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# Enhancing the Carbon Reduction Potential in Ridesplitting through Evolutionary Game Strategies of Tripartite Stakeholders under Carbon-Inclusive Policy

**Zheyin Jin [1], Ye Li [1], Dominique Gruyer [2] and Meiting Tu [1,*]**

[1] The Key Laboratory of Road and Traffic Engineering, Ministry of Education, College of Transportation Engineering, Tongji University, 4800 Cao'an Road, Shanghai 201804, China; jinzheyin@tongji.edu.cn (Z.J.); jamesli@tongji.edu.cn (Y.L.)
[2] Laboratory on Perception, Interactions, Behaviors, and Simulation of the Road and Street Users (PICS-L), COSYS Department, University Gustave Eiffel—IFSTTAR, 25 allée des Marronniers, building IFSTTAR—UGE, 2nd floor, office 52, 78000 Versailles, France; dominique.gruyer@univ-eiffel.fr
* Correspondence: meitingtu@tongji.edu.cn

**Abstract:** The advancement of emission reduction benefits in ridesplitting relies on a comprehensive carbon reduction incentive policy initiated by the government and implemented through the collaborative efforts of multiple stakeholders. The aim of this study is to understand the implementation mechanism and explore the carbon reduction potential of the Carbon-Inclusive Policy. A framework has been developed to explore an evolutionary stabilization strategy through a three-party evolutionary game model, which considers the crucial stakeholders of the government, shared mobility companies, and travelers. A comprehensive sensitivity analysis has been conducted across various scenarios on key factors to ensure the robustness and accuracy of findings. The study's primary findings indicate that the government's level of commitment to the Carbon-Inclusive Policy significantly influences strategic decisions and the pace of evolution among the three stakeholders in the evolutionary game. Companies critically assess the economic viability of ridesplitting, particularly in light of development costs and subsidy incentives. Government backing and increased ridesplitting adoption by travelers serve to mitigate risks, incentivizing companies to actively promote ridesplitting. Furthermore, the study emphasizes the necessity of balancing individual, company, and societal interests for sustainable transportation development, advocating for reasonable carbon tax credits and the promotion of novel development concepts such as Environmental, Social, and Governance (ESG) principles. These findings serve as a significant resource for policymakers navigating the complexities of integrating carbon considerations into transportation policy frameworks, contributing to a deeper theoretical understanding of Carbon-Inclusive Policy implementation in the sector.

**Keywords:** Carbon-Inclusive policy; ridesplitting; evolution game; travel behavior; urban sustainability

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## 1. Introduction

In the face of escalating global efforts to mitigate carbon emissions and promote sustainable development, the transport sector has emerged as the most rapidly growing source of $CO_2$ emissions, presenting a significant challenge. Within the European Union, road vehicles contribute to 80% of transport-related $CO_2$ emissions, with private automobiles accounting for more than half of this figure [1]. Despite the existence of legally binding obligations for numerous countries to reduce $CO_2$ emissions, as stipulated by the Kyoto climate change conference, transport emissions have continued to exhibit an upward trajectory. The promotion of a sustainable transport system necessitates a paradigm shift from private vehicle usage to more energy-efficient modes of transportation [2]. This transformation can be achieved through the optimization of transport infrastructure, including the implementation of innovative public transport systems and the promotion of ridesplitting [3]. However, it is imperative to note that relying solely on technological advancements may prove insufficient in meeting sustainability targets. Consequently, policies aimed at encouraging alterations in travel behavior, such as adjusting travel modes and reducing trip frequency, are essential. The integration of environmental policies with economic and security benefits can significantly enhance their efficacy. These policy measures are crucial for the realization of a sustainable transport system.

In response to the growing global focus on combating carbon emissions and fostering sustainable development, China's Carbon-Inclusive Policy has emerged as a potent instrument for incentivizing eco-friendly behaviors across the transportation industry. This policy, akin to the UN Carbon Offset Platform, quantifies carbon reduction through applications and offers commercial incentives, typically in the form of exchanging carbon credits for consumer vouchers. It emphasizes quantifying and valuing energy-saving and carbon reduction behaviors among small and micro-companies, community households, and individuals, establishing a positive guidance mechanism combining commercial incentives, policy encouragement, and verified emission reduction transactions. Designed to integrate emissions reduction incentives into stakeholders' decision-making processes, the Carbon-Inclusive Policy interfaces with existing mechanisms such as carbon emissions trading systems.

Ridesplitting, which is a form of pooled ride-sourcing service made possible by digital ride-hailing platforms, allows multiple individuals to share a single vehicle for a particular journey or commute. Various studies have quantified the emission reduction benefits of ridesplitting [4,5]; therefore, promoting the development of ridesplitting services could assist in improving transportation system efficiency and reduce urban emissions.

Within the ridesplitting scenario, three primary stakeholders play a pivotal role in shaping the outcome of the Carbon-Inclusive Policy: travelers, shared mobility companies, and the government. It is crucial to analyze the interplay of behavioral strategies among the three stakeholders within the carbon inclusion framework. Measures need to be devised to safeguard the interests of companies and travelers while simultaneously enhancing environmental benefits.

However, the analysis of the Carbon-Inclusive Policy within the ridesplitting development context is still in its nascent stage. Although many studies have emphasized ridesplitting's benefits, particularly in reducing GHG emissions [6–9], they alone are insufficient for guiding detailed policy formulation, which needs to balance the interests among different stakeholders. The existing research on carbon reduction incentive policies in transportation primarily focuses on policy formulation [10], with relatively few equilibrium analyses of stakeholders during policy implementation. Meanwhile, the current research on the Carbon-Inclusive Policy is still at an early stage, predominantly relying on theoretical analysis and argumentation to explore its operational principles and overall structure [11–14]. Although some of these studies recognize the impact of carbon-inclusive incentives on the growth of China's transportation sector and traveler decision-making, which has favorable ramifications for efforts to reduce carbon emissions, there is limited attention given to investigating the incentive effect of the carbon-inclusive mechanism from an individual perspective through conclusive mathematical analysis.

To address this limitation, the main research objective of this paper is to develop a tripartite behavior evolutionary game model involving the government, companies, and travelers, investigating the effects of their behavior changes on the ridesplitting industry. Furthermore, utility functions incorporating a carbon preference incentive mechanism will be established. By aligning the interests of individual users, companies, and the environment, our proposed solution aims to maximize gains for all stakeholders. This study aims to fill a research gap by examining the strategic choices made by various stakeholders during the implementation of the Carbon-Inclusive Policy. It seeks to identify key influencing factors and elucidate how such policies can drive the evolution of green and low-carbon operational modes in shared mobility.

As shown in the Figure 1, the contributions of this work are presented as follows:

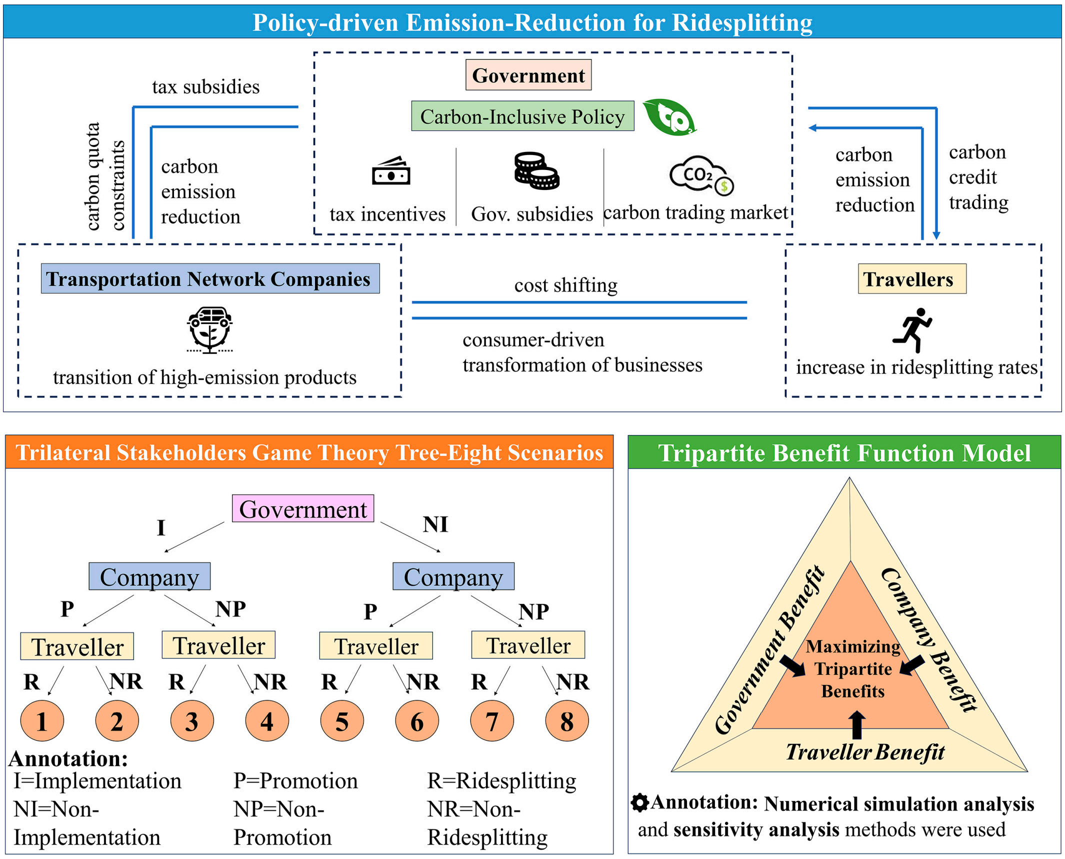

**Figure 1.** A Framework considering three stakeholders of the government, shared mobility companies and travelers in ridesplitting scenarios.

(1) By elucidating the mechanism of the Carbon-Inclusive Policy and establishing an evolutionary game model based on three-party interest subjects, it fills the research void regarding the emission reduction mechanism of users' online ridesplitting behavior driven by carbon inclusion;

(2) In the context of ridesplitting, a framework has been developed to delve into the evolutionary stabilization strategy within the tripartite game, considering various scenarios.

(3) Construction of utility functions with a carbon preference incentive mechanism as the focal point and Identified the key variables affecting the decision-making of the three parties, adopted numerical simulation analysis and sensitivity analysis methods to provide policy implications for the parties, to provide important decision-making references.

## 2. Literature Review

### 2.1. Research on Ridesplitting for Carbon Reduction

Ridesplitting is a term used to describe grouping travelers with a common origin or destination into a single vehicle and has emerged as an effective strategy for alleviating congestion.

