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Greenhouse Gas Emission Savings with Dynamic Ride-sharing

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Abstract

Ride-sharing can reduce the greenhouse gas emission in noncommercial passenger highway vehicles by grouping individuals into fewer vehicles and reducing the number of miles that vehicles must travel. In this paper, we first present an integer programming model to maximize the system greenhouse gas emission savings for the dynamic ride-sharing system. Then adopt the existed optimization methods and simulation environment to estimate the potential greenhouse gas emission savings that could result from an increase in ride-sharing. Finally, we firstly calculate the total emission savings for the given simulation environment. From our analysis, we can draw a conclusion that the system greenhouse gas emission savings come from two aspects, firstly, the total vehicle travel miles will be shorten through participating the ride-sharing system, thus the emissions will be largely reduced. Secondly, the different travel speeds result in different emission rates, while the ride-sharing systems can ease the traffic congestion, which is relate to the travel speed of vehicles, there are emission savings with the speed increase.

Keywords:greenhouse gas emission, dynamic ride-sharing, integer programming, travel miles saving, speed.

1. INTRODUCTION

Greenhouse gas emissions from transportation takes a great proportion in total U.S. greenhouse gas emissions, which accounted for about 27% in 2013, making it the second largest contributor of U.S. greenhouse gas emission. Greenhouse gas emissions from transportation have increased by about 16% since 1990. The number of vehicle miles traveled by passenger cars and light-duty trucks increased 35% from 1990 to 2013. This historical increase is largely due to increased demand for travel and the limited gains in fuel efficiency across the U.S. vehicle fleet (U.S. EPA, 2013). So if we can tackle with the greenhouse gas emission from transportation well, there will be a great reduction in greenhouse gas emissions. Many countries see reducing transport emissions as one of their key targets. For many years, though the United States has developed an extensive multimodal system that includes road, air, rail, and water transport, which are capable of moving large volumes of passengers and goods long distances, automobiles and light trucks still dominate the passenger transportation system, and the highway share of passenger miles traveled in 2013 was about 87 percent of the total (U.S. department of transportation 2011).

There has been a special outpouring of concern for the single-occupant passenger automobiles dominated daily trips between home and workplace, with 94 percent of the nation’s workforce driving to and from work (U.S. department of transportation 2011) and while just 10 percent of workers commuted in carpools of two or more people, that means there are 84 percent drivers drive alone to their destinations, if we can take use of the vacant seats of the 84 percent vehicles, there will be a huge fuel saving for highway transportation. And it is reported that 55 percent of these trips are made by car or van, 18 percent by sport utility vehicle (SUV), and 10 percent by pickup truck (U.S. EPA, 2013).

From the above data analysis, it is obvious that private automobile usage with only a driver is the dominant transportation mode producing carbon dioxide emissions (Hensher, 2008).Ride-sharing systems that bring together people with similar itineraries and time schedules to share rides and aims to use the empty car seats more efficiently, and could substantially increase the efficiency of urban transportation systems, then reducing fuel consumption, and greenhouse gas emission (Agatz et al., 2010). There are many literature about the advantages of ride-sharing (Ferguson,1997; Kelley, 2007; Chan and Shaheen, 2012;Wang et al., 2016), but they just discuss the impact of ride-sharing on the participants, society and environment from the view of qualitativeno further model is built. Of course, some researches have come down to the quantitative model, such as Jacobson and King investigate the tradeoff between saving fuel and spending time to pick up additional passengers and find that ride-sharing will be made more attractive by increasing per-vehicle-trip costs (Jacobson and King, 2009). Caulfield uses COPERT4 model to estimate the CO2 emissions saved by ride-sharing (Caulfield, 2009). Minett and Pearce try to find out if casual carpooling reduces energy consumption, and address a research on the quantitative of energy consumption reduction from ride-sharing (Minett and Pearce, 2011).

