committee and adhered to principles of algorithmic fairness, non-discrimination, and informed consent. User participation was voluntary, and all data were protected in accordance with FAIR principles (findable, accessible, interoperable and reusable) to ensure the ethical use of artificial intelligence.

CASE STUDY: PILOT IMPLEMENTATION OF THE PROPOSED SYSTEM

To empirically validate the proposed dynamic fare framework supported by predictive algorithms and blockchain technology, a controlled pilot study was designed and implemented in a real urban environment. This case study was developed in collaboration with a public transport operator serving a Latin American city with approximately 1.2 million inhabitants. The city operates a medium-capacity bus transport system equipped with electronic fare validation and 4G connectivity across the vehicle fleet, providing the minimum technical conditions required to deploy the proposed system architecture.

Operational context and route selection

To ensure methodological robustness, three high-demand trunk routes were selected. These routes operate at frequencies below 10 minutes and serve areas with differing demographic densities and socioeconomic profiles. Two groups were defined:

- Experimental group: routes where the proposed dynamic pricing system supported by blockchain technology was applied.
- Control group: routes where the traditional flat-fare pricing scheme was maintained.

The experiment was conducted over six consecutive weeks, covering weekdays, weekends, and public holidays, to control for variability in passenger demand behavior.

Technical and operational system implementation

The LSTM based predictive model, trained on historical data, was deployed on cloud servers with real time inference executed every 10 minutes. Forecast outputs fed a pricing engine that computed optimal fares segmented by time slot and projected occupancy level. These fares were recorded and enforced through smart contracts deployed on a private blockchain based on Hyperledger Fabric (Androulaki et al., 2018).

Fare updates were communicated through smart bus stops and the operator's mobile application. On-board ticket validators queried the applicable fare in real time via a secure API and executed the corresponding deduction through blockchain-based smart contracts, which were cryptographi-

DOI https://doi.org/10.22533/at.ed.8208312611031

cally signed and immutably stored (Christidis & Devetsikiotis, 2016).

Integrated system architecture

The functional architecture of the proposed system comprises the following main components:

- Data acquisition module: Collects real time information from multiple sources, including IoT sensors (onboard passenger counts and traffic conditions), external APIs (weather and urban events), and historical demand and user behavior data (Zhang et al., 2019).
- Demand prediction engine: Employs multivariate LSTM models trained on time-series data to forecast passenger demand up to 60 minutes in advance.
- Dynamic pricing algorithm: Integrates demand forecasts, segment-level elasticity estimates, and contextual conditions to continuously generate optimal fares.
- Blockchain layer: Implemented using Hyperledger Fabric, managing fare transactions through smart contracts that:
  - Validate fare conditions and execute automated payments.
  - Record events in an immutable ledger for auditability.
  - Provide partial public access for citizen verification (Christidis & Devetsikiotis, 2016).

Quantitative results of the pilot study

System performance indicators were evaluated by comparing experimental routes with control routes. The main results were as follows:

- Improved demand prediction accuracy: The model achieved an average R^2 of 0.87, reducing mean absolute error by 19% compared to a traditional ARIMA model (Hyndman & Athanasopoulos, 2018).
- Increase in average daily revenue per route: An average revenue increase of 12.4% was observed, driven by higher willingness to pay during peak hours and increased occupancy during off peak periods enabled by reduced fares.
- Reduction in fare evasion: By automating and recording each transaction on the blockchain, more than 1,000 unauthorized validation attempts were detected and corrected through forensic log analysis, resulting in a 7% reduction in fraud related losses.
- System latency: The average fare query and validation time was 342 ms, meeting real time operational requirements (<400 ms).

Qualitative evaluation: User perception

A total of 400 structured surveys were conducted with frequent users from both experimental and control conditions, administered at terminals and through the mobile application. Key findings include:

- 76% of users in the experimental group perceived greater fare fairness, positively valuing lower prices during off-peak hours.
- 68% reported increased trust in the system due to perceived traceability and transparency, attributed to explicit communication regarding the use of blockchain technology.
- However, 14% expressed confusion regarding fare variability, highlighting challenges related to user communication and digital inclusion.

In addition, semi structured interviews were conducted with transport company officials and local regulatory authorities. Institutional barriers to large scale adoption were identified, including legal restrictions on variable pricing in public services and the need for regulatory updates to recognize smart contracts as legally valid instruments for fare management (Saberi et al., 2019).

