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Article

Enhancing operational and infrastructure integration in shared mobility

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ABSTRACT

The carpooling system is an automated system that eases travelers' misery and helps them find cars quickly. One application that will be turbocharged is carpooling, where solo drivers to work can ask other passengers in our application for a ride. It provides the car user with an easy-to-use platform between the car owner and the car user. The existing carpooling schemes aim to reduce carbon footprint and environmental impact by matching passengers and drivers along the way. However, they are generally severely deficient in features, including inefficient static route planning, low-quality ride-matching algorithms, and a lack of high-quality user trust mechanisms. Our proposed system can resolve these problems by operating algorithmically (e.g., using A-Star, which dynamically adjusts to optimize routes based on the real environment) and by leveraging advanced machine learning models, such as clustering and recommendation systems, to improve the precision of ride matching. We also enhance the trust feature by providing comprehensive profiles of drivers with verified contact details, vehicle condition reports, user ratings, and reviews, thereby offering an efficient, dependable, and secure carpooling experience.

1. Introduction

The rapid expansion of urban populations has led to significant transportation challenges, including increased traffic congestion, higher fuel consumption, and elevated air pollution levels. Conventional transportation systems are struggling to cope with the growing demand for efficient mobility solutions. Among the various alternatives, carpooling has gained attention as a sustainable and cost-effective way to reduce traffic congestion and environmental impact. By allowing multiple passengers to share a single vehicle, carpooling minimizes the number of vehicles on the road and optimizes resource utilization. Despite its potential benefits, existing carpooling systems face several limitations. Most platforms rely on static route planning, which does not adapt to real-time traffic conditions. Additionally, traditional ride-matching algorithms often fail to account for user preferences, leading to inefficient matches and reduced user satisfaction. Another critical challenge is the lack of robust trust mechanisms, which discourages users from participating in shared mobility systems due to safety concerns. To address these challenges, this study proposes an intelligent carpooling system that integrates advanced computational techniques. The system utilizes dynamic route optimization through the A* algorithm, machine learning models for efficient ride matching, and blockchain technology to ensure secure and transparent interactions. By combining these technologies, the proposed system aims to provide a reliable, efficient, and user-centric solution for urban mobility.

2. Literature review

Carpooling has been widely recognized as an effective strategy for reducing traffic congestion and promoting sustainable transportation. Previous studies have highlighted its potential to complement public transport systems by addressing last-mile connectivity issues. Integrated mobility solutions that combine carpooling with public transportation networks have been shown to enhance accessibility and reduce commuting time. Several researchers have explored the environmental and economic benefits of carpooling. It has been demonstrated that shared mobility significantly reduces greenhouse gas emissions and fuel consumption while lowering travel costs for users. Moreover, carpooling improves traffic flow and reduces demand for parking infrastructure, making it a viable solution for densely populated urban areas. The adoption of carpooling systems is influenced by various social and psychological factors. Trust, convenience, and perceived usefulness play a crucial role in determining user participation. Studies based on the Technology Acceptance Model (TAM) suggest that users are more likely to adopt carpooling platforms when they perceive them as reliable and easy to use. Therefore, integrating trust-building mechanisms with user-friendly interfaces is essential to increasing adoption rates. Recent advancements in artificial intelligence and machine learning have enabled the development of more efficient ride-matching algorithms. Clustering techniques and recommendation systems have been successfully applied to group users based on travel patterns, thereby improving matching accuracy. Additionally, real-time data processing enables dynamic route adjustments, enhancing system efficiency. Blockchain technology has also emerged as a promising tool for improving trust and transparency in shared mobility systems. By providing a decentralized and immutable ledger, blockchain ensures secure data storage and prevents unauthorized modifications. This technology can be used to verify user identities, maintain ride histories, and facilitate secure transactions.

Despite these advancements, several challenges remain, including scalability, infrastructure limitations, and user adoption barriers. This study builds upon existing research by integrating multiple technologies into a unified framework to address these issues. Another measure that can be critical to combating congestion in urban traffic is carpooling, which reduces environmental pollution and maximizes transportation efficiency. When used alongside public transportation, carpooling mechanisms offer radical options to augment last-mile services and overcome current barriers in the transportation systems of metropolitan regions. Integrated automobile sharing and transportation will offer better connectivity, eliminating last-mile service distances that reduce the efficiency of public transit [1]. Carpool paths, when timed to the transport timetable, ensure a steady flow of commuters by providing ideal access to transport infrastructure and shortening their commuting time [2]. A feasibility study of carpooling systems in new markets was conducted by Ref [3], which established the potential market opportunities and operational constraints of public transport infrastructure. It turned out that formulating sound government policy resolutions and well-thought-out marketing plans is the key driver in developing systems that avoid economic, cultural, and infrastructural barriers.