This paper proposes a centralized system optimal model to realize the system optimal emission in the dynamic ride-sharing system, where drivers and riders announce their travel information, including their origins, destinations and departure time-windows, to the riding-sharing system. System automatically matches the drivers and riders according to some rules or procedure determined in advance in a short time. If a driver and a rider are matched by the system, the driver will drive his/her car to pick up the rider at rider's departure place, then deliver the rider to the destination and after that the driver go to his/her destination. This dynamic ride-sharing is different from conventional on-demand transportation primarily with regards to the supply of drivers and vehicles. Instead of being employed by a company and regarding making profit as objective, drivers in a ride-sharing system are private independent entities, drivers will not specifically generate a travel for picking up riders, and just share a ride on their way to destinations.

Dynamic ride-sharing system setting that aims to minimize the total travel cost have been addressed by Agatz (Agatz et al., 2011). Furthermore, Kleiner et al. propose an auction algorithm to tradeoff the minimization of Vehicle Kilometers Travelled (VKT) with the overall probability of successful ride-shares(Kleiner et al., 2011), and Wang et al. also propose stable match game for the dynamic ride-sharing(Wang et al., 2015). But all the literature mentioned above do not consider the greenhouse gas emission model for the dynamic ride-sharing system. Furthermore, as our best of knowledge, little literature mentioned the relationship between ride-sharing and speed, and no literature addressee research on the CO_2 emission impact of the speed in ride-sharing system. In this paper, we will formulate the emission model based on the above research, which maximizes the total greenhouse gas emission saving in the dynamic ride-sharing system.

The remainder of the paper is structured as follows. In Section2, we build a centralized system optimal model for our dynamic ride-sharing system and formulate a series of constraints. In Section 3, we explain our approach to solve the dynamic ride-share problem. In Section 4 we present a simulation study based on the travel demand model of the Atlanta Regional Commission and then we discuss and analysis the CO_2 emission of the simulation model. Finally, in Section 5, we summarize our main insights and discuss directions for future research.

2. CENTRALIZED SYSTEM OPTIMAL MODEL

Dynamic ride-sharing system setting that aims to minimize the total travel cost have been addressed by Agatz et al., (2011), they divided the total distance, which is the key factor for emission, between the participants. In this section, we will formulate a centralized model for the dynamic ride-sharing system, which aims to realize the system emission optimum.

In our dynamic ride-sharing system, all the participants who enter the system are absolutely rational to their match, if there is a cost saving with a feasible time window, there will be a successful ride-sharing matches. If one driver is matched with a rider, they will exit the system immediately. For the unmatched participants, they will drive alone or remain in the system for the next match. More specifically, we assume that:

(1). All participants are individual rational to their match, none of the participants prefers driving alone. That means the participants will share a ride when there exists a feasible positive cost reduction match.

(2). If the participants are not matched, they will drive their own cars to the destinations or remain in the system for the next match if time is feasible.

(3). One driver can only match with one rider.

(4). The emission of greenhouse gas totally depends on the travel distance, the travel congestions make no impact on the emission.

2.1 Notations

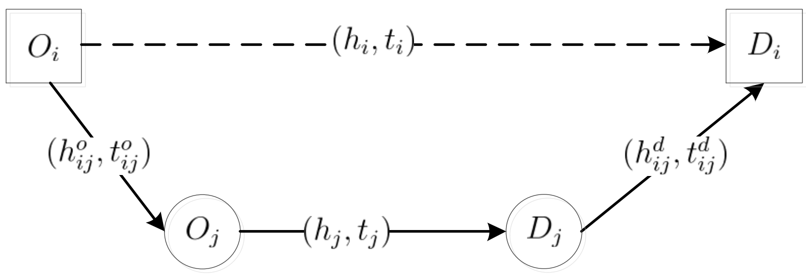

Figure 1.A shared ride between driver *i* (square) and rider *j* (circle).

