

A SIMULATION FRAMEWORK FOR SHARED AUTONOMOUS TAXI SYSTEMS

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The shared autonomous taxis system (SATS) has been regarded as a promising traffic mode for improving travel flexibility and reducing travel costs. This study aims to examine the potential benefits of replacing all taxis with ride-sharing autonomous vehicles. Specifically, two sharing strategies are discussed: non-detour sharing, in which a subsequent customer is picked up only if no detour is required, and detour sharing, where the detour may cause delay for the first customer. An agent-based simulation is developed to demonstrate the advantage of the SATS. Results show that the non-detour and detour sharing strategies can respectively reduce fleet size by 19% and 27%, reduce waiting time by 62% and 82%, reduce operational costs by 16% and 24%, and reduce CO2 emissions by 17% and 19% in comparison with a non-sharing strategy.

Key Words : Shared autonomous taxi system (SATS), autonomous vehicle (AV), ride-sharing, agent-based model, detour sharing

1. INTRODUCTION

There has been rapid development in the field of autonomous vehicles (AVs) in recent years. Many automobile manufacturers and IT companies around the world are testing their AV products on real road networks, including Google, Uber, Tesla, and Toyota¹. Some countries have put AVs into operation in limited areas, though not on whole public road network. For example, the Singapore operating company called “nuTonomy” uses AVs as taxis within a 2.5 square mile area². Much evidence points to AVs becoming a reality in the near future.

AVs can be designed to connect with each other and can exchange the traffic information relating to the road network³. Since driver error is the primary cause of car accidents, and traffic regulation violations are the main reason for crashes⁴, the human error that make the roads unsafe are expected to be

eliminated when, with AVs, human drivers are replaced by machines. With these advantages, AVs are expected to make transportation safer, more efficient and more comfortable while reducing costs, reducing environmental impact and reducing congestion⁵.

With urban taxi systems as they are today, a driver can only serve a single customer or group of customers on a point-to-point journey. Many empty taxis cruise the streets looking for customers. The average occupancy rate of a taxi in New York City, for example, is only 1.2 passengers per trip⁶, which means that the current system is inefficient. Empty taxis impose an economic burden by increasing traffic congestion on the urban road network. Meanwhile, the system is unable to meet all taxi demand during peak hours. Measures to solve such problems are urgently needed.

With the aim of solving the problems noted above and making optimal use of AVs, this study investi-

gates the efficiency of a shared autonomous taxi system (SATS) through simulation experiments. In the studied system, customers are encouraged to share a taxi with other customers who have similar itineraries, resulting in a discounted fare for the customer. It is assumed that customers can call a shared autonomous taxi (SAT) using a smartphone or website. A taxi is automatically assigned by SATS to pick the customer up, with both unoccupied taxis and taxis occupied by other customers considered. By taking advantage of unoccupied seats in taxis a SATS can reduce the total number of taxis required on the road network.

In this study, sharing by only two customers is considered and on this basis the benefits of SATS are evaluated. In particular, sharing is divided into two cases, non-detour sharing and detour sharing, based on whether a detour from the first customer’s route is necessary or not. Non-detour sharing means that sharing a taxi with the second customer will not require the taxi to detour from the first customer’s route. As for detour sharing, in this case the taxi

needs to make a detour to pick up or drop off the second customer.

Non-detour and detour sharing cases can be further classified into different forms according to specifics of the origins/destinations of the two customers and the route. Table 1 shows all possible forms of non-detour cases and detour cases.

This paper is organized as follows. In Section 2, a review of the literature on taxi sharing and the performance of shared autonomous vehicles is presented. Section 3 discusses the design of the shared autonomous taxi system considered in this study and presents three simulation scenarios. A case study and results are given in Section 4. This is followed by the conclusion and a discussion of future work in Section 5.

2. LITERATURE REVIEW

In the effort to optimize conventional taxi systems in terms of convenience to customers and mitigating

Table 1 Classification of non-detour and detour routes

Number	Route form	Same origin	Same destination	Detour required
(1)		✓	✓	
(2)		✓		
(3)			✓	
(4)		✓		
(5)				
(6)				
(7)			✓	✓
(8)				✓
(9)		✓		✓
(10)				✓

Notes,

- , ■ , — : origin, destination and route of 1st customer, respectively
- , ■ , — : origin, destination and route of 2nd customer, respectively
- , ■ , — : origin, destination and route shared by both customers, respectively
- ✓ : yes