The benefits of carpooling cannot be limited to reducing traffic issues. The system can be utilized to promote long-term sustainability by providing an environmentally friendly mode of commuting that reduces gas emissions and fuel consumption [4]. According to the research findings, the comprehensive use of carpooling has a twofold positive impact on commuters' economy and fuel consumption. Usage is a significant driver of reduced environmental impact in the transportation system [5]. According to studies by [6], traffic-induced air pollution is mitigated when cars are not used for commuting to workplaces but rather by carpooling with colleagues and is fuelled [7]. The number of psychological and social influences prompts people to decide to carpool. The impression of convenience and trust in the system, along with social pressures, are the reasons why drivers are ready to register for carpooling [8]. These factors must be addressed during carpooling site design and reward mechanism development in cases where adoption rates are highest. App-based carpooling offers customers a user-friendly platform that improves their carpooling experience, even while imposing flexibility on access to carpooling. The findings of the study proposed by [9] indicated that the model that could be employed to determine the intention of commuters to adopt carpooling apps is the Technology Acceptance Model (TAM). The available research findings confirm that carpooling service users are guided by two variables in their decision-making regarding transportation technology: the convenience of the platform and its perceived utility.

To realize effective carpooling arrangements, it is crucial to balance the route control. The application of machine learning algorithms is also proving efficient for generating optimal carpool routes, a practice that is gaining traction among researchers [10,11] who are developing various methods. Ref [12] implemented machine learning processes to optimize carpool matches, which improved system performance and user satisfaction. People share economic benefits and positive environmental outcomes by carpooling. The twofold financial and environmental benefits of urban carpooling were analyzed by [13], demonstrating the consequences of this scheme, including the farming down of transport costs and reduced congestion in cities [14]. Cities with carpooling facilities will be smarter and will offer several advantages. To empower mobility systems in smart cities, Ref [15] has developed a user-friendly carpooling platform. Personal vehicle-sharing services are offered to urban commuters by organizations that use data analytics [16]. The extensive benefits of carpooling that cannot be incorporated in their entirety into immature market differentiations face a number of barriers. Since Ref [17] suggests the main criterion according to which it is impossible to carpool, it is the insufficiency of the infrastructure, economic pressure, and the non-availability of support on the governmental level. The new technological approaches that link carpooling and mass transportation systems, as well as the development of mobile apps, are solutions that cut across implementation barriers [18]. Blockchain technology is considered an efficient tool for carpooling, accelerating the process and increasing transparency. The advantages of blockchain in carpooling stem from its role as a secure, decentralized platform that provides users with transparency.

The carpooling system optimization [19] will be based on the emergence of advanced technologies, including blockchain technology, artificial intelligence (AI) [20], and machine learning, which will provide additional optimization. It was demonstrated in Ref [21] that AI helps maximize the efficiency of a carpool route, since current information is handled manually when modifying transportation routes. The multi-agent systems in Ref [22] can greatly improve the effectiveness of the carpooling system through instant decision support systems that combine traffic-condition data and personal preferences with the vehicle's availability to the user. One popular solution to the federal urban mobility dilemma, increasingly seen as a way out of the commuting issue, is carpooling [23]. The adoption of carpooling systems depends on four emerging market factors. Ref [24] noted obstacles and opportunities arising in such markets, including cultural and infrastructural barriers that have been stymying universal adoption. However, when carpooling is well supported, it is possible to significantly reduce urban traffic speeds and positively influence the environment (as stressed in the research). It transpired to be due to psychological and social factors, with carpool adoption strongly influenced by trust, safety, and community building. According to their research, although social isolation may be a concern, carpooling is not a vice, as it can mitigate social isolation and improve mental health and community spirit among carpoolers [25]. The carpooling perspectives on environmental and economic sustainability were examined using Outlook (to capture a broad perspective) [26]. By their studies, they have determined that carpooling can result in the perceived effect of reducing carbon emissions and road jams, and the inflow of cars on the road can be managed, and economic benefits accrued in the form of reduced cost of commuting and reduced use of strained yet paid-off disposal of the road transport systems [27].

Ref [28] examined carpooling among workmates and found that it results in lower fuel consumption, improved traffic flow, and reduced commuting delays. These aspects make workplace carpooling highly effective at enhancing mobility in urban areas [29]. Ref [30] scrutinized the issue of presentability of carpooling to larger transportation schemes. Their study identified convenience, cost-effectiveness, and energy savings and, as such, demonstrated how carpooling will help reduce emissions and parking requirements, thus making urban areas sustainable [31].

The primary objective of this research is to enhance the operational efficiency and infrastructure integration of shared mobility systems. Specifically, the study aims to analyze the limitations of existing carpooling platforms and develop an advanced system that improves ride-matching accuracy, route optimization, and user trust. Another key objective is to integrate digital technologies with urban transportation infrastructure to create a scalable and sustainable mobility solution. Hence, the main objectives can be summarized as follows:

- To examine the existing operational and infrastructure challenges in shared mobility systems.
- To develop strategies for improving integration between digital platforms and urban transport infrastructure.