(1)Parameters:

I— Set of driver, $I = \{1,2,\cdots,i,\cdots n\}$

J — Set of rider, $J = \{1,2,\cdots,j,\cdots m\}$

O_P— Set of origin, $P \in I \cup J$

D_P — Set of destination, $P \in I \cup J$

t_p — Travel time of participant $p \in P$ from origin to destination.

h_p — Travel distance of participant $p \in P$ from origin to destination.

t_{ij}^o — The travel time from the origin of driver i to the origin of rider$j$.

h_{ij}^{o} — The travel distance from the origin of driver i to the origin of rider$j$.

t_{ij}^{d} — The travel time from the destination of rider$j$ to the destination of driver i.

h_{ij}^{d} — The travel distance from the destination of rider$j$ to the destination of driver i.

t_{ij} — Total travel time to complete the match between driver i and rider$j$.

s_{ij} — Total travel distance to complete the match between driver i and rider$j$.

$[ed_p, ld_p]$ — Departure time window for participant $p \in P$, ed_p, ld_p respectively denote the earliest and latest departure time from the origin of participant p.

$[ea_p, la_p]$ — Arrival time window for participant $p \in P$, ea_p, la_p respectively denote the earliest and latest arrival time to the destination of participant p.

α_{ij} — Unit travel distance for greenhouse gas emission of the match between driver i and rider$j$.

(2)Decision variable :

x_{ij} — A match between driver i and rider$j$.If driver i and rider$j$is a feasible match, $x_{ij} = 1$, otherwise, $x_{ij} = 0$.

DRS systems can provide opportunities to increase the mobility of people that do not have access to public transit or a private vehicle, and it is an important means to reduce travel costs, congestion and pollution. In our formulation, we focus on exploring ride-share optimization problems in which the ride-sharing system seeks to minimize the total travel distance, which is inconsistent with the objective of maximizing the emission saving.

2.2Constraints

(1) One to one match constraints:

$$x_{ij} * (1 - x_{ij}) = 0, \forall ij \quad (1)$$

We use this equation to represent the match between driver i and rider$j$. Actually x_{ij} is 0-1 binary variable. $x_{ij} = 1$, means driver i are matched with rider$j$, otherwise, driver i are not matched with rider j.

$$\sum_{j=1}^{m} x_{ij} \leq 1, \forall i \quad (2)$$

Every driver can be only matched with one rider. In our paper, one driver can only pick up one rider, and the driver will take the rider directly to his destination, then the driver drive alone to his own destination.

$$\sum_{i=1}^{n} x_{ij} \leq 1, \forall j \quad (3)$$

Every rider can be only matched with one driver. If one rider is successfully matched with a driver, he/she will exit the system immediately, and he/she will never establish a match with any other drivers.

(2) Time feasible constraints :

$$\max\left(ed_i + t_{ij}^o, ed_j\right) \le \min(la_i - t_{ij}^d - t_j) \quad (4)$$

$$t_{ij}^d + t_j + t_{ij}^o \le la_i - ed_i \quad (5)$$

In order to check the time feasibility of a match (i,j), we construct an implied time window for each participants in the match, we denote the implied time window for a participant p(either $i$or $j \in P$) by $[ed_p, ld_p]$ and $[ea_p, la_p]$. To check the time feasibility of the match, the intersection of the implied time windowshas to be non-empty, we propose equation (4) to satisfy the constraint. The constraint (5) is formulated to satisfied the maximum ride time for the diver$i$.

(3) Positive distance saving constraints:

$$h_{ij} > 0 \quad (6)$$

The motivation of participate in the ride-sharing system is to gain benefit trough the match, if there are no profits for the participants, the matches between drivers and riders will be unsustainable and infeasible. We denote s_{ij} is the distance saving of the match between driver i and rider j, Where, $s_{ij} = h_i - h_{ij}^o - h_{ij}^d$. It's necessary for feasible match between driver and rider that there is a positive distance saving.

2.3Objective function

$$\max \qquad z = \sum_{(i,j)} x_{ij} \alpha_{ij} s_{ij} \quad (7)$$

In this section, we formulate the system optimum objective, which aims to maximize the system's greenhouse gas emission. The weight s_{ij} assigned to feasible match arc (i,j) is simply the travel distance savings. Let x_{ij} be a binary decision variable equal to 1 if ride-share match (i,j) is proposed, and 0 ifnot. To complete the specification, we denote α_{ij} as the quantity of greenhouse gas emission per unit travel distance of the match between driver i and rider j.