The literature review shows that current ridesplitting research predominantly centers on four main areas. Numerous experts have conducted extensive investigations into driver-passenger matching and empty vehicle management scheduling, with optimization studies considering different objectives [7,8,15–19]. Several theories have focused on order allocation and pricing mechanisms, incorporating factors such as additional waiting time, passenger detour trip distance [20,21], driver's total trip distance [22], minimizing passenger expenditure [23], market equilibrium [24], and other multi-objective scenarios. Additionally, some scholars have estimated spatio-temporal demand and supply models for ridesplitting services.

Numerous studies have investigated the social and environmental benefits of ridesplitting services, quantifying emission reductions using real or simulated data. Previous research has revealed that ridesplitting can cut cumulative trip length by up to 40% in New York [7] and, on average, decrease travel distances by 22% compared to non-ridesplitting modes in major cities [25] and by 8.21% in mid-sized cities [8]. Several studies have shown that promoting electric vehicles (EVs) in ridesplitting could reduce $CO_2$ emissions by 57% compared to fuel-related emissions from ridesplitting alone [26], with reduced fuel-consumption reaching 22.88% and 15.09% in optimal and realistic scenarios in Shanghai [27]. Some authors have also mentioned that the $CO_2$ emission savings from ridesplitting actually depend on the day period considered [10]. Additionally, authors have qualified the emission factors of both regular ridesourcing and ridesplitting trips to evaluate the emission reductions per ride-km from ridesplitting, indicating an average $CO_2$ emission reduction rate of 28.7% for ridesplitting [6]. Others have compared $CO_2$ emissions between ridesplitting trips and their substituted regular ridesourcing, finding that the $CO_2$ emission reduction rate of ridesplitting varies between trips, averaging 43.15 g/km [9].

Despite the environmental benefits demonstrated by previous studies on ridesplitting, factors such as delays and detours significantly constrain people's willingness to carpool for trips, which also affects emission reduction efforts [28]. That is why the market share of ridesplitting only accounts for a small fraction of the total travel. For instance, ridesplitting trips accounted for only 17% of Didi's ride-hailing trips in Hangzhou, China [29], and were not widely adopted compared to ridesourcing and taxi services in Los Angeles County [30]. These findings suggest the need for further research on incentives to promote ridesplitting adoption.

### 2.2. Research on Incentives for Ridesplitting

To promote ridesplitting, policymakers should conduct thorough analyses of traveler adoption behavior and the factors influencing the development of ridesplitting by service providers. These analyses will support informed decision-making in the future.

According to the review that analyzes the factors influencing people's choice of ridesplitting [31], some early research has uncovered that various demographic attributes, such as gender, age, income, and level of education, can impact ridesplitting intentions. Additionally, some studies have explored the influence of psychological factors using social psychological theories.

Reviewing studies on incentives for ridesplitting reveals three main categories. Firstly, research on the incentive effect of social responsibility suggests that the sustainability concept influences people's attitudes toward ridesplitting [32]. Regarded as an environmentally friendly way [33], people are motivated by a sense of social responsibility to take part in ridesplitting. Studies suggest that combining positive social-psychological factors with low-carbon transport policies moderately affects individuals' willingness to choose ridesplitting [17,34–36]. However, some authors question whether travelers prioritize individual issues over societal concerns [37]. The economic attributes of ridesplitting, such as time perceptions and familiarity with the travel mode [38], appear to be more prominent, involving factors like saving money and travel comfort [39].

Category two focuses on the incentive effect of technical development provided by digital ride-hailing platforms. Driver-rider matching and order allocation algorithms play a crucial role in the overall performance and efficiency of ride-sharing systems [40–43]. Well-designed regulatory policies implemented through digital ride-hailing platforms can achieve a better balance between multiple competing goals [44], thereby reducing the transaction security risk for passengers during ridesplitting [45–47]. However, researchers have also identified limitations, including the non-universal application of matching technology for multi-person ridesplitting, with one important factor being insufficient price discounts and incentives associated with ridesplitting [48].

The third category pertains to policy incentives. Several policies have been implemented to encourage ridesplitting, including the establishment of ridesplitting lanes, differential pricing during periods of congestion, and adjustments to fuel taxes on ridesplitting vehicles [49,50]. In addition to governmental policies, the platforms also offer various preferential measures to promote ridesplitting. These include a points reward program [51] and referral bonuses [40,41]. Another common incentive method involves compensating passengers who have a negative ridesplitting experience [52].

Among the studies addressing policy incentives, only a few have specifically focused on ridesplitting choice behavior with respect to carbon emission reduction incentives. While existing studies have primarily focused on ridesplitting choice behavior concerning carbon emission reduction incentives [23,53], few have delved into the holistic consideration of ridesplitting systems based on carbon emission reduction incentives. Their emphasis remains confined to assessing the rationality of incentives in maximizing environmental benefits, leaving a prominent gap in research in this domain.

### 2.3. Research on Game Theory in Ridesplitting Services

Comparative studies between ridesplitting and regular ridesourcing modes under the influence of policies have been infrequent, indicating a need for further investigation. Numerous authors have acknowledged that travel choice behavior is profoundly influenced by government policies [54,55] and is based on bounded rationality [56]. Scholars began to pay attention to travel choice behavior under bounded rationality. Among the theoretical methods applied to analyze travel mode choice in metropolitan areas, the evolution game model stands out as one of the most widely used [57–59]. This model, rooted in evolutionary theory and game theory, operates under the premise of bounded rationality, constituting a long-term repetitive game within a specific-sized group [60,61]. Evolutionary game theory, validated for traffic choice analysis [62], offers an effective means for dynamically describing and optimizing the competitive dynamics between ridesplitting and regular ridesourcing modes.

The existing literature predominantly focuses on maximizing the benefits of a single party. For instance, ridesplitting studies primarily explore maximizing emission reduction benefits from the government's perspective [10], maximizing revenue for shared mobility companies [63], and minimizing travel costs for passengers [64]. However, there is currently a notable research gap since the release of the Carbon-Inclusive Policy. Specifically, there is a lack of investigation into ridesplitting choice behavior concerning carbon emission reduction incentives from a holistic perspective that considers the interests of multiple stakeholders, including the government, shared mobility companies, and passengers.

The Carbon-Inclusive Policy, a noteworthy carbon reduction incentive mechanism proposed by China in 2017, is typically spearheaded by governmental bodies and collaboratively endorsed by internet companies [13]. Leveraging application software platforms, this policy systematically calculates carbon emission reductions resulting from diverse low-carbon behaviors. Commercial incentives play a pivotal role in this mechanism, involving initiatives such as exchanging carbon credits for consumer coupons and granting carbon tax exemptions. Additionally, the policy fosters low-carbon behaviors among the public and companies in daily consumption through the impetus of social environmental responsibility. This is exemplified by initiatives like ranking friends based on users' "carbon account" points, thereby creating a multifaceted approach to encouraging sustainability in everyday practices. Carbon-Inclusive Policy is designed to interface with existing mechanisms, such as carbon emissions trading systems, with the aim of integrating emissions reduction incentives into the decision-making processes of stakeholders.

The Carbon-Inclusive Policy necessitates striking a proper balance between the government, shared mobility companies, and travelers. Information asymmetry between the government and shared mobility companies, coupled with imperfect reward and punishment mechanisms [65], may diminish the impact of the government's carbon reduction incentives on companies and result in a detrimental subsidy cycle. Consequently, companies may modify their business strategies, slowing down ridesplitting development and reducing travelers' willingness to adopt it.

There exists a research gap concerning how to effectively coordinate the interests of multiple stakeholders in the ridesplitting scenario during policy implementation to maximize the goal of carbon emission reduction. It is imperative to integrate the interests of the three stakeholders and propose a comprehensive framework to harmonize the interests of all parties for the effective implementation and realization of the Carbon-Inclusive Policy

### *2.4. Summary*

In summary, addressing the aforementioned limitations requires dissecting the benefits, costs, and optimization objectives of each party to ensure effective policy implementation. The existing literature on Carbon-Inclusive Policy research and practice is still in its nascent stages. Some studies have recognized the positive impact of carbon inclusion incentives on carbon emission control and reduction in transportation and low-carbon development [66]. However, the considered scenarios and factors are often too generalized. Importantly, there is a research gap in identifying the key variables that influence the decision-making of the government, shared mobility companies, and ridesplitting participants regarding the application of Carbon-Inclusive Policy in ridesplitting scenarios. Further investigation is needed to understand the dynamic relationship between multiple interests and their decision-making processes. It is imperative to enhance the efforts of shared mobility companies in promoting green and low-carbon concepts and establish a beneficial feedback mechanism among various stakeholders. Additionally, it is necessary to propose a comprehensive framework that integrates the interests of the three stakeholders and identifies key variables influencing their decision-making. Utilizing numerical simulation and sensitivity analysis, this study provides policy implications for each party.

## 3. Methodology

### *3.1. Evolutionary Game Model*

#### 3.1.1. Basic Assumptions

**Assumption 1.** *The basic components of an evolutionary game are the players, strategy set, probability of strategy selection, and the payoff functions. In this paper, the players comprise the government, travelers opting for ridesplitting or ride-hailing for specialized trips, and the companies offering corresponding services. In an evolutionary game, stability is achieved when the proportions of players using different strategies remain constant over time. The government's behavior primarily involves choosing to implement the Carbon-Inclusive Policy or not. For the government, let* $x$ *represent the probability of policy implementation, then the probability of choosing not to implement policies is* $1 - x$*. For the companies, let* $y$ *denote the probability of promoting ridesplitting travel patterns, and the probability of choosing not to promote such patterns is* $1 - y$*. Traveler behavior primarily entails choosing between ridesplitting and ride-hailing (involving a single ride where the rider travels and bears the ride cost alone). Let* $z$ *represent the probability of choosing ridesplitting, then the probability of choosing ride-hailing is* $1 - z$*.*

**Assumption 2.** *The three players (the government, the companies, and the travelers) are assumed to have bounded rationality, meaning their decision-making is limited by the information they have, their cognitive limitations, and the time available to make decisions. The three players will adequately calculate and compare all the possible outcomes to protect their own interests and identify the strategy that can best serve these interests.*

#### 3.1.2. Parameter Setting

Table 1 presents the parameters utilized within the framework of the evolutionary game model. The specific values of the parameters will be discussed in Section 4.1.