Example of a smart contract

```
contract DynamicFare {
    address public operator;
    uint public baseFare;

    constructor(uint _baseFare) {
        operator = msg.sender;
        baseFare = _baseFare;
    }

    function calculateFare(uint demandIndex, uint weatherFactor) public view returns (uint) {
        return baseFare + (demandIndex * 2) + weatherFactor;
    }

    function payFare() public payable {
        require(msg.value >= baseFare, "Fare too low");
        // Logic for token transfer and confirmation
    }
}
```

Lessons learned for improving scalability

The pilot study demonstrated that the proposed implementation is technically feasible, socially accepted, and financially beneficial, if it is supported by a user centred design and a flexible regulatory framework. Scaling the model requires further improvements in the following areas:

- Interoperable digital infrastructure.
- Open protocols for transport-related APIs.
- Technical training for operational staff.
- Inclusion mechanisms for users without access to the internet or smartphones.

This study shows that the combination of predictive algorithms and blockchain technology can not only optimize revenue management but also enhance the transparency and credibility of urban fare systems.

RESULTS AND DISCUSSION

The analyses derived from the pilot study make it possible to assess the effectiveness of the proposed framework from quantitative, qualitative, and systemic perspectives. The discussion interprets these results considering the research questions and the theoretical framework presented in Sections 1 and 1.2. Results are presented first, followed by an interpretative discussion aligned with the research questions defined in Section 1.

Results

The effects of the implemented system are analysed across four dimensions: predictive accuracy, economic performance, user trust, and operational robustness.

Predictive accuracy of the model

The comparison between the LSTM model and classical approaches (such as ARIMA and Prophet) shows a substantial improvement in hourly demand forecasting accuracy. The LSTM model achieved a coefficient of determination of $R^2 = 0.87$, compared to $R^2 = 0.74$ for ARIMA, along with a 19.3% reduction in MAE. These results are consistent with prior literature, where long short-term memory models have demonstrated superior performance in scenarios characterized by seasonality and multiple exogenous factors (Huang et al., 2020; Hochreiter & Schmidhuber, 1997).

This increase in predictive accuracy enabled greater stability in fare allocation, preventing underpricing during peak demand periods and overpricing during off-peak intervals. Moreover, the inclusion of external variables (such as weather conditions and public events) enhanced model robustness under nonlinear conditions, including holidays and days with heavy rainfall.

Economic impact and fare efficiency

The dynamic pricing engine achieved an average increase of 12.4% in daily revenue compared to the flat fare system. This improvement was not driven by a generalized price increase, but rather by elasticity-based price differentiation, which increased users' willingness to pay during peak hours and improved occupancy during low-demand periods through context-aware discounts (Train, 2009; Chen, 2016).

From a microeconomic perspective, the system enabled a more efficient reallocation of surplus by aligning prices with perceived value across different time periods

Evaluated factor	Result	Observation
Average daily revenue	+12.4%	Increase after implementation
Prediction accuracy (R^2)	0.87	Multivariate LSTM with Bayesian optimization
User acceptance level	76%	On-board surveys in weeks 3 and 6
Fare fraud incidence	–89%	Compared to reference period
Transactional latency (average)	342 ms	Complies with urban operation SLAs

Table 1. Socioeconomic impact matrix

and user segments. In the long term, this may contribute to a better balance between the operator's financial sustainability and service accessibility for passengers.

User perceived trust and transparency

Qualitative data extracted from surveys revealed that more than 76% of users perceived greater fare fairness due to the system's explainable pricing logic. In addition, 68% reported increased trust in the fare collection process, attributed to the traceability enabled by blockchain technology. These findings support the hypotheses proposed by Christidis and Devetsikiotis (2016), who argued that the inherent immutability and auditability of blockchain technology can enhance perceived equity in automated systems.

However, 14% of users reported confusion regarding fare variability, highlighting the importance of improving communication strategies and user friendly visualization tools. This aligns with research on civic technology and digital adoption, which emphasizes that transparency must be accompanied by digital literacy to foster effective user trust (Meijer et al., 2012).

Technical performance and system scalability

The solution exhibited an average latency of 342 ms, remaining within real time operational thresholds (<400 ms), even under peak traffic conditions. This demonstrates the technical feasibility of combining predictive algorithms with smart contract execution without compromising system performance (Androulaki et al., 2018).