3. Related work

As urbanization increases, more individuals prefer driving cars to using public transport. Some of the immediate problems that have arisen as a consequence are traffic jams, increased greenhouse gas emissions that lead to global warming, and the depletion of non-renewable fuel sources. Against this backdrop, carpooling is considered a potential solution and is advantageous to both drivers and passengers. Carpooling also reduces fuel expenditure and significantly reduces environmental impact. It may reduce road overcrowding by encouraging many commuters to share a single car or motor vehicle, thereby reducing carbon emissions and saving fuel while easing congestion in the central urban area.

The emergence of ride-sharing applications, exemplified by the systems mentioned above [e.g., Babacar, Uber POOL, and academic models, if possible], has already shown that they can become a reality and be effective. However, they are mostly set to a timetable and booked on a ride platform over a long period, which could limit the user's maneuvering. Comparatively, the modern dynamic car, symbolizing services, allows the user to organize journeys based on their own hobbies and availability, enabling spontaneous trips rather than mandatory ones. Dynamic ridesharing is relatively accommodating and offers several advantages: it gives users greater control, enables more effective use of the vehicle, and fosters a sense of community among users. These systems agree that smart transportation solutions are important because they address the environmental and societal issues posed by urban mobility.

4. Proposed system

The proposed system, referred to as “Carpool Innovate,” is designed to overcome the limitations of existing carpooling platforms by incorporating advanced technologies and user-centric features. The system consists of three primary components: the driver module, the passenger module, and the administrative module. The driver module enables vehicle owners to register and provide ride services. Drivers undergo a verification process to ensure reliability and safety. Once registered, they can manage ride requests, update trip details, and interact with passengers through the platform. The passenger module allows users to search for available rides, submit requests, and communicate with drivers. The system prioritizes user convenience by offering personalized ride recommendations based on preferences and travel patterns.

The administrative module plays a central role in managing system operations. It oversees user registration, monitors ride assignments, and ensures compliance with security protocols. The system employs a proximity-based algorithm to efficiently match drivers and passengers, minimizing waiting time and detours. A key feature of the proposed system is its dynamic route optimization capability. Unlike traditional systems that rely on fixed routes, this system uses real-time data to adjust routes based on traffic conditions. Machine learning algorithms are used to analyze user behavior and improve matching accuracy over time. Additionally, blockchain technology is integrated to enable secure, transparent transactions, enhancing user trust. The identified system, named Carpool Innovate, will be employed to address existing loopholes in current carpooling systems, particularly in fixed routing, poor ride matching, and a lack of robust trust systems. The design is built around usability, system efficiency, and high-level data security. It has three stakeholders: the Driver, the administrator (admin), and the user, who is another role in the system. Communication between these elements is so well planned that carpooling is smooth for all parties involved.

The Driver module allows car owners to register for a secure dashboard and access a personalized dashboard. Once checked, they can perform several key roles, such as initiating or ending a ride, checking administrative updates, and confirming user-submitted ride requests. This module will be followed to ensure that only proven, trusted drivers vetted in the system are considered, fostering a sense of safety and reliability. The key facilitator of the system is the admin module. Our administrator would also begin registering in the system and then oversee user registration. The admin module assigns rides using a proximity-based algorithm and manages the entire ride-matching process. The admins can view the profiles of users and drivers, optimize all matches, and set the vehicles' locations to the users' preferred locations. The Passenger module is oriented to users. The process will be initiated when users are required to enter their registration information, which will then be verified manually by the admin. Once authenticated, the user can log in to the system, make ride requests, and view assigned drivers. Users may restart if their ride request is denied or they choose a poor match. Drivers are quickly reranked by location, availability, and past response rate. It briefly lowers the priority of the refused match. When the search radius is automatically modified to speed transmission, users find it easier and less bothersome. The system architecture diagram illustrates the interaction and workflow of these three modules. Communication among the user, the Driver, and the administrators occurs as shown in Figure 1.