**Table 1.** Description of Parameters in the Evolutionary Game Model.

| Parameter | Description |
|---|---|
| $Q$ | The number of incentives provided by the government to companies that promote and develop ridesplitting services. |
| $P$ | The value of carbon tokens awarded by the government to travelers who choose ridesplitting. |
| $E$ | Environmental benefits (in terms of carbon reduction) achieved when groups of travelers choose ridesplitting. |
| $v$ | The government's environmental value coefficient, as determined by evaluation systems. $v$ equals 1 when the Carbon-Inclusive policy is not implemented. |
| $F$ | Carbon tax revenue from the government and proceeds from the auction of emission reduction allowances for companies. |
| $M$ | The cost of labor and material resources consumed by the government to implement the policy. |
| $R$ | Costs for companies to promote and support ridesplitting. |
| $T1$ | Revenues gained by companies under the ridesplitting model. |
| $T2$ | Additional revenue gained by companies due to improved social image as a result of promoting carbon reduction through ridesplitting. |
| $\Delta Q = \alpha Q$ | The concession offered by companies to consumers, derived from the government's direct subsidy. $\alpha$ represents the concession coefficient. |
| $K$ | The direct and indirect losses of the companies when the companies do not develop and promote the ridesplitting mode of online ridesplitting. |
| $A$ | The gain of ridesplitting by travelers. |
| $B$ | The gain from ride-hailing for travelers. |
| $\beta R$ | The benefits of promoting ridesplitting by the platform to travelers, and $\beta$ is the profitability factor. |
| $i_1$, $i_2$, $i_3$ | Carbon tax coefficients under different conditions:The carbon tax coefficients paid by companies when they promote ridesplitting are $i_1$, the carbon tax coefficients carried by commuters when they do not promote ridesplitting are $i_2$, and the carbon tax coefficients paid by companies when they do not promote ridesplitting are $i_3$. |

### 3.1.3. Payoff Matrix of Evolutionary Game

Based on the above assumptions and analysis, we considered two different scenarios: one without government regulations and the other with government regulations. The payoff matrix among tripartite stakeholders is shown in Table 2.

**Table 2.** Evolutionary game payoff matrix.

| Trilateral Strategy Combination | Government Benefits | Company Benefits | Traveler Benefits |
|---|---|---|---|
| Implementation\support\ridesplitting | $F\cdot i_1 + vE - P - M - Q$ | $T1 + T2 + (1-\alpha)Q - R - F\cdot i_1$ | $A + \alpha Q + P + \beta R$ |
| Implementation\support\ride-hailing | $F\cdot(i_1 + i_2) - M - Q$ | $T2 + Q - R - F\cdot i_1$ | $B - F\cdot i_2$ |
| Implementation\unsupport\ridesplitting | $F\cdot i_3 + vE - P - M$ | $-K - F\cdot i_3$ | $A + P$ |
| Implementation\unsupport\ride-hailing | $F\cdot(i_2 + i_3) - M$ | $-K - F\cdot i_3$ | $B - F\cdot i_2$ |
| Non-implementation\support\ridesplitting | $E$ | $T1 + T2 - R$ | $A + \beta R$ |
| Non-implementation\support\ride-hailing | 0 | $T2 - R$ | $B$ |
| Non-implementation\unsupport\ridesplitting | $E$ | $-K$ | $A$ |
| Non-implementation\unsupport\ride-hailing | 0 | $-K$ | $B$ |

### 3.1.4. Replicated Dynamic Differential Equations and Replicated Dynamic Analysis

Based on the payoff matrix, Equation (1) represents the expected payoff of the government choosing to implement the Carbon-Inclusive policy. Equation (2) represents the expected payoff of the government choosing not to implement the Carbon-Inclusive policy. Equation (3) calculates the average expected return to the government:

$$\begin{aligned}\Pi_{11} = (i_1F + vE - P - M - Q)yz + [(i_1 + i_2)F - M - Q]y(1 - z) \\ +(i_3F + vE - P - M)(1 - y)z + [(i_2 + i_3)F - M](1 - y)(1 - z)\end{aligned} \quad (1)$$

$$\Pi_{12} = Eyz + E(1 - y)z \quad (2)$$

$$\Pi_1 = x\Pi_{11} + (1 - x)\Pi_{12} \quad (3)$$

Thus, the replicator dynamics equation of the government is as follows:

$$F(x) = dx/dt = x(\Pi_{11} - \Pi_1) = x(1 - x)\{(-M + (i_2 + i_3)F - Pz - Qy + (i_1 - i_3)Fy - i_2Fz + (v - 1)Ez)\} \quad (4)$$

Similarly, Equations (5) and (6) represent the dynamic differential equations for the replication of companies and travelers:

$$F(y) = dy/dt = y(\Pi_{21} - \Pi_2) = y(1 - y)(K - R + T2 + Qx + zT1 - i_2Fx + i_3Fx - Q\alpha xz) \quad (5)$$

$$F(z) = dz/dt = z(\Pi_{31} - \Pi_3) = z(1 - z)(A - B + Px + i_2\mathrm{Fx} + R\beta y + Q\alpha xy) \quad (6)$$

**I** Analysis of government decision replication dynamics

(1) In the government's replication dynamic equation *F(x)* (Equation (4)), the equation *F(x)* $\equiv$ 0 is observed when $0 < y = \frac{(M - i_2F - i_3F + Pz + i_2Fz - Ez(v - 1))}{(-Q + i_1F - i_3F)} < 1$, In this range, the government's strategy choice reaches a steady state, irrespective of the value of $x$.

(2) $\left.\frac{d\,F(x)}{dx}\right|_{x=0} < 0$ and $\left.\frac{d\,F(x)}{\mathrm{dx}}\right|_{x=1} > 0$ are observed when $0 < y < \frac{(M - i_2F - i_3F + Pz + i_2Fz - Ez(v - 1))}{(-Q + i_1F - i_3F)} < 1$, the evolutionary stability point occurs at $x = 0$, indicating that the government has decided not to implement the Carbon−Inclusive Policy.

(3) $\left.\frac{d\,F(x)}{\mathrm{dx}}\right|_{x=0} > 0$ and $\left.\frac{d\,F(x)}{\mathrm{dx}}\right|_{x=1} < 0$ are observed when $0 < \frac{(M - i_2F - i_3F + Pz + i_2Fz - E\cdot(v - 1))}{(-Q + i_1F - i_3F)} < \mathrm{y} < 1$, the evolutionary stability point occurs at $x = 1$, signifying that the government ultimately opts to adopt a Carbon-Inclusive Policy.

The analysis of the government's evolutionary stability strategy for the Carbon-Inclusive Policy reveals a complex interplay of economic, environmental, and social factors. The policy's success hinges on balancing multiple parameters, including the government's environmental valuation ($v$), carbon tax structures ($i_1$, $i_2$, $i_3$), subsidy efficiency ($Q$, $P$), and environmental benefits ($E$). The government's probability of adopting the policy ($x$) increases as administrative costs ($M$), traveler incentives ($P$), and company subsidies ($Q$) decrease or as carbon tax revenue ($F$) and environmental benefits ($E$) increase.

The model suggests that strong governmental commitment to environmental goals can offset implementation costs, while effective carbon tax differentials can incentivize desired behaviors. Specifically, the difference between $i_1$ (tax when companies promote ridesplitting) and $i_3$ (tax when companies do not) creates an incentive structure. If ($i_1F$–$i_3F$) is substantial, it could drive policy adoption by offsetting implementation costs ($M$) and subsidies ($Q$). Balancing subsidies between companies and travelers is crucial for maximizing impact while minimizing expenditure. Furthermore, the inclusion of corporate social responsibility benefits ($T2$) and traveler decision-making factors ($A$, $B$) adds layers of complexity, necessitating a dynamic, adaptive policy approach.

**II** Analysis of decision replication dynamics of shared mobility companies and travelers

Following a similar methodology used to analyze the government's decision replication dynamics, we derive the following results for companies and travelers:

(1) In the company's replication dynamic equation $F(y)$ (Equation (5)), the equation $F(y) \equiv 0$ is observed when $0 < z = \frac{-(K-R\ +\ T2\ +\ Qx-i_2Fx\ +\ i_3Fx)}{(T1\ -Q\alpha x)} < 1$, In this range, the platform company's strategy choice reaches a steady state, irrespective of the value of $y$. When $z$ takes a value lower or higher than the specified threshold, the company's ultimate decision will lean towards either adopting or not adopting the promoted ridesplitting travel patterns;

(2) In the traveler's replication dynamic equation $F(z)$ (Equation (6)), when $0 < x = \frac{-(A-B\ +\ R\beta y)}{(P\ +\ i_2F\ +\ Q\alpha y)} < 1$, $F(z) \equiv 0$, indicating that the strategy choice of the traveler is kept constant in the steady state regardless of the value of $x$. When $x$ takes a value lower or higher than the specified threshold, the travelers' ultimate decision will lean towards either taking or not taking ridesplitting trips.

These findings underscore the interrelated nature of decisions among stakeholders and the presence of critical thresholds that can trigger shifts in behavior. Companies should focus on optimizing the cost-benefit ratio of ridesplitting promotion, leveraging government subsidies to reach the tipping point where promotion becomes consistently beneficial. Governments need to calibrate their policies to exceed the critical threshold that influences both company and traveler decisions, considering the balance between incentives (subsidies, carbon credits) and disincentives (carbon taxes). Strategies should aim to create a positive feedback loop where increased traveler adoption encourages more company investment, which in turn makes ridesplitting more attractive to travelers.

### 3.1.5. Solving for Stable Strategy Equilibrium Points

We used MATLAB R2022a to compute the Jacobian matrix of the dynamic differential equations, solve for equilibrium points, and determine their eigenvalues. Table 3 presents the joint equation ($F(x) = 0$, $F(y) = 0$, $F(z) = 0$), which reveals eight pure strategy equilibria in the system: *E1* (0, 0, 0), *E2* (1, 0, 0), *E3* (0, 1, 0), *E4* (0, 0, 1), *E5* (1, 1, 0), *E6* (1, 0, 1), *E7* (0, 1, 1), and *E8* (1, 1, 1). It is worth noting that there could potentially exist additional mixed−strategy equilibria satisfying the equation. However, given that a three−way evolutionary game necessitates pure-strategy Nash equilibria for asymptotic stability, only the asymptotic stability of the eight pure-strategy equilibria requires examination.

