Dynamic Pricing and Matching in P2P Ride-Sharing: Insights from MATSim Simulations in Dunkirk

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SHORT SUMMARY

This paper presents a dynamic peer-to-peer (P2P) ride-sharing system designed to reduce urban congestion and improve transportation efficiency. The system combines a distance-based dynamic pricing model with a penalized column generation algorithm to optimize rider-driver matching while respecting fare constraints and travel preferences. We evaluate the system using the MATSim simulation platform with real commuting data from Dunkirk, France. Different scenarios were tested by varying the number of participating drivers. Results show that with 80% of eligible travelers acting as drivers, the system achieves a 75% ride-matching rate, reduces total trips by 17%, while maintaining fare affordability. These findings demonstrate the potential of MATSim as a powerful tool for simulating and optimizing large-scale ride-sharing systems under realistic urban conditions. Our approach offers a scalable, cost-effective solution for improving mobility in growing urban areas.

Keywords: Simulation-Based Optimization, Shared-Mobility Solutions, Multi-Agent Systems, Dynamic Pricing

1 INTRODUCTION

Urban areas are increasingly dealing with traffic congestion, environmental degradation, and parking shortages, largely driven by the extensive use of low-occupancy personal vehicles, which average only 1.45 riders per car in Europe. These inefficiencies not only worsen traffic but also cause significant economic losses, reaching nearly 1% of the EU's GDP (European Environment Agency, 2022). As urbanization continues, the demand for innovative transportation solutions becomes more urgent.

Peer-to-peer (P2P) ride-sharing is a promising solution to some of these urban mobility challenges. This model allows private vehicle owners to offer rides to passengers heading in the same direction, helping to reduce vehicle numbers on the road, lower emissions, and decrease transportation costs for users (Gupta & Shanbhag, 2021). The effectiveness of such a system, however, depends on designing a dynamic pricing model that incentivizes both riders and drivers (Alisoltani et al., 2024).

Various dynamic pricing models have been explored, taking into account factors like trip length, travel time, and rider preferences (Agarwal et al., 2022). However, many existing models fail to adequately consider real-time traffic conditions and user-specific fare limits, which are crucial for successful adoption (Alisoltani et al., 2024). In response, this paper introduces a novel pricing model for P2P ride-sharing, which adjusts fares based on travel distance, number of passengers, and traffic conditions. The model encourages ride-sharing by reducing the fare per rider as the number of participants increases, thus aligning the interests of both riders and drivers. A significant challenge in P2P ride-sharing lies in real-time rider-driver matching, where the system must handle dynamically changing conditions and user demands. To address this, we propose a Penalized Column Generation algorithm, which optimizes the matching process by balancing driver revenue with rider preferences and fare limits. This algorithm efficiently computes high-quality assignments while handling the complexity of real-time operations (Alisoltani et al., 2022).

The effectiveness of the proposed system is evaluated using the MATSim platform, which simulates the dynamics of urban transportation networks. We applied the model to the city of Dunkirk, France, assessing the impact of P2P ride-sharing on reducing traffic congestion and improving transportation efficiency.

2 Methodology

Our study proposes a dynamic P2P ride-sharing system that optimizes the assignment of riders to drivers, balancing both rider preferences and driver incentives. The system integrates a pricing mechanism and a column generation-based optimization algorithm to ensure efficient ride-matching while accounting for multiple constraints, including fare limits, vehicle capacities, and travel time. In the P2P ride-sharing framework, individuals are divided into two groups: drivers and riders. Drivers use their personal vehicles to transport riders, while riders submit ride requests via a digital platform. Each ride request includes the following details: origin and destination locations, latest arrival time, number of seats required, and maximum allowable fare. The ride-sharing platform's primary task is to match riders with drivers based on these criteria, ensuring that the assignments optimize vehicle utilization and minimize total travel costs. The ride-sharing system operates in discrete time intervals, where ride requests are aggregated and assigned to available drivers at the beginning of each time window. The system matches drivers and riders in real-time and considers various factors, including travel distance, time windows, vehicle capacity, and fare limits. The assignments are recalculated periodically to incorporate new requests and changing traffic conditions, ensuring an adaptive system that can efficiently respond to real-time urban mobility needs. The key challenge is to efficiently assign riders to drivers so that both driver revenue and ride-sharing efficiency are maximized. We formulate the problem as a mixed-integer programming (MIP) optimization problem. The goal is to maximize the overall revenue for drivers, calculated as the total fares collected from riders minus the drivers' total travel costs. The optimization also takes into account a penalty function, which is applied if the fare assigned to a rider exceeds their specified maximum fare limit. This results in a soft constraint model, where fare violations are minimized but allowed within certain bounds.