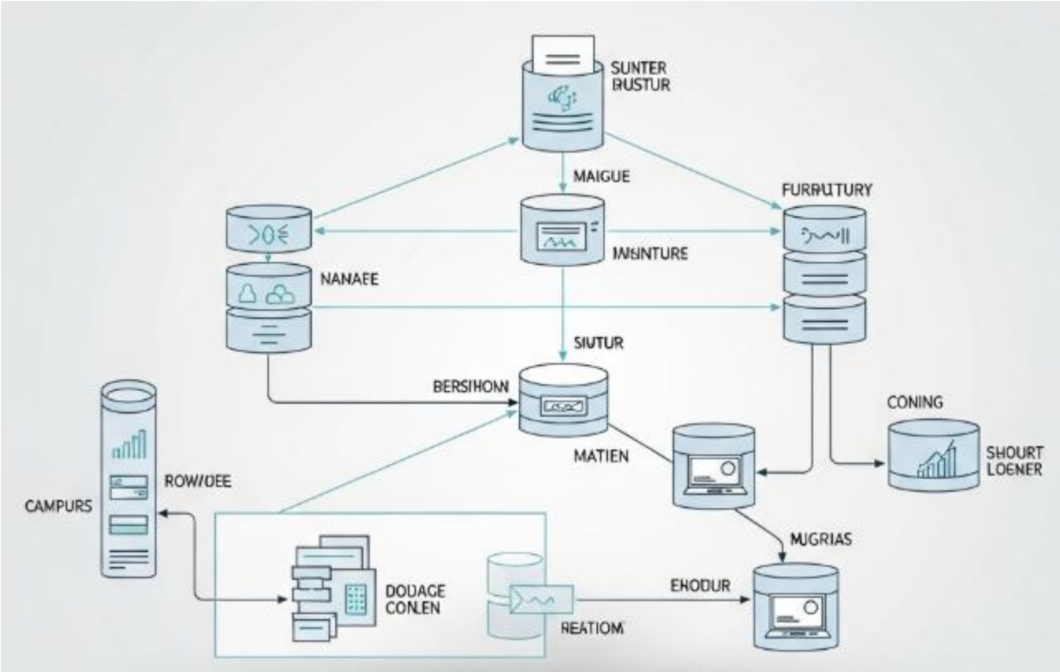

Figure 1. System architecture diagram

It outlines the flow of information between registration, ride assignment, and confirmation, with attention to system security, authentication, and integration with a backend database. The architecture of the proposed system is based on a three-layer model comprising the presentation, application, and data layers. The presentation layer provides a user interface that allows drivers and passengers to interact with the system. It is designed to be responsive and accessible across multiple devices, including smartphones and web platforms. The application layer handles the core functionalities of the system, including ride matching, route optimization, and communication between users. The A* algorithm is used to determine the most efficient routes, while machine learning models optimize ride matching. The communication module ensures seamless interaction between drivers and passengers.

The data layer is responsible for storing user profiles, vehicle information, and transaction records. Advanced encryption techniques are used to protect sensitive data and ensure privacy. Blockchain integration further enhances data security by providing an immutable record of transactions and user activities. The proposed system was evaluated using a simulated dataset due to the unavailability of real-world ride-sharing data. The dataset consisted of 1,000 users, including both drivers and passengers, over a period of seven days. An urban grid model was used to simulate realistic travel patterns under varying traffic conditions at different times of the day. Key performance metrics were defined to assess the system's effectiveness. Matching accuracy was measured as the percentage of successful ride matches within acceptable constraints. User trust was evaluated using a feedback-based rating system. Average detour time was calculated to determine the efficiency of route optimization. The simulation results were compared with those of a baseline system to evaluate performance improvements. The use of controlled conditions ensured consistency and repeatability of the results.

5. Ease of use

The sharing system is designed to work on both mobile devices and the web, so many people can use it across a wide range of digital platforms. The user interface was designed using adaptive web design principles, so it works well on computers, tablets, and phones. The app works on both Android and IOS devices. Cross-platform compatibility is very important because it makes sure that customers can use the system on any device. This makes the system more accessible and broadens its reach. The user interface is simple, clean, and quick. It helps users find rides, update their personal or vehicle profiles, and choose routes that work best for them. The app is easy to use for anyone, no matter how good they are with computers, thanks to its layout.

The system's design lets people make decisions and change schedules in real time, which makes things run more smoothly. The A* algorithm is used to find the best route by taking into account the user's inputs and the current road conditions. Grouping approaches are used to match rides. Real-time alerts keep drivers and passengers up to date on the trip's progress, expected arrival time, and any changes. This will make it much easier for everyone to understand each other. The server keeps users' contact information, location data, and payment information safe and secure. This is done to ensure everything is as safe as possible. We keep careful records of every transportation transaction to ensure everything is clear and verifiable. These architectural and design choices make the sharing app easy to use, efficient, and safe, and adaptable to changing traffic conditions and passenger needs. Trust is a critical factor in the success of carpooling systems. To address this issue, the proposed system incorporates blockchain technology as a decentralized trust mechanism. Unlike traditional centralized databases, blockchain ensures that data cannot be altered without consensus, thereby preventing fraud and unauthorized modifications. The system uses a permissioned blockchain architecture, which restricts access to authorized participants. This approach ensures data privacy while maintaining transparency. Consensus mechanisms such as

August 2026| Volume 05 | Issue 03 | Pages 118-127

Practical Byzantine Fault Tolerance (PBFT) or Proof of Authority (PoA) are employed to validate transactions efficiently. Blockchain is used for multiple purposes within the system, including user identity verification, ride history tracking, and secure payment processing. By maintaining a transparent and tamper-proof record of all transactions, the system enhances user confidence and promotes trust among participants. Figure 2 illustrates the system registration and login process for aviation users, using ride requests and confirmations. It also draws attention to the form of the admin's position in granting and sanctioning user requests. Figure 3 below illustrates the flowcharts the administrator will follow to submit a user request and determine vehicle availability in the area when allocating rides. It introduces the use of algorithms to support intelligent decision-making. The activity diagram in Figure 4 illustrates the Driver's activities: logging in, viewing ride requests, confirming trips, and leaving. It is also concerned with the efficient communication between the driver and the admin interface.