**Table 3.** Stability of equilibrium point.

| **Equilibrium Point** | **Eigenvalue** | | | **ESS Stability Condition** |
|---|---|---|---|---|
| | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | |
| (0, 0, 0) | $A - B$ | $F \cdot i_2 - M + F \cdot i_3$ | $K - R + T2$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (1, 0, 0) | $M - F \cdot i_2 - F \cdot i_3$ | $A - B + P + F \cdot i_2$ | $K + Q - R + T2 - F \cdot i_1 + F \cdot i_3$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (0, 1, 0) | $R - K - T2$ | $A - B + R\beta$ | $F \cdot i_1 - Q - M + F \cdot i_2$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (0, 0, 1) | $B - A$ | $K - R + T1 + T2$ | $F \cdot i_3 - M - P - E + Ev$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (1, 1, 0) | $M + Q - F \cdot i_1 - F \cdot i_2$ | $A - B + P + F \cdot i_2 + Q\alpha + R\beta$ | $R - Q - K - T2 + F \cdot i_1 - F \cdot i_3$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (1, 0, 1) | $B - A - P - F \cdot i_2$ | $E + M + P - F \cdot i_3 - Ev$ | $K + Q - R + T1 + T2 - F \cdot i_1 + F \cdot i_3 - Q\alpha$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (0, 1, 1) | $B - A - R\beta$ | $R - K - T1 - T2$ | $F \cdot i_1 - M - P - Q - E + Ev$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |
| (1, 1, 1) | $B - A - P - F \cdot i_2 - Q\alpha - R\beta$ | $E + M + P + Q - F \cdot i_1 - Ev$ | $R - Q - K - T1 - T2 + F \cdot i_1 - F \cdot i_3 + Q\alpha$ | $\lambda_1 < 0; \lambda_2 < 0; \lambda_3 < 0$ |

If a given equilibrium point is ascertained to be stable, it is essential to ensure that $\lambda_1$, $\lambda_2$, and $\lambda_3$ are all negative. Consequently, the evolution conditions must be met, wherein $B - A - P - F - i_2 - Q\alpha - R\beta < 0$, $E + M + P + Q - F - i_1 - Ev < 0$, and $R - Q - K - T1 - T2 + F - i_1 - F - i_3 + Q\alpha < 0$, with the aim of driving the system towards the desired state of converging to a uniform and stable equilibrium point (1, 1, 1).

The analysis of the stable outcomes pertaining to the evolution of ridesplitting emission reduction within the government-platform-travelers tripartite yields the following conclusions:

(1) In the context of the tripartite game's evolution, the decision-making choices made by each stakeholder engage in mutual interactions, surpassing the constraints inherent in the conventional two-subject evolutionary game;

(2) In order to achieve the optimal state *E8* (1, 1, 1) within the government-company-traveler triple stakeholder framework, several critical factors impacting the decision-making of the government, companies, and travelers need to fulfill the following conditions: Firstly, the government's revenue must surpass its expenditures related to management costs, subsidies to companies and individuals, as well as revenue generated from individual ridesplitting trips, combined with benefits accrued from the government and companies. Secondly, the overall revenue from ridesplitting trips, encompassing income from private ridesplitting and carbon tax expenditures, should exceed the revenue obtained from private car trips. Lastly, the platforms' total revenue from ridesplitting mode development, including government subsidies, must outweigh the costs associated with ridesplitting mode development, minus its carbon tax payments.

### *3.2. Three-Party Benefit Maximization Ridesplitting Policy Model*

Policymakers face the challenge of optimizing ridesplitting strategies to balance the interests of individuals, companies, and society at large. While increasing ridesplitting rates can benefit the environment, it is important to consider the fiscal burdens on governments and businesses, which can impact both transportation sustainability and economic viability. This study presents a comprehensive ridesplitting policy model that maximizes welfare across three key stakeholders: the government, companies, and travelers. The model proposes a strategy to harmonize environmental benefits, company profitability, and traveler well-being. By integrating influential factors within a unified decision-making framework, this model offers a visual representation of the intricate interplay among these factors in maintaining equilibrium. Building upon the variables presented in Table 2, Table 4 introduces additional variables specific to this ridesplitting policy model, along with their descriptions.

**Table 4.** Description of Parameters in the Three-Party Benefit Maximization Ridesplitting Policy Model.

| Parameter | Description |
|---|---|
| $\delta$ | The rate of change in the proportion of travelers opting for ridesplitting. |
| $SCC$ | The social cost of carbon, representing the economic cost of an additional ton of carbon dioxide emissions. |
| $a$ | A scaling coefficient that relates the number of ridesplitting instances to their environmental impact. |
| $K$ | The total number of ridesplitting trips within a specified period. |
| $d$ | The percentage reduction in $CO_2$ emissions attributable to each ridesplitting trip, compared to individual rides. |
| $U0$ | A constant representing the baseline utility of the transportation system before policy implementation. |

#### Model Construction and Parameter Description

Based on the evolutionary game model's parameters, when an active strategy combination is adopted by all three stakeholders—namely the government, companies, and travelers—the ensuing impact on the benefit functions is contingent upon the following factors:

**I** The government's benefit function

A change δ in the ridesplitting ratio affects key factors: environmental benefits *E* from reduced emissions, carbon tax revenue *F*, government subsidies *Q*, and incentives *P* for companies and individuals. The environmental benefit *E* from ridesplitting emission reductions is crucial and linked to managing carbon emissions. The social cost of carbon (SCC) determines this cost. Some researchers proposed a precise method for calculating SCC [67]. In 2015, SCC was estimated at $31.2 per ton, and it will rise to $61 per ton by 2023 and further to $102.5 per ton by 2050. The precise value of carbon tax revenue remains uncertain. Global carbon tax rates vary widely, ranging from $1 per ton in Poland to $119 per ton in Sweden by the end of 2019, and regions had rates below $10 per ton.

The environmental benefit *E* from ridesplitting emission reduction and its impact on carbon tax revenue *F* can be estimated by comparing the value of carbon emission control cost and carbon tax. For this model, we assume an initial carbon tax price of 20 yuan per ton in China for 2016.

Applying the principle of diminishing marginal utility, it can be observed that as the subsidy increases, the incentive effect of each unit of subsidy for travelers diminishes. The relationship between the government's input in ridesplitting subsidies *Q* and the number of ridesplitting instances by travelers Δ*P* can be expressed through a decreasing function, as illustrated in Equation (7):

$$K = a \ \times \ln(\Delta Q + \Delta P \ +1) \tag{7}$$

From Equation (7), it can be deduced that if the ridesplitting ratio changes by δ, the resulting alteration in government input subsidies amounts to $\left(P + Q + 1\right) \times \left(e^{\delta+1} - 1\right)$.

Based on the above analysis, the variation in the government's benefit function can be expressed by the following Equation (8):

$$\Delta GovernmentBenefit = -\ dF\delta \ + d\delta \times SCC - (P \ + Q \ +1) \ \times \ (e^{\delta+1} - 1) \tag{8}$$

**II** The companies' benefit function

Upon a change of δ in the ridesplitting ratio, several factors undergo alterations, including the direct and potential benefits (*T*1 and *T*2) reaped by companies as a result of ridesplitting, the subsidies *Q* received from the government, and the cost investment *R* required by firms to promote ridesplitting. The relationship between the cost input R and the growth of carpool volume also satisfies the principle of diminishing marginal benefit.

The variation in the companies' benefit function can be expressed by the following Equation (9):

$$\Delta Enterprises\ Benefit = (T1 + T2)\delta + \delta(1 - \alpha)Q - (R + 1) \times \left(\mathrm{e}^{\delta+1} - 1\right) \tag{9}$$

**III** The traveler's benefit function

In the event of a variation of δ in the proportion of ridesplitting, there will be modifications in the benefits (*A* and *B*) attained by travelers through both ride-hailing and ridesplitting. Additionally, the government subsidies *P* received, corporate concessions $\alpha Q$, and costs invested by companies in ridesplitting development, as captured by the benefit value ($\beta R$) of the traveler group, will also experience changes. The extent of change in the travelers' benefit function can be mathematically expressed by the following Equation (10):

$$\Delta UserBenefit = \delta(A - B) + \delta(\alpha Q + P + \beta R) \tag{10}$$

In summary, the total utility function for all three parties is given by Equation (11):

$$U = \Delta GovernmentBenefit + \Delta EnterprisesBenefit + \Delta UserBenefit + U0 \tag{11}$$

## 4. Results and Discussion

### *4.1. Simulation Analysis and Sensitivity Analysis*

In this study, we employ MATLAB R2022a to conduct a numerical simulation investigating the evolutionary dynamics.

To determine the initial values for our evolutionary game model, we first analyzed data from the GAIA Initiative of DiDi Chuxing, a dataset of ride-hailing orders. We utilized the full sample of DiDi ride-hailing order data from November 1, 2016, in the central urban area of Chengdu (longitude from 104.04254 to 104.12944E, latitude from 30.65307 to 30.72748N, using the GCJ-02 coordinate system). The dataset includes the following key information, as summarized in Table 5.

**Table 5.** Order dataset.

| Category | Data Type | Example | Notes |
|---|---|---|---|
| Driver ID | String | ACLnrof5tvbps3nBvuyBhqrfavskou7g | Anonymized |
| Order ID | String | vCAllto9vpeqv2kqvqwFkkuk7ouewr4l | |
| ST | String | 1479296319 | Start Time |
| ET | String | 1479296966 | End Time |
| SLon | String | 104.12009 | Start and end coordinates, GCJ-02 coordinate system |
| SLat | String | 30.65871 | |
| ELon | String | 104.09782 | |
| ELat | String | 30.66372 | |

After performing data cleaning, we identified ridesplitting trips by analyzing the overlap of start and end times for trips under the same DriverID in the order dataset. Our analysis revealed that approximately 4% of the total rides were ridesplitting trips.

Based on our analysis of the DiDi data and consideration of the current market conditions, we set the initial strategy selection probabilities for the government, shared mobility companies, and travelers in our evolutionary game model to (0, 0.33, 0.04). These values represent the market response at a point when the government is considering but has not yet implemented the Carbon-Inclusive policy:

Government (0): representing the current non-adoption of the Carbon-Inclusive policy;
Companies (0.33): indicating a moderate level of support for the ridesplitting mode;
Travelers (0.04): reflecting the current 4% proportion of ridesplitting among all rides.

These initial values capture the market dynamics at a crucial juncture: when the government is on the verge of implementing the Carbon-Inclusive policy, companies are already showing some support for ridesplitting, and travelers have a baseline level of engagement with ridesplitting services. This starting point allows us to explore how the system might evolve once the policy is officially implemented and how it could transition to a state with wider adoption of ridesplitting and full implementation of the Carbon-Inclusive policy.

It should be highlighted that the system dynamics model is designed to unveil dynamic changes. Precise results are not a necessity for variable assignments; rather, they facilitate the model in capturing the system's trends and the influence of regulatory adjustments [68]. Hence, in establishing the initial values for variables, our primary focus lies in assessing the sensitivity of variable changes to players' strategic choices rather than aiming for an exact representation of the benefits or costs incurred by all parties. Taking the relevant studies [69,70] and real-world scenarios into account, along with considerations for parameter interdependencies, equilibrium point constraints on λ1–λ3, and the necessity to uphold a constant ridesplitting group selection ratio, we proceed to calibrate the initial values for each parameter: $\alpha = 0.3$, $A = 13$, $B = 14$, $T1 = 12$, $T2 = 4$, $M = 3$, $P = 6$, $Q = 6$, $\beta = 0.32$, $R = 9.48$, $E = 20$, $v = 1.5$, $F = 16$, $i_1 = 0.5$, $i_2 = 0.4$, $i_3 = 0.6$. We set the parameters in the system dynamics model as INITIAL TIME = 0, TIME STEP = 0.01, and Units for TIME: Year.