Nevertheless, bottlenecks were identified in synchronization between blockchain nodes and on-board fare validators during passenger boarding, particularly in areas with limited mobile connectivity. Scaling the solution to a metropolitan level will require the integration of edge computing techniques and asynchronous consensus mechanisms to accommodate intermittent connectivity environments (Xu et al., 1998).

Critical synthesis and opportunities for improvement

The results indicate that the proposed framework is viable, effective, and socially acceptable; however, several challenges must be addressed to enable large scale adoption by transport operators:

- The need for local regulatory frameworks recognizing smart contracts as legally valid instruments (Saberi et al., 2019).
- Digital inclusion measures to prevent the exclusion of users without access to smartphones or mobile applications.
- Transparent, user centred communication strategies to explain the logic underlying dynamic fare pricing.

Accordingly, future iterations of the model could benefit from multiagent approaches, online feedback mechanisms (reinforcement learning), and participatory governance mechanisms that involve citizens in the validation of fare setting rules.

Discussion

The implementation of an integrated framework combining dynamic pricing based on predictive algorithms with blockchain technology in the passenger transport sector entails significant implications from technological, economic, regulatory, and social perspectives. This section discusses the findings of the pilot study in relation to existing literature, identifies the study's limitations, and outlines directions for future research. These limitations are common in real world pilot studies and reflect the trade--off between experimental control and ecological validity. Overall, the findings provide affirmative evidence for both RQ1 and RQ2 under real-world operational conditions.

Comparison with previous studies

The results obtained are consistent with prior research demonstrating the effectiveness of machine learning algorithms, particularly recurrent neural networks such as LSTM, in modelling and forecasting demand behavior in transport systems (Zhang et al., 2019; Oh et al., 2022). Compared to traditional models (e.g., ARIMA), LSTM networks' ability to capture non-linear relationships and long-term temporal dependencies significantly reduces forecasting error and improves real time fare allocation.

Regarding the blockchain component, previous studies have argued that its integration into mobility systems enhances transaction traceability, reduces fraud, and facilitates the decentralization of business processes (Saberi et al., 2019; Christidis & Devetsikiotis, 2016). In this context, the use of smart contracts not only automated fare transactions but also introduced a reliable layer of algorithmic governance without compromising operational efficiency.

The novelty of this study lies in the practical integration of both technologies within a real operational environment, an aspect that has been scarcely explored in prior work, which has largely focused on simulations or theoretical proposals (Xu et al., 2021). This empirical approach contributes applied evidence regarding both the benefits and limitations of the system under real-world conditions.

Theoretical and practical contributions

From a theoretical standpoint, this article contributes to the literature on transport economics, cyber-physical systems, and digital governance by demonstrating that the convergence of artificial intelligence and blockchain technology can generate meaningful synergies in the management of dynamic public services. From a practical perspective, the proposed framework:

- Enables demand elasticity based dynamic fare differentiation, a feature that remains largely under implemented in urban public transport.
- Introduces operational transparency, which can strengthen the legitimacy of transport operators in the eyes of users and public authorities.
- Serves as a foundational architecture for Mobility as a Service (MaaS) ecosystem, where interoperability and traceability are critical (Kamargianni et al., 2016).

Moreover, the proposed approach can be adapted to other public services that rely on variable pricing structures, such as energy supply, water services, or public parking systems.

DOI https://doi.org/10.22533/at.ed.8208312611031

Limitations of the study

Despite its findings, this study presents several limitations. First, the pilot period was relatively short (six weeks) and limited to three specific routes, which may affect the generalizability of the results to other urban contexts with different passenger mobility patterns. Second, the operator's preexisting technological infrastructure facilitated system implementation, which may not be easily replicable in less digitally mature transport systems. Such limitations are inherent to real-world pilot deployments and reflect the trade-off between experimental control and ecological validity.

Furthermore, although improvements in perceived transparency were observed, long term user adoption and actual price elasticity responses were not directly evaluated. Estimating sustained effects will require longer term studies and the development of individual level behavioural models using discrete choice techniques (Train, 2009).

Implications for transport policy and public authorities

The results have important implications for transport policymakers and regulatory authorities. In many countries, existing regulations restrict or prohibit dynamic pricing in public transport under the premise of ensuring passenger equity. However, the model proposed in this study suggests that, if properly designed, dynamic pricing can promote equity by differentiating fares according to users' ability to pay, time of travel, and service conditions.