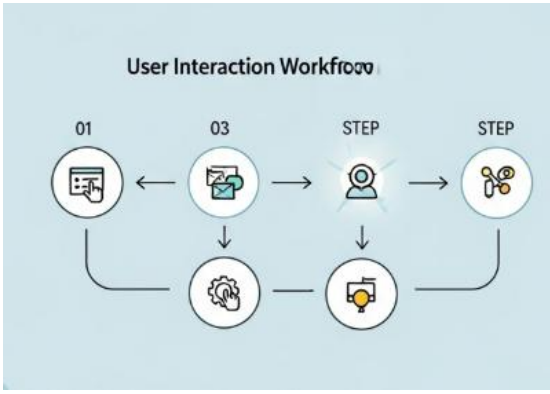

Figure 2. User interaction workflow diagram

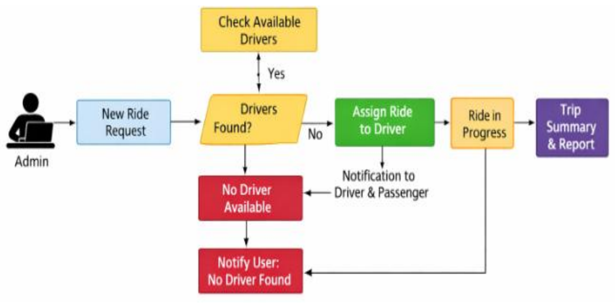

Figure 3. Admin ride assignment flow diagram

Figure 5 is a conceptual diagram of the platform's web and mobile user interfaces, demonstrating features such as ride search, route entry, profile management, and ride tracking [32].

6. System architecture

The proposed carpooling system has a three-layer architecture, as shown in Figure 6. The presentation layer, application layer, and data layer comprise the architecture, which is designed to provide scalability, flexibility, and secure data management.

6.1 Presentation layer (user interface)

The Presentation Layer provides a Graphical User Interface (GUI), allowing users to interact with the system.

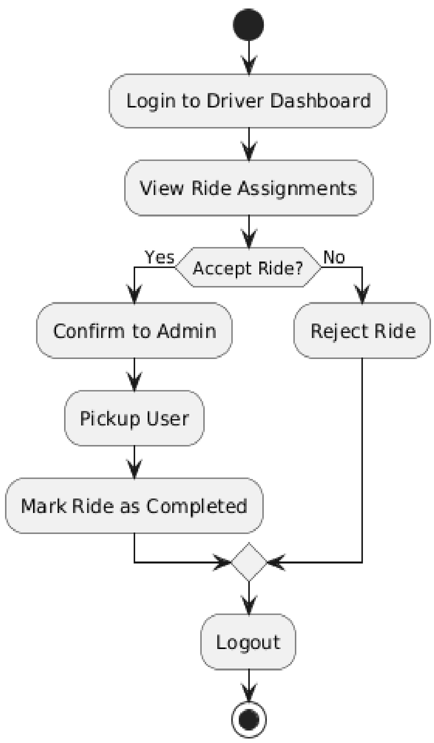

Figure 4. Driver dashboard activity diagram

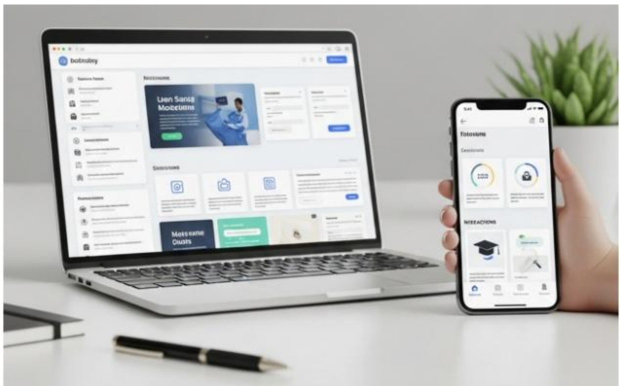

Figure 5. Web and mobile App UI wireframe

Two main types of users may be accommodated by the system:

- **Driver** – Offers a ride by registering the vehicle details and travel route.
- **Passenger** – Searches and requests available rides.

System services cannot be accessed until users log in. Their function determines whether they can:

- Offer a ride (Driver), or
- Search for a ride (Passenger).

The user interface allows users to enter trip parameters, including the origin, destination, journey time, and vehicle information.

6.2 Application layer (business logic layer)

Management of system operations and decision-making procedures is the responsibility of the application layer. The following elements make up its constituent parts:

Ride matching module: Matches passengers with drivers based on:
- Route similarity
- Source and destination proximity
- Availability

Route optimization module: Implements the A* (A-star) path-finding algorithm to determine the most efficient route:

$$f(n) = g(n) + h(n) \quad (1)$$

Where:
$g(n)$= Cost from start node to node n

$h(n)$= Heuristic estimate from node n to the goal

Clustering algorithm: Clustering methods are used in order to reduce the number of diversions and streamline the process of grouping passengers:

$$\sum_{i=1}^{n} \sum_{j=1}^{k} || x_i - \mu_j ||^2 \quad (2)$$

Clustering methods are used in order to reduce the number of diversions and streamline the process of grouping passengers.