#### 4.1.1. Evolutionary Game Phase Diagram

Figure 2 presents the phase diagram illustrating the three-party evolutionary game, depicting strategy selection and interactions among the government, shared mobility companies, and travelers from various perspectives. While the time required and evolutionary paths to reach equilibrium vary with different initial values, all parties eventually converge to a stable equilibrium point (1, 1, 1). The evolutionary game system demonstrates robust stability and equilibrium. Unlike traditional two-subject evolutionary games, this tripartite system demonstrates a high degree of interconnectedness in decision-making processes. The small distance between adjacent points and frequent curve crossings signify clear cooperation and interaction among the government, shared mobility companies, and travelers.

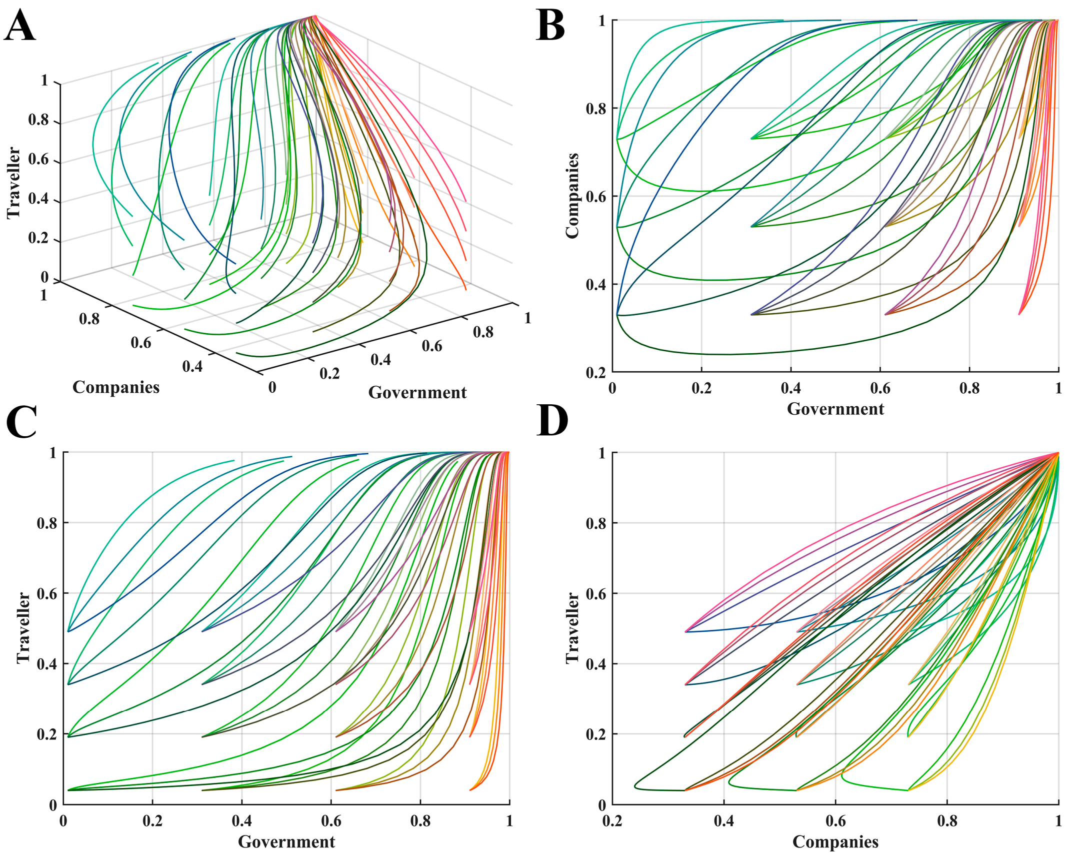

**Figure 2.** Evolutionary game phase diagram. (**A**) 3D interaction among Government, Companies, and Travellers. (**B**–**D**) 2D projections: (**B**) Government-Companies, (**C**) Government-Travellers, and (**D**) Companies-Travellers, each with the third party's strategy fixed.

#### 4.1.2. Influence of Initial Selection Probability on Three-Party Strategy Evolution

In Figure 3A–D, we incrementally enhance the government's initial willingness to adopt the Carbon-Inclusive policy from 0.01 to 0.91 while keeping the other parameters constant. The different colored lines in the Figure 2 represent various trajectories of strategy evolution over time for the three parties involved (Government, Companies, and Travellers). Each line indicates the dynamic path that the strategies of these parties follow as they interact with each other under different initial conditions and parameters. The color variation helps to visually distinguish between the different paths. The V-shaped trend is observed in the company's probability of promoting ridesplitting when the government's willingness to adopt carbon-inclusive strategies is initially low. This indicates that a certain threshold of government commitment is necessary to catalyze significant changes in company behavior. Once this threshold is surpassed, the rate of adoption accelerates rapidly. Conversely, as the government's initial probability increases, both companies and individuals show stronger and faster inclinations toward the strategy. Notably, companies are more responsive to the government's Carbon-Inclusive Policy compared to travelers.

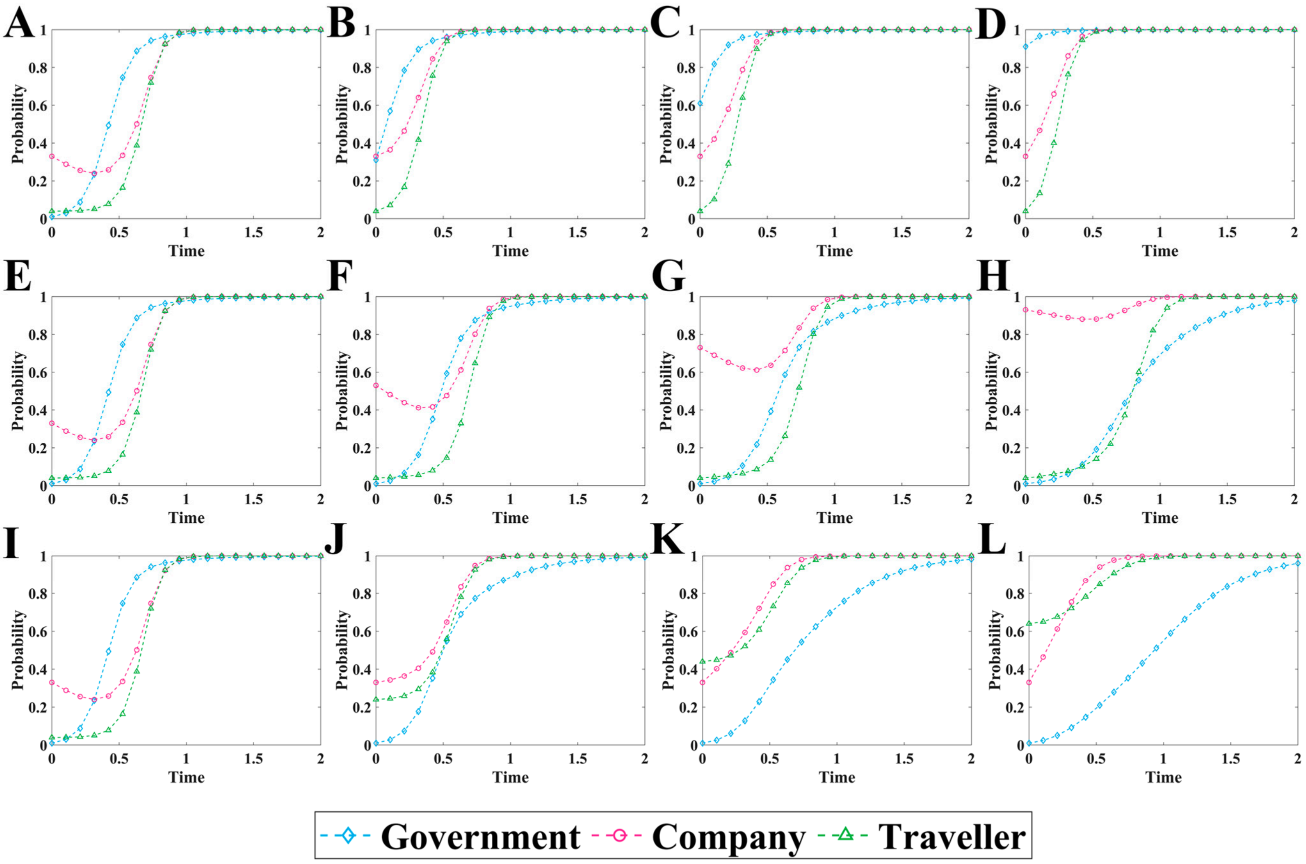

**Figure 3.** Time evolution of strategy adoption probabilities for Government, Company, and Traveller under various scenarios. (**A**–**D**): Low initial probabilities for all parties. (**E**–**H**): Medium initial probabilities. (**I**–**L**): High initial probabilities. Each column represents different parameter settings: (**A**,**E**,**I**): baseline scenario; (**B**,**F**,**J**): increased government subsidies; (**C**,**G**,**K**): enhanced company investments; (**D**,**H**,**L**): improved traveller awareness. The x-axis shows time, and the y-axis represents the probability of adopting the cooperative strategy for each party.

Moreover, our model reveals that the increased willingness of companies to promote ridesplitting correlates with a deceleration in the government's adoption of Carbon-Inclusive strategies (Figure 3E–H). This suggests that proactive companies' initiatives might inadvertently reduce the perceived urgency for governmental action. In contrast, travelers' ridesplitting choices are less sensitive to changes in the initial value of the platform company due to factors like personal travel demands and economic considerations.

The analysis of traveler behavior (Figure 3I–L) reveals that as the proportion of travelers opting for ridesplitting increases, there is a notable enhancement in companies' willingness to promote this service, accompanied by a decrease in the urgency for governmental intervention in adopting Carbon-Inclusive strategies. This finding indicates that public awareness campaigns and initiatives targeting individual travel choices may result in significant systemic benefits.