3. METHODOLOGY

As Agatz et al. said, any dynamic ride-sharing systems must make decision on potential matches at many time points during the day (Agatz et al., 2011). Each time the provider executes a procedure for planning matches, there are likely to be future requests that are not yet known. A common mechanism for handling uncertainty of this type when planning is to use a deterministic rolling horizon solution approach, in which plans are made using all known information within a planning horizon, but decisions are not finalized until necessitated by a deadline. In this section, we continue to using the rolling horizon strategy proposed by Agatze et al., (2011).

Matching problems are often concerned with bipartite graphs, in a weighted bipartite graph, each edge has an associated value. A maximum weighted bipartite matching is defined as a matching where the sum of the values of the edges in the matching have a maximal value. The maximum weighted bipartite matching is commonly used to solve the ride-sharing match problems, as for ride-sharing problem, the bipartite graph consists of two disjoint sets of vertices, a set representing drivers D and a set representing riders R. An edge between a driver and a rider exists if the match is feasible, with a weight that represents the positive savings in distance when traveling together compared to when each of them drives separately, the conceptual setting of ride-sharing match have been described in Figure 2.

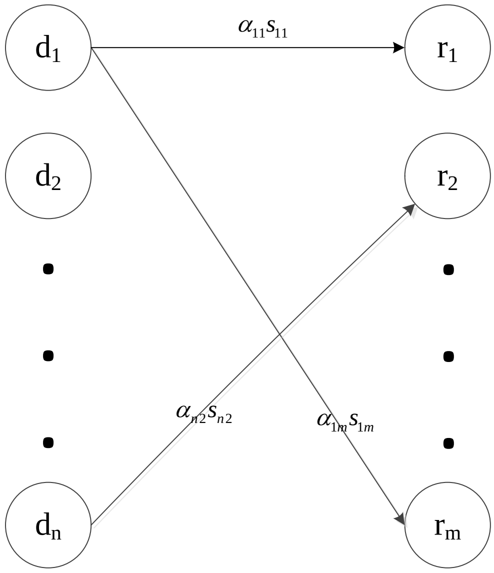

Figure 2. The conceptual setting of ride-sharing match.

In this paper, we adopt the maximum weighted bipartite matching method to solve the ride-sharing match problem, where, the emission saving $\alpha_{ij}\,s_{ij}$ is equal to the weight assigned to feasible match arc(i,j). To complete the specification, let x_{ij} be a binary decision variable equal to 1 if ride-share match (i,j) is proposed, and 0 ifnot. And then, a formulation of the maximum weight bipartite matching optimization problem to maximize system emission savings uses objective function $\sum_{(i,j)} x_{ij}\,\alpha_{ij}\,s_{ij}$, along with the constraints (1)-(6).

4. COMPUTATIONAL EXPERIMENTS

In this section, we now present the results of a set of computational experiments in dynamic ride-share matching systems. We not only get the optimal system distance savings, but also calculate the CO_2 emission benefits owing to the miles saving of ride-sharing system. Furthermore, we relax the influence of the vehicle travelling speed, and we give method to calculate the total CO_2 emission savings on account of participating the ride-sharing systems. In this section, we implement a simulation environment using the C++ programming language and CPLEX 11.1 as the linear and integer programming solver.

4.1Simulation setup

In Agatz et al. (2011), we developed a ride-sharing simulation environment based on the 2009 travel demand model for the metropolitan Atlanta region, developed by the Atlanta Regional Commission (ARC). The ARC is the regional planning and intergovernmental coordination agency for the 10-county Atlanta area, a sprawling region with a population of approximately 5 million people occupying 6,500 square miles. The travel demand model for the region is used in this study to generate daily vehicle trips by purpose between all pairs of travel analysis zones within the region.