Communication module: After a passenger selects a suitable driver:
- A ride request is sent.
- The driver may accept or decline.
- Upon acceptance, both parties coordinate meeting time and location.

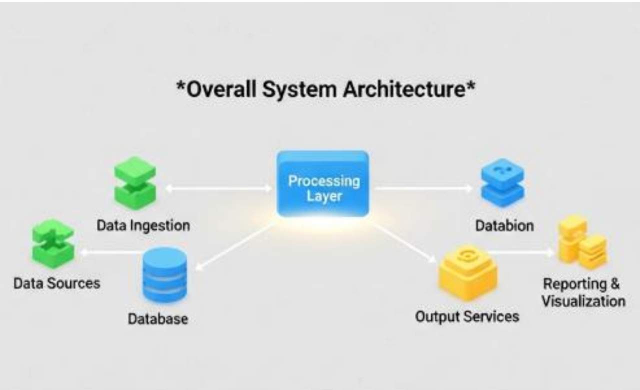

Figure 6. Overall system architecture diagram

6.3 Data layer (database management)

The Data Layer securely stores:
- User profiles (Drivers and Passengers)
- Vehicle information
- Trip details
- Transaction records

To protect users' privacy and data, all information is stored in an encrypted database system and secured by security measures.

6.4 Units of measurement

This study follows the International System of Units (SI). Distances are measured in kilometers (km), fuel consumption in liters (L), and speed in kilometers per hour (km/h). Decimal notation follows standard formatting (e.g., 0.5 km).

7. Blockchain integration for trust and security

The proposed carpooling system uses blockchain technology as a decentralized trust mechanism to solve distrust, data manipulation, identity theft, and payment disputes. Blockchain deployment adds computational and operational expenses, thus it must be justified technically and economically.

7.1 Rationale for blockchain integration

The simulation results indicate significant improvements in system performance after the implementation of advanced technologies. Matching accuracy increased substantially, demonstrating the effectiveness of machine learning algorithms in improving ride matching. User trust scores also showed notable improvement due to the integration of blockchain-based verification mechanisms. Additionally, the average detour time was significantly reduced, indicating the efficiency of dynamic route optimization. User feedback further confirmed the system's effectiveness, with high satisfaction reported for features such as route optimization, driver verification, and communication tools. These findings suggest that the proposed system offers a more efficient and reliable carpooling experience than traditional platforms. Blockchain technology is a distributed, immutable ledger system that prevents data from being updated without the network's agreement. Blockchain technology, in contrast to conventional centralized databases, guarantees:
- Immutability of records
- Decentralized verification
- Transparent transaction history
- Cryptographic security
- Elimination of a single point of failure

In a carpooling ecosystem where multiple unknown parties interact, trust becomes a fundamental requirement. The system leverages blockchain in the following areas:
- User identity verification (drivers and passengers)
- Ride history validation
- Vehicle condition certification records
- Secure and traceable payment transactions
- Rating and reputation management

7.2 Blockchain vs. traditional secure database

Traditional encrypted databases, such as SQL systems with TLS encryption and access control, provide a high level of security; yet they remain centralized, and users must place their faith in a single authority. Table 1 compares blockchain and the traditional secure database.

Table 1. Blockchain vs. traditional secure database comparison

Parameter	Traditional Secure Database	Blockchain-Based System
Data Control	Centralized authority	Decentralized consensus
Data Modification	Admin can modify records	Immutable once recorded
Trust Model	Trust in the system owner	Trust in cryptographic protocol
Transparency	Limited	Transparent ledger
Single Point of Failure	Yes	No
Fraud Resistance	Moderate	High

7.3 Type of blockchain architecture

Our system uses a permissioned private blockchain, not a public one. The goal of this design decision is to:

- Ensure controlled access to sensitive user data.
- Maintain regulatory compliance and data privacy.
- Achieve higher transaction throughput.
- Reduce operational and transaction costs compared to public networks.

Block validation is only conducted by validated nodes, such as platform administrators, trusted validators, and service partners.

Consensus mechanism: The proposed system uses PBFT or PoA consensus protocols instead of energy-intensive PoW. These methods save energy, confirm transactions more quickly, and work well in permissioned blockchain networks. They also tolerate malfunctioning or malicious nodes, guaranteeing safe, reliable, and fast validation of ride records, user identification data, and payment transactions in the carpooling platform.