### 4.1.3. Sensitivity Analysis

To evaluate the effectiveness of the policy from multiple dimensions, several core parameters were selected for sensitivity analysis: Parameters $Q$ and $P$, representing government subsidies to companies and individuals, respectively, directly influence the attractiveness and effectiveness of the Carbon-Inclusive policy. Parameter $F$, denoting government economic benefits from carbon taxes and emission reduction auctions, is crucial for assessing the policy's sustainability. Parameter $E$ signifies the emission reductions, embodying the policy's core environmental objective. Parameter $R$ pertains to the economic feasibility of corporate participation by representing the costs companies incur in promoting ridesplitting. These parameters collectively encompass subsidy levels, government revenue, environmental benefits, and corporate costs. Analyzing these aspects ensures the policy's ability to promote low-carbon development while balancing economic, social, and environmental interests.

Each subfigure in Figure 4 illustrates the evolutionary strategies of the government, companies, and travelers under different values of the key parameters. Parameter $E$ can be used for the assessment of how environmental gains influence stakeholder decisions. Figure 4A reveals that decreasing *E-values* substantially impacts government strategic choices. Extremely low environmental gains may lead to policy abandonment, while higher gains have diminishing returns on stakeholder behavior beyond a certain threshold. Parameter $F$ can evaluate the policy's financial sustainability. Figure 4B demonstrates that while excessive increases in $F$ have limited impact, insufficient carbon tax revenue (low *F-values*) significantly reduces corporate willingness to promote ridesplitting due to inadequate constraints. Extremely low *F-values* may lead to government abandonment of the policy, highlighting the importance of balanced economic returns in maintaining policy momentum. Parameters $P$ and $Q$ represent government subsidies to individuals and companies. These were selected to directly assess the policy's attractiveness and effectiveness from both corporate and public perspectives. $P$ impacts travelers' ridesplitting choices and indirectly affects corporate behavior (Figure 4C). Higher *P-values* positively influence public adoption of ridesplitting and corporate promotion efforts. Meanwhile, $Q$ significantly influences corporate decision-making (Figure 4D), as insufficient subsidies weaken companies' willingness to develop ride-splitting. However, excessively high incentives can burden government finances, potentially reducing long-term policy sustainability. The optimal subsidy level balances corporate incentivization with fiscal responsibility.

Finally, parameter $R$ is used to evaluate the economic feasibility of corporate behavior. Figure 4E illustrates that excessive promotion costs weaken companies' willingness to develop ridesplitting, emphasizing the need for a cost structure that aligns with potential benefits.

The analysis reveals complex interactions among parameters. $E$ and $F$ primarily affect government decisions, with $E$ having a more pronounced effect on policy adoption thresholds.

$Q$ and $R$ most significantly influence corporate strategies, highlighting the importance of balancing incentives and costs for businesses. P directly impacts traveler behavior while indirectly affecting corporate strategies, demonstrating the interconnected nature of stakeholder decisions.

The sensitivity analysis suggests that an effective Carbon-Inclusive policy requires sufficient environmental gains $E$ to justify government commitment. Balanced carbon tax revenues $F$ to maintain policy sustainability without overburdening stakeholders. Calibrated subsidies ($Q$ and $P$) that incentivize participation without straining government resources. Manageable corporate costs $R$ that allow for profitable ridesplitting promotion. The intricate relationships between variables underscore the need for a holistic approach to policy implementation, where adjustments to one parameter necessitate careful consideration of impacts across all stakeholder groups.

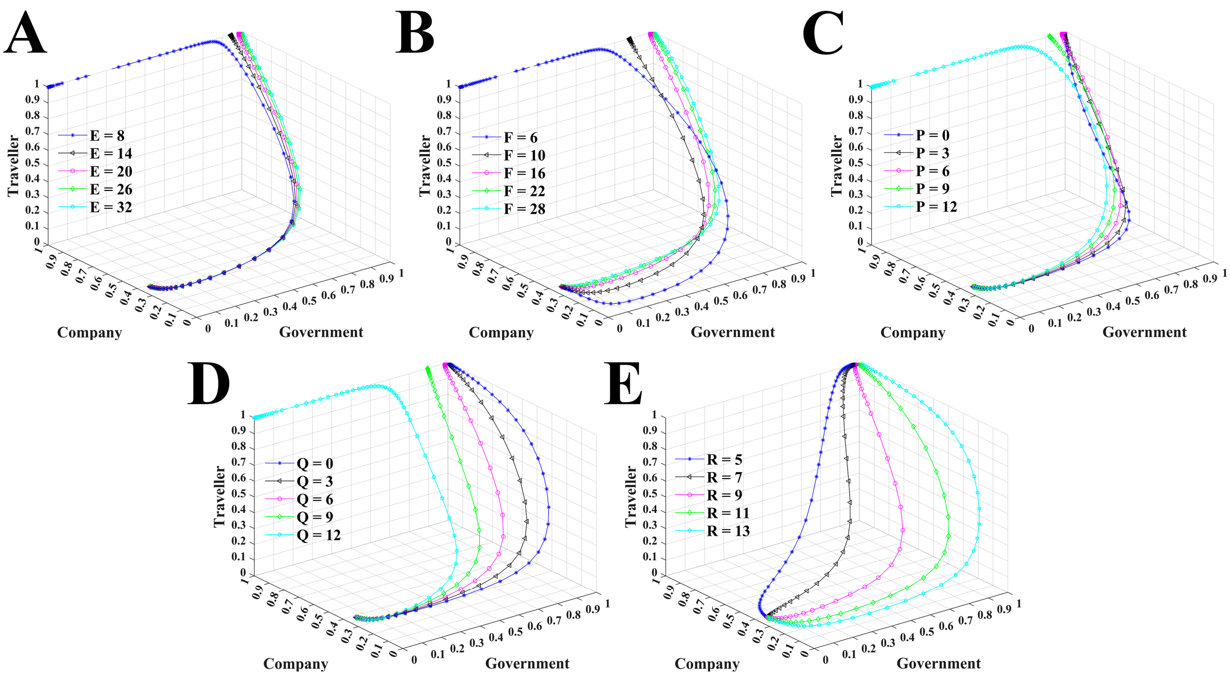

**Figure 4.** Sensitivity analysis of parameters E, F, P, Q, and R on evolutionary strategies of Government, Company, and Traveller. (**A**): Impact of emission reductions *E* on stakeholder decisions. (**B**): Effect of government economic benefits *F* from carbon taxes and emission reduction auctions on policy sustainability. (**C**): Influence of individual subsidies *P* on traveller behavior and indirect impact on company strategies. (**D**): Impact of company subsidies *Q* on corporate willingness to promote ridesplitting. (**E**): Effect of corporate promotion costs *R* on companies' strategies for ride-splitting development. Each subfigure demonstrates how varying parameter values affect the evolutionary trajectories of the three stakeholders, with axes representing the probability of adopting cooperative strategies for Government, Company, and Traveller.

### 4.2. Policy Model Analysis

Figure 5 presents the recommended ridesplitting ratio values obtained in 2016, 2023, and 2050, derived from the ridesplitting policy model established in the previous section. These values are based on various social costs of carbon scenarios and the recommended ridesplitting ratio for maximizing tripartite benefits. Additionally, the recommended ridesplitting ratio values for 2050 are provided after increasing the initial carbon tax. Based on these findings, the following conclusions can be drawn:

(1) In 2016, a lower social cost of carbon corresponds to a lower ridesplitting ratio at the system optimum. As the social cost of carbon increases annually, the ideal state in 2023 requires a ridesplitting ratio of 39%, while the optimal ridesplitting ratio in 2050 approaches 90%. This highlights the increasing importance of ridesplitting for carbon emission reduction as time progresses and the social cost of carbon rises;

(2) The chosen carbon tax value significantly impacts the measured optimal ridesplitting ratio. Increasing the carbon tax amount by 100% effectively reduces the required ridesplitting ratio to 56% in 2050, according to calculations. This result underscores the efficacy of carbon taxation. A balanced approach that combines subsidies for shared mobility with penalties for high-emission transportation modes—specifically, carbon taxes—may be more effective than relying solely on subsidies to promote carpooling. Furthermore, such an integrated strategy is likely to be more politically feasible;

(3) An increase in the ridesplitting ratio leads to higher total tripartite benefits for the government, companies, and individuals. This demonstrates that ridesplitting offers a range of economic, social, and environmental advantages, benefiting all parties involved. These findings underscore the vitality and sustainability of the ridesplitting mode, particularly in the context of government promotion and company research and development.

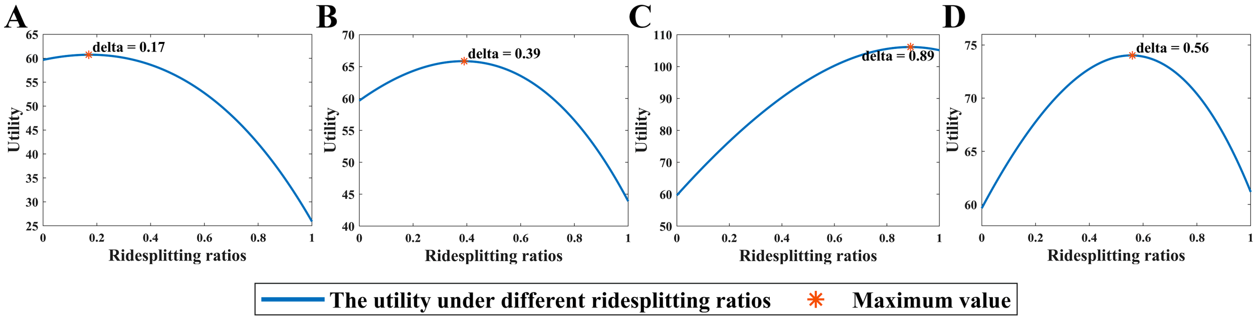

**Figure 5.** Optimal ridesplitting proportions under different social carbon costs. (**A**): Scenario for 2016, showing a low optimal ridesplitting ratio (delta = 0.17) due to lower social carbon costs. (**B**): Scenario for 2023, indicating an increased optimal ridesplitting ratio (delta = 0.39) as social carbon costs rise. (**C**): Projected scenario for 2050, demonstrating a significantly higher optimal ridesplitting ratio (delta = 0.89) due to further increased social carbon costs. (**D**): Alternative 2050 scenario with doubled carbon tax, resulting in a lower optimal ridesplitting ratio (delta = 0.56) compared to (**C**). Each subfigure illustrates the relationship between ridesplitting ratios (x-axis) and total utility (y-axis), with the maximum value point marked, representing the optimal ridesplitting proportion for maximizing tripartite benefits under different social carbon cost conditions.