An updated regulatory framework is therefore required to recognize the legal validity of smart contracts, define standards for fare traceability, and establish mechanisms for technological auditing. Public authorities must also ensure that digitalization does not exclude vulnerable groups by promoting cross subsidization schemes, alternative payment channels, and digital literacy initiatives for public transport users.

Future research directions

Several avenues for future research emerge from this study:

- Evaluating reinforcement learning models to enhance feedback loops between demand prediction, pricing decisions, and user responses.
- Exploring the integration of multiple transport operators within a federated blockchain-based system, fostering interoperability among buses, metro systems, and shared bicycles.
- Analysing indirect environmental impacts, such as reductions in traffic congestion and emissions resulting from more temporally distributed demand.

The fusion of artificial intelligence and blockchain technology in transport fare systems represents a significant step toward transforming urban mobility systems into more adaptive, efficient, and transparent paradigms.

CONCLUSIONS AND RECOMMENDATIONS

This article has demonstrated the technical, operational, and economic feasibility of a dynamic fare pricing system for passenger transport based on the integration of machine learning–based predictive models and blockchain technology.

Conclusions

The proposed framework has empirically validated that the combined application of these technologies can significantly improve the efficiency of public transport fare systems, users' perceived fairness, and overall system transparency.

First, the use of LSTM models for demand forecasting exhibited a high level of predictive accuracy ($R^2 > 0.87$), outperforming traditional approaches in scenarios characterized by temporal variability and external influencing factors (Zhang et al., 2019; Oh et al., 2022). This predictive capability proved essential for optimizing dynamic fare adjustments based on expected demand and user segmentation within the transport system.

Second, the blockchain based infrastructure, implemented through smart contracts, enabled the automation of fare decisions while ensuring transaction immutability, auditability, and traceability, thereby fostering user trust (Christidis & Devetsikiotis, 2016). This technological layer functioned not only as a distributed ledger system but also as a platform for algorithmic governance.

Third, the observed economic benefits, such as an average 12.4% increase in daily revenues and a more balanced demand distribution, suggest that dynamic pricing strategies are not only technologically viable but also economically sustainable. Moreover, the improvement in perceived fare fairness among users (76% acceptance) indicates that automated systems, when transparently designed, can enhance the legitimacy of transport operators (Saberi et al., 2019).

Nevertheless, the study also highlights challenges related to system scalability, the digital divide affecting certain social groups, and the need for appropriate regulatory frameworks to legitimize and supervise the proposed processes. From a methodological standpoint, the study demonstrates the feasibility of evaluating AI blockchain systems through controlled pilot designs that combine quantitative performance metrics with qualitative institutional analysis. This methodological approach can be replicated in other regulated service contexts where algorithmic decision making and public accountability must coexist.

Recommendations

Based on the pilot study, the following recommendations are proposed for different stakeholder groups:

1. Transport operators

- Invest in analytical processes and digital infrastructure that enable real time data collection and support predictive algorithms for dynamic pricing.
- Design communication and fare visualization strategies that clearly explain system principles, thereby strengthening user trust and reducing perceptions of arbitrariness.

2. Governments and public regulators

- Establish regulatory frameworks that recognize the use of smart contracts in public fare management while ensuring robust auditing mechanisms and the protection of user data.

- Promote digital inclusion policies to prevent the exclusion of users without access to technological tools, through targeted subsidies or alternative payment mechanisms.

3. Researchers and developers

- Explore reinforcement learning approaches within predictive algorithms to enable adaptive price adjustments in volatile environments, accounting for real time user responses.
- Develop interoperable decentralized architectures across different mobility operators to support transparent, auditable, and synergistic MaaS ecosystems (Kamargianni et al., 2016).

4. Multilateral organizations and sustainable mobility funders

- Support pilot projects in mid-sized cities as living laboratories to validate adaptive fare management models and assess their impact on inclusive urban mobility.

Future perspectives

In the long term, the integration of artificial intelligence, blockchain technology, and intelligent transport systems has the potential to reshape urban mobility toward a more equitable, efficient, and participatory paradigm. This article represents an initial step in this direction by proposing a replicable and scalable model, albeit one that remains dependent on contextual conditions such as technological maturity and the governance capacity of public institutions.

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