Scalability and latency management: The system employs multiple optimization algorithms to manage scalability and latency. Large data files, such as vehicle condition reports, are kept off-chain and verified using cryptographic hashes. Layer-2 techniques manage microtransactions and ride payments before on-chain settlement, decreasing network congestion. Batch processing maximizes efficiency by grouping ride transactions. PBFT or PoA consensus reduces latency, ensuring blockchain integration does not slow ride-matching or payment confirmation.

8. Method

The system was evaluated on a synthetic dataset because real-world ride-sharing data was unavailable due to privacy constraints. A fake dataset was used to evaluate the technology since ride-sharing data was private. Over 7 days, the 1,000 simulated users were 40% drivers and 60% passengers. A modeled urban grid with residential and commercial clusters randomly distributed, source and destination locations [33]. Morning and evening route costs are adjusted to simulate low, medium, and high traffic. Drivers were assumed to accept trip requests with a diversion of up to 15 minutes. Ride completions and verification status gradually increased trust ratings. Metropolitan commute trends are estimated without ride-sharing platform data using general transportation statistics.

8.1 Implementing the system framework

The system architecture design specifies that it is to be experimented with, depending on the proofing and implementation of the system's fundamental components, such as route optimization and the ride-matching algorithm. Such topics as interface design, matching algorithms, user coordination, trust and safety, social interaction, critical mass adoption, and incentives (political, economic, motivational) are identified through a comparative analysis of the key issues in dynamic carpooling. Such aspects are also addressed through system recommendations to improve usability and adoption. The model block diagram is shown in Figure 7. Table 2 highlights the key trust mechanisms to be adopted in the ride-sharing application, which may boost users' confidence and safety. Each feature, such as user ratings, profile display, driver verification, etc., plays a role in fostering a safe and trusting atmosphere. The table also categorizes the relative effect of each of those features on user trust as medium-high.

Table 2. The key trust mechanisms to be adopted in the ride-sharing application

Trust feature	Description	Impact On User Trust
User Ratings and Reviews	User-based feedback system to rate drivers and passengers	Medium
Profile Transparency	Display of user details like ride history and verified contact	Medium
Driver Verification	Verification Of Identifying, driving license, and vehicle documents	High
Ride History	Records Of Ride by users or drivers	Medium

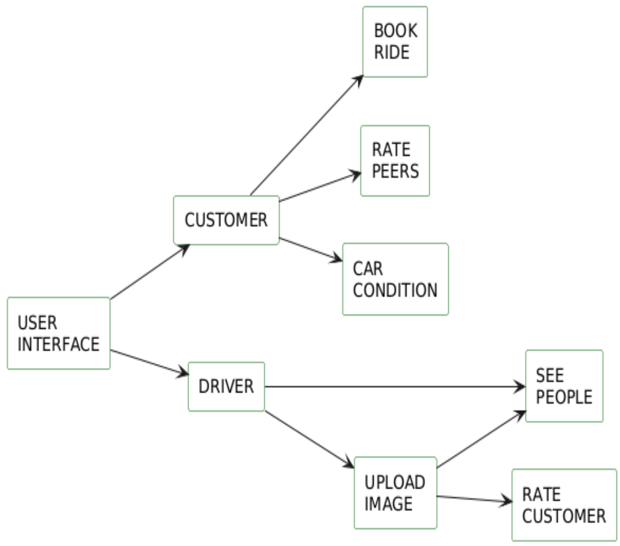

Figure 7. Block diagram of the model

9. Results and analysis

We conducted a simulation analysis using simulated datasets to assess the trend in urban commuting and confirm the utility of our proposed carpooling system. It was simulated with 1000 or more users over 7 days, under varying commuter indications and traffic conditions [34]. To ensure repeatability, the following is a formal definition of the major assessment measures.

9.1 Matching accuracy (MA)

Accuracy in matching is defined as the percentage of optimal ride requests that result in a successful match.

$$MA = \left(\frac{N\_correct\ matches}{N\_total\ requests}\right) \times 100 \quad (3)$$

Where:

- $N\_correct\ matches$= Number of rides matched within acceptable detour and preference constraints
- $N\_total\ requests$= Total ride requests

9.2 User trust resolution (UTR)

The improvement in the user's trust score after the adoption of the blockchain-based verification system is measured by User Trust Resolution.

$$UTR = \left(\frac{T_{after} - T_{before}}{T_{before}}\right) \times 100 \quad (4)$$

Where:

- T_{before}= Average trust score before enhancement
- T_{after}= Average trust score after enhancement

Trust score is measured on a 5-point Likert scale.

9.3 Average detour time (ADT)

$$ADT = \frac{\sum_{i=1}^{n} D_i}{n} \quad (5)$$

Where:

- D_i= Additional time added to ride i
- n= Total matched rides

As Table 3 indicates, the system's performance indicators improve significantly once an ML clustering algorithm and blockchain-based trust functionality are introduced. A comparison of the relative accuracy of the traditional and proposed systems across various time periods (Morning, Afternoon, Evening, Peak Hours) is shown in the bar graph in Figure 8 [35]. The user responses to key facets of the system, as summarized in Table 4, indicate that the system has been received very favorably, and respondents especially like features related to transparency and coordination.