## 5. Conclusions and Policy Recommendations

This study presents an approach to understanding the complex dynamics of carbon emission reduction in the ridesplitting industry through a three-party evolutionary game model involving the government, shared mobility companies, and travelers. Through the establishment of a three-party evolutionary game model, the stability and evolutionary outcomes of the system under various strategies are analyzed, leading to the following conclusions:

(1) The evolutionary game model reveals a sophisticated, interdependent relationship among stakeholders that transcends traditional two-subject game theories. The government's policy choices exert a dominant influence on both companies and travelers while simultaneously being influenced by their strategic decisions. Policymakers must adopt a dynamic approach to carbon reduction strategies, continuously adjusting incentives and regulations based on real-time feedback from industry and consumer behaviors. This adaptive policy framework could potentially accelerate the transition to low-carbon transportation systems more effectively than static, long-term plans;

(2) The model demonstrates varying degrees of responsiveness among stakeholders to policy changes. Companies exhibit higher sensitivity to government initiatives compared to travelers. Meanwhile, traveler behavior significantly influences both companies' strategies and government urgency in policy implementation, yielding substantial systemic benefits;

(3) Sensitivity analysis of crucial factors reveals that an effective Carbon-Inclusive policy requires a delicate balance of these parameters. Policymakers must ensure sufficient environmental gains to justify government commitment, balanced carbon tax revenues to maintain policy sustainability, calibrated subsidies to incentivize participation without straining government resources, and manageable corporate costs to allow for profitable ridesplitting promotion.

While higher ridesplitting ratios lead to greater carbon reduction benefits, it is crucial for policymakers to consider the intricate interplay between government incentives, market forces, and consumer behavior. This study presents a ridesplitting policy model that aims to maximize the interests of the government, companies, and travelers by determining the ridesplitting ratios in 2016, 2023, and 2050. The model projects an increasing optimal ridesplitting ratio over time, correlating with rising social costs of carbon.

Based on the above findings, the policy implications are as follows:

(1) Balancing Market Mechanisms and Policy Interventions for Effective Carbon Emission Reduction: The government should strategically employ a combination of market

mechanisms and targeted policy interventions to implement Carbon-Inclusion policies effectively. The primary market-based instruments should include strengthening the carbon trading market to facilitate efficient allocation of emission reduction efforts and implementing a well-calibrated carbon tax system to internalize environmental costs. Additionally, differentiated economic incentives can be utilized to guide companies and individuals toward sustainable practices. Meanwhile, to address market failures and accelerate the transition, the government should strategically employ a combination of market mechanisms and targeted policy interventions. In the initial phase, targeted subsidies should be provided to ride-sharing companies, making carpooling services more competitive and attractive to consumers. As ridesplitting matures, the government should gradually reduce subsidies, transitioning to a market-driven model. This balanced approach combines short-term policy support with long-term market mechanisms, ensuring the sustainable development of ridesplitting services and fair competition across all transportation modes while aligning with broader carbon reduction goals;

(2) Strengthen the Promotion of ESG and Sustainable Development Concepts: Encouraging shared mobility companies to embrace Environmental, Social, and Governance (ESG) principles and other emerging sustainable development concepts can enhance their societal value. Promoting these concepts among companies can fortify their commitment to carbon reduction and sustainability, fostering active collaboration with carpool travel policy development;

(3) Establish Rational Carbon Tax Levels: A well-calibrated carbon tax system should be implemented to internalize environmental costs. It is advisable to introduce carbon taxes gradually, starting with lower rates and increasing them over time to allow industries to adapt. Differentiated tax rates based on emission levels and company size should be employed to ensure fairness.

While this study provides some insights into the implementation of the Carbon-Inclusive Policy in the ridesplitting sector, several limitations warrant consideration and present opportunities for future research: (1) Stakeholder scope: The current model focuses on three primary stakeholders: the government, shared mobility companies, and travelers. Future studies should expand this scope to include other affected parties, such as traditional taxi businesses, to provide a more comprehensive understanding of the policy's broader economic and social implications. (2) Carbon tax credit optimization: An in-depth exploration of the impacts of varying carbon tax credit levels on ridesplitting adoption would provide valuable data for policy refinement. Additionally, assessing the feasibility of implementing Environmental, Social, and Governance (ESG) principles in the ridesplitting industry could offer crucial guidance for sustainable transportation development. (3) Empirical validation: While the evolutionary game model provides theoretical insights, empirical studies quantifying the actual carbon reduction achieved through the implementation of the Carbon-Inclusive Policy would furnish practical evidence to support policy formulation and decision-making processes. (4) Regional variability: The current study's findings may not be universally applicable due to regional differences in transportation infrastructure, cultural attitudes towards shared mobility, and existing environmental policies.

By addressing these research gaps, future studies can contribute to a more nuanced and holistic understanding of the complex interplay between policy, technology, and sustainable transportation practices.

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## References

1. Hosseini, K.; Choudhari, T.P.; Stefaniec, A.; O'Mahony, M.; Caulfield, B. E-bike to the future: Scalability, emission-saving, and eco-efficiency assessment of shared electric mobility hubs. *Transp. Res. Part Transp. Environ.* **2024**, *133*, 104275. [CrossRef]
2. Potter, S. Exploring Approaches Towards a Sustainable Transport System. *Int. J. Sustain. Transp.* **2007**, *1*, 115–131. [CrossRef]
3. Hosseini, K.; Stefaniec, A.; O'Mahony, M.; Caulfield, B. Optimising shared electric mobility hubs: Insights from performance analysis and factors influencing riding demand. *Case Stud. Transp. Policy* **2023**, *13*, 101052. [CrossRef]
4. Litman, T. Comprehensive evaluation of energy conservation and emission reduction policies. *Transp. Res. Part Policy Pract.* **2013**, *47*, 153–166. [CrossRef]
5. Wu, X.; MacKenzie, D. Assessing the VMT effect of ridesourcing services in the US. *Transp. Res. Part Transp. Environ.* **2021**, *94*, 102816. [CrossRef]
6. Li, W.; Pu, Z.; Li, Y.; Tu, M. How does ridesplitting reduce emissions from ridesourcing? A spatiotemporal analysis in Chengdu, China. *Transp. Res. Part Transp. Environ.* **2021**, *95*, 102885. [CrossRef]
7. Santi, P.; Resta, G.; Szell, M.; Sobolevsky, S.; Strogatz, S.H.; Ratti, C. Quantifying the benefits of vehicle pooling with shareability networks. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 13290–13294. [CrossRef] [PubMed]
8. Zhu, P.; Mo, H. The potential of ride-pooling in VKT reduction and its environmental implications. *Transp. Res. Part Transp. Environ.* **2022**, *103*, 103155. [CrossRef]
9. Li, W.; Li, Y.; Pu, Z.; Cheng, L.; Wang, L.; Yang, L. Revealing the $CO_2$ emission reduction of ridesplitting and its determinants based on real-world data. *arXiv* **2022**, arXiv:2204.00777. [CrossRef]
10. Yin, B.; Liu, L.; Coulombel, N.; Viguié, V. Appraising the environmental benefits of ride-sharing: The Paris region case study. *J. Clean. Prod.* **2018**, *177*, 888–898. [CrossRef]
11. Li, C.; Ren, Z.; Wang, L. Research on the driving path of carbon inclusive system to green behavior of the public: Based on procedural grounded theory and multiple intermediary model. *Environ. Sci. Pollut. Res.* **2023**, *30*, 80393–80415. [CrossRef] [PubMed]
12. Li, R.; Fang, D.; Xu, J. Does China's carbon inclusion policy promote household carbon emissions reduction? Theoretical mechanisms and empirical evidence. *Energy Econ.* **2024**, *132*, 107462. [CrossRef]
13. Liu, H. Commonly Benefiting Carbon Institution: Theoretical Analysis, Referential Experience and Framework Design. *Stud. Social. Chin. Charact.* **2018**, *5*, 86–94+112.
14. Yang, G.; Xiang, X.; Deng, F.; Wang, F. Towards high-quality development: How does digital economy impact low-carbon inclusive development?: Mechanism and path. *Environ. Sci. Pollut. Res.* **2023**, *30*, 41700–41725. [CrossRef]
15. Braverman, A.; Dai, J.G.; Liu, X.; Ying, L. Empty-Car Routing in Ridesharing Systems. *Oper. Res.* **2019**, *67*, 1437–1452. [CrossRef]
16. Feng, G.; Kong, G.; Wang, Z. We Are on the Way: Analysis of On-Demand Ride-Hailing Systems. *Manuf. Serv. Oper. Manag.* **2021**, *23*, 1237–1256. [CrossRef]
17. Lee, A.; Savelsbergh, M. Dynamic ridesharing: Is there a role for dedicated drivers? *Transp. Res. Part B Methodol.* **2015**, *81*, 483–497. [CrossRef]
18. Vazifeh, M.M.; Santi, P.; Resta, G.; Strogatz, S.H.; Ratti, C. Addressing the minimum fleet problem in on-demand urban mobility. *Nature* **2018**, *557*, 7706. [CrossRef]
19. Zhang, R.; Pavone, M. Control of robotic mobility-on-demand systems: A queueing-theoretical perspective. *Int. J. Robot. Res.* **2016**, *35*, 186–203. [CrossRef]
20. Iglesias, R.; Rossi, F.; Wang, K.; Hallac, D.; Leskovec, J.; Pavone, M. Data-Driven Model Predictive Control of Autonomous Mobility-on-Demand Systems. In Proceedings of the 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, Australia, 21–25 May 2018; pp. 6019–6025. [CrossRef]
21. Pelzer, D.; Xiao, J.; Zehe, D.; Lees, M.H.; Knoll, A.C.; Aydt, H. A Partition-Based Match Making Algorithm for Dynamic Ridesharing. *IEEE Trans. Intell. Transp. Syst.* **2015**, *16*, 2587–2598. [CrossRef]
22. Jung, J.; Jayakrishnan, R.; Park, J.Y. Dynamic Shared-Taxi Dispatch Algorithm with Hybrid-Simulated Annealing. *Comput.-Aided Civ. Infrastruct. Eng.* **2016**, *31*, 275–291. [CrossRef]
23. Qian, X.; Zhang, W.; Ukkusuri, S.V.; Yang, C. Optimal assignment and incentive design in the taxi group ride problem. *Transp. Res. Part B Methodol.* **2017**, *103*, 208–226. [CrossRef]
24. Alonso-Mora, J.; Samaranayake, S.; Wallar, A.; Frazzoli, E.; Rus, D. On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 462–467. [CrossRef]
25. Liu, X.; Li, W.; Li, Y.; Fan, J.; Shen, Z. Quantifying Environmental Benefits of Ridesplitting based on Observed Data from Ridesourcing Services. *Transp. Res. Rec. J. Transp. Res. Board.* **2021**, *2675*, 355–368. [CrossRef]
26. Yu, B.; Li, X.; Xue, M. Impacts of shared mobility on energy consumption and emissions in China. In *Transport and Energy Research*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 223–242. [CrossRef]