In the experiments, unless specifically stated otherwise, we generate five different random trip announcement streams based on a 2% participation rate, a 30 min announcement lead-time, and a time-flexibility of 20 min, where the parameters setting is the same with Agatz et al., (2011). And furthermore, we assess the value of the optimization-based approaches for ride-share matching by the bipartite matching with bundle constraints binary integer programming approach.

4.2 Computational results

We compute the following statistics to demonstrate the benefits of the ride-sharing for the CO_2 emission, consider three different participation rate levels: 1%, 2%, and 4%. The averages are computed over the five separate announcement streams, the average speed between any origins and destinations is set as 30 mile/hour:

1. Total system-wide vehicle CO_2 emission reduction (E)

2. Total system-wide vehicle miles savings (M)

(1) Impact of participate rate level on CO_2 emission

The average passenger vehicle emits about 411 grams of CO_2 per mile. This number can vary based on two factors: the fuel economy of the vehicle and the amount of carbon in the vehicle's fuel. Most vehicles on the road in the U.S. today are gasoline vehicles, and they average about 21.6 miles per gallon (West, 2001). Every gallon of gasoline creates about 8,887 grams of CO_2 when burned. Therefore, the average vehicle when driving one mile has tailpipe CO_2 emissions of about:

$$CO_2\ emission\ per\ mile = \frac{CO_2\ per\ gallon}{MPG} = \frac{8887}{21.6} = 411\ grams \quad (8)$$

Tabla 1 Impact of participate rate level on CO2 emission

Participation Rate	CO_2 emissionreduction (E) (Kg)	Total miles savings (M) (mile)
1%	0.025million	0.06million
2%	0.058million	0.14million
3%	0.115million	0.28million

From the Table 1, we can see that the participation rate levels have a significant influence on the system-wide vehicle distance savings and when the participation rate level set as 1%, that means 50,000 participants take part in the ride-sharing system, there will be approximately 0.06 million miles total distance savings, if we assume all the vehicles burn gasoline, and all the vehicles have the same speed. There will be a large reduction in the CO_2 emission per day, which can be seen from the table 1 is 0.025 million kilograms per day. And the higher participation rate level there will be a more CO_2 emission savings, along with the participation rate level vary from 1% to 4%, the CO_2 emission savings range from 0.025 million kilograms per day to 0.115 million kilograms per day.

(2) Impact of rolling horizon strategy on CO_2 emission

In this section, we consider the influences of rolling horizon strategies on the CO_2 emission, which comes from changing the re-optimization timing. The strategy that re-optimizes after each minute coincides with a strategy that runs an optimization each time a new announcement is made. In our base case, we assume the potential ride-sharing matches established through optimization are not finalized until as late as possible. Here, we examine another strategy, in which all the matches are found after the optimization run, they will be finalized immediately.

Table 2 presents the results for the 2% participation rate announcement streams. The results show that different rolling horizon strategies have huge impact on the CO_2 emission, when we set the optimization time is 1 minute, the immediate strategy will produce 22621.5 kilogram CO_2 less than the latest strategy. And we can also notice that along with the increase of the frequency, the latest strategy will have a bigger CO_2 emission savings, while the immediate strategy is opposite to the latest strategy, less frequency will take benefit on CO_2 emission. So the optimization frequency depends on the chosen strategy, if the latest optimization strategy is adopted, we should set a high frequency to run the optimization, on the contrary, if the immediate strategy is adopted, less frequency will be better.