The objective function aims to maximize the total revenue for all drivers while minimizing penalties due to fare violations. To achieve this, the assignment of riders to drivers considers the following: 1) Fare limits: riders specify a maximum fare they are willing to pay, and the system tries to assign fares below or equal to this limit. 2) Vehicle capacity: Each driver has a capacity limit based on the number of seats in their car. Multiple riders can share a vehicle, but their combined seat requirement must not exceed the vehicle's capacity. 3) Time windows: Riders have specified the latest arrival times, and the system must ensure that they are dropped off before these deadlines. 4) Maximizing shared rides: The system encourages shared rides to reduce the number of vehicles on the road and improve overall urban mobility.

To ensure fairness and efficiency in the P2P ride-sharing system, a dynamic pricing model is implemented based on the concept of shareability defined in Alisoltani et al. (2022). The fare for each rider is determined based on the travel distance and the number of shared riders. The dynamic pricing scheme adjusts fares according to two possible sharing scenarios:

1. Shareable-First-In-First-Out (FIFO): In this scenario, riders are picked up and dropped off in the order they were added to the system. The fare for each rider is computed based on the portion of the shared ride they contribute to, with a reduced cost for shared segments.

2. Shareable-First-In-Last-Out (FILO): In this scenario, the drop-off order is reversed, where the last rider picked up is the first to be dropped off. The pricing is adjusted to reflect the additional travel time and distance for each rider.

A P2P ride-sharing trip, starting from the driver's origin and ending at the driver's destination, can involve different combinations of these two scenarios. Using Equation 1, we can derive the trip fare for rider n, considering all possible sharing scenarios:

$$F_n = P_{Fixed} + P_{distance}(y^n_{O_n D_n}.TD_{O_n D_n} + \sum_{ij \in L, i,j \neq O_n, D_n} \frac{y^n_{ij}.TD_{ij}}{N^{ij}_o}) \tag{1}$$

Where P_{Fixed} is the fixed cost each rider pays, P_{distance} is the price per distance unit, TD_{ij} is the distance between each two stops i and j, L is the set of links, O_n and D_n are the origin and destination points for rider n, N^{ij}_o is the number of onboard riders when the driver passes link ij, and $y^m_{i,j}$ is a binary variable that shows if driver m transports a rider from point i to j.

This dynamic pricing model ensures that as more riders share a ride, the per-rider fare decreases, making ride-sharing an attractive financial option. It also balances driver incentives by ensuring that their revenue is maximized based on the total number of passengers and the total travel distance.

To solve the optimization problem efficiently, we use a Penalized Column Generation approach, which is suitable for large-scale ride-sharing assignments. This algorithm iteratively generates and evaluates potential solutions, adding the most promising combinations of drivers and riders

to the model at each step. At the start of each assignment period, an initial set of assignments (or "columns") is generated based on the current set of ride requests. These initial assignments are evaluated based on their time, capacity, and fare limits. During each iteration, the algorithm identifies promising new assignments, which involve matching additional riders to drivers. The system checks whether these new assignments improve the overall solution by maximizing driver revenue and minimizing fare violations. If a rider's assigned fare exceeds their maximum allowable fare, a penalty is added to the objective function. The algorithm balances maximizing driver revenue with minimizing these penalties. The system optimizes the assignment of riders to drivers, ensuring that constraints such as vehicle capacity and time windows are met. The algorithm continues iterating, generating new columns and refining the solution until it converges to an optimal or near-optimal solution. Once the best possible assignments are identified, they are finalized, and the drivers and riders are notified of their ride-sharing arrangement. The process is repeated for each assignment period.

The performance of the proposed P2P ride-sharing system was tested using real-world urban traffic data from the city of Dunkirk, France. We utilized the MATSim simulation platform to simulate the dynamics of urban mobility, accounting for real-time traffic conditions, vehicle routing, and ride-sharing behavior. The simulation evaluates the impact of our dynamic pricing model and column generation algorithm on system efficiency, including metrics such as the total number of shared rides, driver revenue, and rider satisfaction.

3 Results and Conclusion

To evaluate the effectiveness of the proposed P2P ride-sharing system, a simulation was conducted using real commuting data from Dunkirk, focusing on travelers eligible for ride-sharing. The study modeled different scenarios by varying the number of drivers among morning commuters. Key parameters such as fare thresholds and driver incentives were incorporated based on real-world taxi pricing and socio-economic rider profiles.

The results reveal that increasing the number of peer drivers significantly improves ride-matching rates. In one scenario, where 80% of travelers acted as drivers, the system achieved a 75% match rate. This led to a 17% reduction in the total number of trips, demonstrating the system's potential to alleviate congestion. Meanwhile, average rider fares increased by 16%, remaining within acceptable limits. Driver revenues remained stable across scenarios, indicating strong economic incentives for participation.

These results underscore the capability of MATSim to model and assess large-scale, dynamic ride-sharing systems under realistic urban conditions. By integrating behavioral constraints, fare thresholds, and traffic dynamics, our MATSim-based approach provides a robust and scalable framework for developing cost-effective, sustainable urban mobility solutions.

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