27. Yan, L.; Luo, X.; Zhu, R.; Santi, P.; Wang, H.; Wang, D.; Zhang, S.; Ratti, C. Quantifying and analyzing traffic emission reductions from ridesharing: A case study of Shanghai. *Transp. Res. Part Transp. Environ.* **2020**, *89*, 102629. [CrossRef]
28. Zhang, Z.; Gao, K.; He, H.-D.; Yang, J.-M.; Jia, R.; Peng, Z.-R. How do travel characteristics of ridesplitting affect its benefits in emission reduction? evidence from Chengdu. *Transp. Res. Part Transp. Environ.* **2023**, *123*, 103912. [CrossRef]
29. Chen, X.; Zahiri, M.; Zhang, S. Understanding ridesplitting behavior of on-demand ride services: An ensemble learning approach. *Transp. Res. Part C Emerg. Technol.* **2017**, *76*, 51–70. [CrossRef]
30. Brown, A.E. Who and where rideshares? Rideshare travel and use in Los Angeles. *Transp. Res. Part Policy Pract.* **2020**, *136*, 120–134. [CrossRef]
31. Si, H.; Shi, J.; Hua, W.; Cheng, L.; De Vos, J.; Li, W. What influences people to choose ridesharing? An overview of the literature. *Transp. Rev.* **2023**, *43*, 1211–1236. [CrossRef]
32. Alyavina, E.; Nikitas, A.; Njoya, E.T. Mobility as a service and sustainable travel behaviour: A thematic analysis study. *Transp. Res. Part F Traffic Psychol. Behav.* **2020**, *73*, 362–381. [CrossRef]
33. Delhomme, P.; Gheorghiu, A. Comparing French carpoolers and non-carpoolers: Which factors contribute the most to carpooling? *Transp. Res. Part Transp. Environ.* **2016**, *42*, 1–15. [CrossRef]
34. Cui, Y.; Makhija, R.S.M.S.; Chen, R.B.; He, Q.; Khani, A. Understanding and Modeling the Social Preferences for Riders in Rideshare Matching. *Transportation* **2021**, *48*, 1809–1835. [CrossRef]
35. Liu, D.; Du, H.; Southworth, F.; Ma, S. The influence of social-psychological factors on the intention to choose low-carbon travel modes in Tianjin, China. *Transp. Res. PART-POLICY Pract.* **2017**, *105*, 42–53. [CrossRef]
36. Song, Y.; Zhang, L.; Zhang, M. Research on the impact of public climate policy cognition on low-carbon travel based on SOR theory—Evidence from China. *Energy* **2022**, *261*, 125192. [CrossRef]
37. Wang, Y.; Wang, S.; Wang, J.; Wei, J.; Wang, C. An empirical study of consumers' intention to use ride-sharing services: Using an extended technology acceptance model. *Transportation* **2020**, *47*, 397–415. [CrossRef]
38. Dällenbach, N. Low-carbon travel mode choices: The role of time perceptions and familiarity. *Transp. Res. Part Transp. Environ.* **2020**, *86*, 102378. [CrossRef]
39. Nielsen, J.R.; Hovmøller, H.; Blyth, P.-L.; Sovacool, B.K. Of 'white crows' and 'cash savers:' A qualitative study of travel behavior and perceptions of ridesharing in Denmark. *Transp. Res. Part Policy Pract.* **2015**, *78*, 113–123. [CrossRef]
40. Abutaleb, S.; El-Bassiouny, N.; Hamed, S. Sharing rides and strides toward sustainability: An investigation of carpooling in an emerging market. *Manag. Environ. Qual. Int. J.* **2020**, *32*, 4–19. [CrossRef]
41. Agatz, N.; Erera, A.; Savelsbergh, M.; Wang, X. Optimization for dynamic ride-sharing: A review. *Eur. J. Oper. Res.* **2012**, *223*, 295–303. [CrossRef]
42. Chen, J.M.; de Groote, J.; Petrick, J.F.; Lu, T.; Nijkamp, P. Travellers' willingness to pay and perceived value of time in ride-sharing: An experiment on China. *Curr. Issues Tour.* **2020**, *23*, 2972–2985. [CrossRef]
43. Lyu, G.; Cheung, W.C.; Teo, C.-P.; Wang, H. Multi-Objective Stochastic Optimization: A Case of Real-Time Matching in Ride-Sourcing Markets. *Manuf. Serv. Oper. Manag.* **2024**, *26*, 500–518. [CrossRef]
44. Yu, J.J.; Tang, C.S.; Shen, Z.-J.M.; Chen, X.M. A Balancing Act of Regulating On-Demand Ride Services. *Manag. Sci.* **2020**, *66*, 2975–2992. [CrossRef]
45. He, M.; Qin, J.; Wen, M.; Chen, W. Sustaining consumer trust and continuance intention by institutional mechanisms: An empirical survey of DiDi in China. *IEEE Access* **2021**, *9*, 158185–158203. [CrossRef]
46. Raza, S.A.; Khan, K.A.; Salam, J. Impact of environmental triggers on students' behavior to use ride-sharing services: The moderating role of perceived risk. *Curr. Psychol.* **2021**, *42*, 11329–11343. [CrossRef] [PubMed]
47. Shao, Z.; Guo, Y.; Li, X.; Barnes, S. Sources of influences on customers' trust in ride-sharing: Why use experience matters? *Ind. Manag. Data Syst.* **2020**, *120*, 1459–1482. [CrossRef]
48. Alonso-González, M.J.; Cats, O.; van Oort, N.; Hoogendoorn-Lanser, S.; Hoogendoorn, S. What are the determinants of the willingness to share rides in pooled on-demand services? *Transportation* **2021**, *48*, 1733–1765. [CrossRef] [PubMed]
49. Ashrafi, D.M.; Habiba, W.; Alam, I. An assessment of the behavioural intention for using ride-sharing services: Empirical evidence from a developing country. *Malays. J. Consum. Fam. Econ.* **2020**, *24*, 36–62.
50. Shaheen, S.P.; Cohen, A.M.; Bayen, A.P. The Benefits of Carpooling. Institute of Transportation Studies, UC Berkeley, Institute of Transportation Studies, Research Reports, Working Papers, Proceedings. October 2018. Available online: https://econpapers.repec.org/paper/cdlitsrrp/qt7jx6z631.htm (accessed on 29 March 2024).
51. Yang, H.; Shao, C.; Wang, H.; Ye, J. Integrated reward scheme and surge pricing in a ridesourcing market. *Transp. Res. Part B Methodol.* **2020**, *134*, 126–142. [CrossRef]
52. Cohen, M.C.; Fiszer, M.D.; Kim, B.J. Frustration-Based Promotions: Field Experiments in Ride-Sharing. *Manag. Sci.* **2022**, *68*, 2432–2464. [CrossRef]
53. Dejbord, S.; Kang, J.E.; Karwan, M. *An Integrated Personalized Incentive Scheme for Shared Autonomous Vehicles*; SSRN: Rochester, NY, USA, 2022. [CrossRef]
54. Guzman, L.A.; Arellana, J.; Alvarez, V. Confronting congestion in urban areas: Developing Sustainable Mobility Plans for public and private organizations in Bogotá. *Transp. Res. Part Policy Pract.* **2020**, *134*, 321–335. [CrossRef]
55. Hu, X.; Zhu, X.; Chiu, Y.-C.; Tang, Q. Will information and incentive affect traveler's day-to-day departure time decisions?—An empirical study of decision making evolution process. *Int. J. Sustain. Transp.* **2020**, *14*, 403–412. [CrossRef]

56. Wu, C.; Pei, Y.; Gao, J. Evolution Game Model of Travel Mode Choice in Metropolitan. *Discrete Dyn. Nat. Soc.* **2015**, *2015*, e638972. [CrossRef]
57. Gong, H.; Jin, W. Analysis of Urban Car Owners Commute Mode Choice Based on Evolutionary Game Model. *J. Control Sci. Eng.* **2015**, *2015*, e291363. [CrossRef]
58. Li, Q.; Wang, Y.; Li, K.; Chen, L.; Wei, Z. Evolutionary dynamics of the last mile travel choice. *Phys. Stat. Mech. Its Appl.* **2019**, *536*, 122555. [CrossRef]
59. Zhang, W.; He, R.; Ma, C.; Gao, M. Research on Taxi Driver Strategy Game Evolution with Carpooling Detour. *J. Adv. Transp.* **2018**, *2018*, 2385936. [CrossRef]
60. Smith, J.M. The theory of games and the evolution of animal conflicts. *J. Theor. Biol.* **1974**, *47*, 209–221. [CrossRef] [PubMed]
61. Smith, J.M.; Price, G.R. The Logic of Animal Conflict. *Nature* **1973**, *246*, 5427. [CrossRef]
62. Guan, H.Z.; Pu, L. A drivers' choice behavior model based on evolutionary game theory. *J. Beijing Univ. Technol.* **2010**, *36*, 1077–1083.
63. Hosni, H.; Naoum-Sawaya, J.; Artail, H. The shared-taxi problem: Formulation and solution methods. *Transp. Res. Part B Methodol.* **2014**, *70*, 303–318. [CrossRef]
64. Yan, C.; Zhu, H.; Korolko, N.; Woodard, D. Dynamic pricing and matching in ride-hailing platforms. *Nav. Res. Logist. NRL* **2020**, *67*, 705–724. [CrossRef]
65. Song, M.; Zhao, X.; Shang, Y.; Chen, B. Realization of green transition based on the anti-driving mechanism: An analysis of environmental regulation from the perspective of resource dependence in China. *Sci. Total Environ.* **2020**, *698*, 134317. [CrossRef] [PubMed]
66. Li, X.-Y.; Tang, B.-J. Incorporating the transport sector into carbon emission trading scheme: An overview and outlook. *Nat. Hazards* **2017**, *88*, 683–698. [CrossRef]
67. Barrage, L.; Nordhaus, W. Policies, projections, and the social cost of carbon: Results from the DICE-2023 model. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2312030121. [CrossRef] [PubMed]
68. Sterman, J.D. System Dynamics Modeling: Tools for Learning in a Complex World. *Calif. Manag. Rev.* **2001**, *43*, 8–25. [CrossRef]
69. Wang, W.; Zhang, Y.; Feng, L.; Wu, Y.J.; Dong, T. A System Dynamics Model for Safety Supervision of Online Car-Hailing From an Evolutionary Game Theory Perspective. *IEEE Access* **2020**, *8*, 185045–185058. [CrossRef]
70. Zhang, W.; Liu, H.; Chen, Y.; Wan, X. Research on the supervision mechanism of new energy time-sharing rental vehicles in the background of carbon peak. *Sci. Prog.* **2022**, *105*, 003685042210754. [CrossRef]