Tabla 2 Impact of different rolling horizon strategy setting on CO2 emission

Time and strategy	**CO_2 emission reduction (E)**	**Total miles savings (M)**
Latest		
1min	60236.2 kg	146560 mile
2min	59184.0 kg	144000 mile
10min	58657.9 kg	142720 mile
30min	55764.5 kg	135680 mile
Immediate		
1 min	37614.7 kg	91520 mile
5 min	41034.2 kg	99840 mile
10 min	44453.8 kg	108160 mile
30 min	52081.9 kg	126720 mile

(3) Impact of speed on CO_2 emission

While in practical cases, the minimum total travel distance is not equal to minimum total emission, especially in the dynamic ride-sharing systems (Barth and Boriboonsomsin, 2008), which is showed in Figure 3, CO_2 emissions can be lowered by improving traffic operations, specifically through the reduction of traffic congestion. As traffic moves at slower or higher speeds than the optimum of about 70 km/h, energy consumption per unit distance increases. In calculating energy wasted in congested traffic for its occasional Urban Mobility Report, The Texas Transportation Institute (TTI) uses the following formula: 8.8pmg+(0.25*speed). From the above literature, it is obvious that the ride-sharing system result in speed increase and the vehicles travelled with different speed have different fuel consumptions, which result in the generation of CO_2, which means the CO_2 emission of vehicles is relative to the travel speed.

From Figure 3, it is easy to know that if the average speed reduced to 30 km/h from 40 km/h. The energy consumption rate will increase to 4.3 MJ/km from 3.5 MJ/km, which means traffic would consume 23% more energy as the speed reduced. Based on the consumption formulation proposed by TTI the traffic would consume 15% more energy as the speed reduced. If we assume the gasoline is completely burned, which means the C8H18 is totally transformed into CO_2, the CO_2 emission is in proportional to the energy consumption, so the CO_2 emission will show the similar curve as energy consumption, which showed in Figure 4.

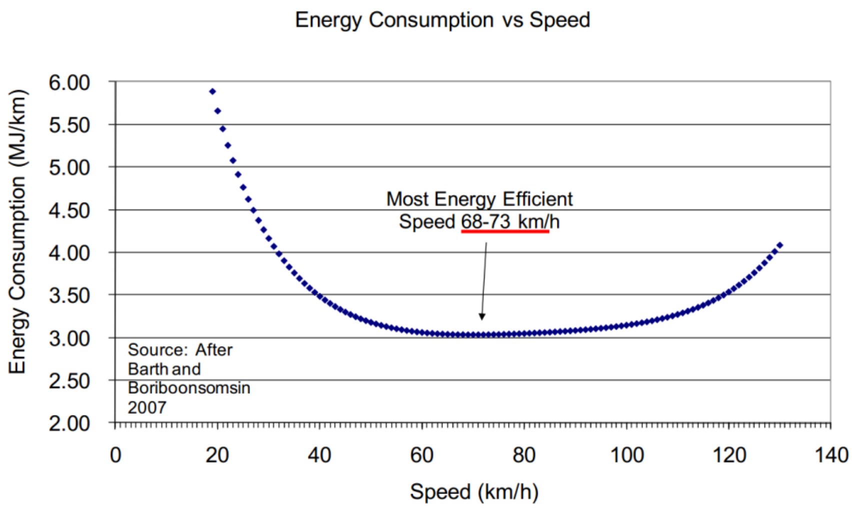

Figure 3. Energy Consumption Impact of Different Traffic Speeds.