Table 3. System performance before and after enhancements

Metric	Baseline System	Proposed System	Improvement (%)
Matching Accuracy	68%	91%	34%
User Trust Score (avg/5)	3.2	4.6	43.75%
Average Detour Time (min)	12	5	-58.30%

Table 4. User feedback summary on key features

Feature	User Satisfaction Rate (%)
Dynamic Route Optimization	89%
Driver Verification System	92%
In-app Messaging & Coordination	86%
User Interface (Usability)	84%

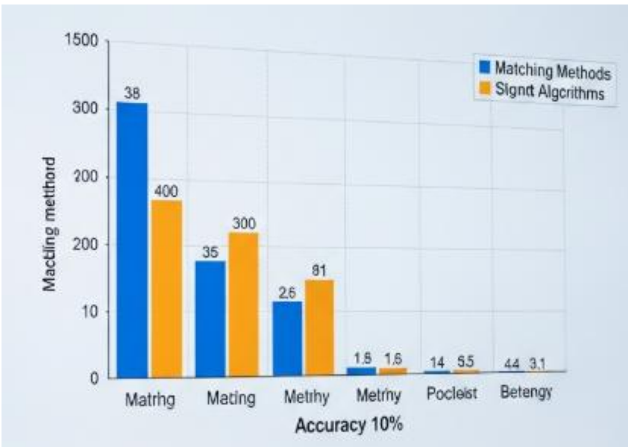

Figure 8. Matching accuracy comparison graph

Figure 9 is a line graph showing average user trust scores over 7 days of system use; after that, there is a steady rise in user trust following the verification process and profile enhancement. The integration of artificial intelligence, machine learning, and blockchain technology represents a significant advancement in shared mobility systems. The proposed system addresses key challenges associated with existing carpooling platforms, including inefficiencies in ride matching and a lack of user trust. By leveraging real-time data and advanced algorithms, the system enhances operational efficiency and user satisfaction. However, implementing such a system may face challenges related to scalability, regulatory compliance, and user adoption. The computational overhead associated with blockchain technology may also impact system performance if not managed effectively. Therefore, further research is required to optimize system design and evaluate its performance in real-world scenarios.

Figure 9. User trust score improvement over time

10. Conclusion

The dynamic carpooling systems have tremendous potential to change transportation in the urban centres as the present study shows. The variant of real-time analysis of data, which is integrated with the developed machine learning algorithms and additional trust systems, can help us to solve the existing problems related to the current carpooling processes of open-source routing and ride matching. The combination of the dynamic route optimization technology with more powerful user profiling systems into the ride matching services when married will increase the precision and responsiveness of the service as well as creation of greater degrees of confidence between the users of the platforms. We have a solution that would help in minimizing traffic congestions and causing less harm to the environment besides creating more satisfaction among users in the system. We will perform thorough research on the user behavior and look at more correlations between traffic data and the urban infrastructure to increase the accuracy of our ride-matching algorithms. Our company has no intention of undermining the privacy of information and develop a convenient platform to offer quality carpooling services in urban areas. This study presents an advanced carpooling system that integrates dynamic route optimization, machine learning-based ride matching, and blockchain technology to enhance efficiency, security, and user trust in shared mobility systems. The proposed framework addresses critical limitations of existing platforms by enabling real-time decision-making, improving matching accuracy, and ensuring transparent and secure interactions among users. Simulation results demonstrate significant improvements in key performance metrics, including matching accuracy, user trust, and detour time, highlighting the effectiveness of the proposed approach. The system has the potential to contribute to sustainable urban transportation by reducing traffic congestion, lowering emissions, and optimizing resource utilization. Despite certain limitations, such as reliance on simulated data and the need for large-scale validation, the findings indicate that integrating advanced technologies can significantly improve the performance and reliability of carpooling systems. Future research should focus on real-world implementation, scalability analysis, and integration with smart city infrastructure to further enhance the applicability of the proposed model.

Despite promising results, several limitations should be acknowledged:

- Instead of deployment, simulated datasets were used for assessment.
- The research was short and did not examine user behavioral adaptation over time.
- Only controlled simulations assessed blockchain scalability and transaction throughput.
- Policy restrictions, economic incentives, and urban disturbances were ignored.

These limitations indicate the need for extended validation in real urban environments.

Future research will focus on expanding and validating the proposed framework through:

- Pilot deployment in selected metropolitan corridors to test system robustness in actual traffic.
- Big data scalability testing with significant user and transaction loads.
- Integrating smart-city infrastructure like IoT traffic sensors and urban mobility dashboards.
- Advanced behavioral modeling to understand ride-sharing preferences and trust.
- Privacy-preserving data architectures to safeguard user data while providing system efficiency.
- Traffic patterns, infrastructure density, and ride-matching optimization performance correlation study.
- These improvements may make the system a safe, intelligent, and ecologically sustainable mobility platform for next-generation urban transportation ecosystems.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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