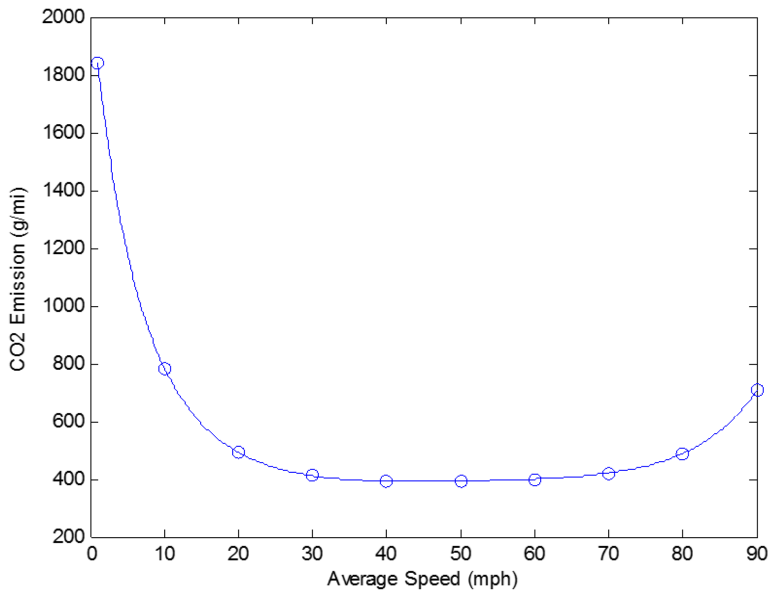

Figure 4.CO_2 Emission Impact of Different Traffic Speeds.

From Figure 4 we can see that, when average speeds are very low, vehicles experience frequent acceleration and deceleration events. They also do not travel very far. Therefore, gram-per-mile emission rates are quite high. In fact, when a car is not moving, a distance-normalized emission rate reaches infinity. Conversely, when vehicles travel at higher speeds, they experience higher engine load requirements and therefore have higher CO_2 emission rates. It can be seen in Figure 4, when the vehicles travel at 30 mile/h, the CO_2 emission rate approximately is 411g/mile, while if the vehicles travel at the peak hour, the travel congestion will take a great effect on the CO_2 emission, when the vehicles travel with an average speed 20 mile/h, the CO_2 emission rate will be 492.28 g/mile. In 2005 the ARC had modeled the potential impact of 2500 three-person express carpools in Auckland, using the ART Model. It predict an increase in average speed from 37.81 kilometers per hour (km/h) to 40.44 km /h. In this paper, we assume that after using ride-sharing system, the travel speed will increase from 20 mile/h to 30 mile/h. From Table 3 we can see that, there will be a huge CO_2 emission savings owing to the increase of speed, which comes from the advantages of ride-sharing system

Tabla 3CO_2 emission impact of different speeds

Participation Rate	CO_2 emissionreduction (E) (Kg)			Total Travel miles
	20mile/h	30mile/h	Savings	
1%	0.158 million	0.132 million	0.026 million	0.32 million
2%	0.315 million	0.263 million	0.052 million	0.64 million
4%	0.630 million	0.526 million	0.104 million	1.28 million

(4)Total CO_2 Emission saving

As mentioned above, the CO_2 emission savings of the ride-sharing systems come from two parts, first part is the total distance saving of participating the ride-sharing systems, which is well known to the researchers, the second part is always neglected by the scholars, the different travel speed will emit different quantity carbon dioxide, as our best of knowledge, little literature mentioned the relationship between ride-sharing and speed, and no literature addressee research on the CO_2 emission impact of the speed in ride-sharing system. In this section, we will calculate the total CO_2 emission savings of the ride-sharing system, which is showed in Table 4.

Tabla 4CO_2 emission impact of different speeds

Participation Rate	CO_2 emission from distance saving(Kg)	CO_2 emission from speed increase(Kg)	Total CO_2 emission savings
1%	0.025 million	0.026 million	0.051 million
2%	0.058 million	0.052 million	0.110 million
4%	0.115 million	0.104 million	0.219 million

5.CONCLUSION

Theoretically the potential for greenhouse gas emission savings from increased ridesharing in noncommercial passenger highway vehicles is substantial. This paper present a formulation for the system optimal greenhouse emission, and adopt the bipartite matching theory to solve the ride-sharing problem. In our study, we take the CO_2 emission impact of speed into consideration, the ride-sharing systems make the vehicle travel speed increase, which have big influences on the CO_2 emission. So we think the total CO_2 emission benefits of the ride-sharing systems come from two parts, the total distance savings and the increase of speed. We implement a simulation environment to examine the proposed methods and we give a simple example to show how to calculate the total CO_2 emission savings of the ride-sharing system.

Future challenges may include: (1) a transportation equilibrium model with ridesharing can be introduced to obtain a more accurate speed increase; (2) matching methods for one driver and multi-riders; (3) a multi-mode transit for participates to choose from (such as public transit)..

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