traffic congestion, a major strategy has been to investigate dial-a-ride and shared taxi systems and such studies can be found in the literature. Teal⁷⁾ found that commuters could be the major users of carpool ride-sharing, which can yield a reduction in travel costs. Even though ride-sharing is generally applied to private cars, commuters can call a taxi for the purpose of sharing. Dial⁸⁾ reported on an autonomous dial-a-ride taxi system in which customers requested a taxi via telephone and only the customer is involved in the process of requesting a ride, assigning the trip, scheduling the arrival and routing the vehicle. The task of a driver is simply to follow instructions provided by the vehicle's computers. The author also investigated an ideal autonomous taxi system with the ability to assign a taxi to a customer in the shortest possible time. Tao⁹⁾ used each customer's choice of maximum acceptable number of sharing customers and acceptable genders as inputs into an algorithm, which then selected the taxi which is able to reach the customer's location most rapidly to provide the service. Orey¹⁰⁾ et al proposed that a customer request might be sent to all or subset of operational taxis and each taxi would feedback its cost associated with the trip to the customer. The customer would then determine the acceptable lowest-cost for taxi-sharing and choose a taxi to use. However, it proves difficult for a customer to select one taxi from the many potential taxis. Ota¹¹⁾ et al studied a data-driven taxi ride-sharing simulation in which taxis cruise the road network even when empty. A trip is assigned to the taxi that offers the lowest additional cost if the passenger is assigned to it. Ma¹²⁾ et al. noted that a ride request, made through a smartphone app, should be assigned to whichever taxi minimizes the increment in travel distance resulting from the request while meeting the arrival time, capacity, and monetary constraints of both the new request and the existing passenger(s).

There have been proposals for autonomous taxi systems since prior to the year 2000, such as the autonomous dial-a-ride taxi system mentioned in Dial⁸⁾. Even though technology for navigation and positioning was at that time not sufficiently advanced, the author described an ideal autonomous system. With the development of AVs, it is now conceivable that a customer could request a SAT and take it to his or her destination. It is assumed that such taxis might be enjoyed alone or shared with other customers. Many scholars believe that deployment of AVs could lead to a reduction in the total number of private cars on urban road networks. Fagnant and Kockelman¹³⁾ designed an agent-based model for shared autonomous vehicle (SAV) operations in which four strategies are used to relocate autonomous vehicles with the aim of minimizing waiting times for future travelers. The authors chose a 5-min interval as the iteration period.

At the beginning of every 5-min interval, travel demand in every zone is pre-determined. A parameter called a "block balance" is proposed, which represents the difference between expected demand and supply for SAVs in the upcoming 5-min period. They concluded that one SAV can replace around 11 conventional cars, comparing the average number of trips served by a SAV with that by a private car. Fagnant¹⁴⁾ et al. studied SAVs in more detail, taking into account variations in link-level travel times. Their proposed model comprises four submodules: SAV location and trip assignment, SAV fleet generation, SAV movement, and SAV relocation. A SAV would be assigned firstly to the traveler who has been waiting for the longest time. Fagnant and Kockelman¹⁵⁾ developed SAV simulations dealing with clients with different origins and destinations, in which dynamic ride-sharing (DRS) is considered. Five conditions were considered to judge whether a ride should be shared, including total travel time and the increment in remaining journey time for current passengers, total travel time increase of a new passenger, the possibility of the new passenger being picked up in the next 5 minutes, and the total travel time of the two passengers. Their experiments suggested that DRS had the potential to reduce total service time (which includes waiting time), travel time, and costs for users. The authors also discussed the optimal SAV fleet size from an economical viewpoint. However, they did not provide delivery rules for the customers in a single shared taxi. This is important because it determines the remaining time and travel time of each individual customer. Burghout¹⁶⁾ et al. replaced private vehicles in Stockholm with SATS in a simulation study. The sharing schemes included passengers with the same origin and destination, same origin but different destinations, and different origin but same destination. Results indicated that only 5% of the current number of private cars would be needed to transport commuters, but travel time increased by 13% on average. Lioris¹⁷⁾ et al. suggested that if the detour time incurred by serving a potential customer exceeds a maximal detour time, that customer should be rejected. Levin¹⁸⁾ et al. reported that, when choosing between an occupied SAV and an unoccupied SAV, the one able to arrive at the customer first should be assigned to the customer. They further proposed that SAVs would increase congestion because of the additional trip made to reach each customer's origin. It was found that the difference in vehicle miles traveled (VMT) between SAV scenarios and non-SAV scenarios was primarily due to the repositioning trips required to pick up the next passenger.

Since all the above results considered the replacement of private cars with SAVs or the use of SAVs

as taxis to serve commuters, it is not clear whether or not it would be beneficial to replace all taxis with AVs.

3. DESIGN OF SHARED AUTONOMOUS TAXI SYSTEM

This section describes the design of the SATS that is studied in this research. The design is based on a simulation platform $G = (N, A, T, D)$, in which N is the set of nodes and A is the set of links. These two components constitute the road network. A set of autonomous taxis T and travel demand D are the other two components of the system. In a SATS, as already mentioned, it is assumed that one taxi can be shared by two customers with similar itineraries. The simulation model for the studied SATS comprises three modules: 1) network and demand; 2) autonomous taxi (AT) assignment; 3) AT generation. The remainder of this section discusses these modules in detail.

(1) Network and Demand

The Sioux Falls network is chosen for simulation. It contains of 24 nodes, 76 links and 552 O-D pairs, as shown in Figure 1. The demand part of the module dynamically generates new travel demand. At each iteration period t , customers requesting ATs at nodes on the network are generated. It should be noted that the demand considered during each iteration period t consists of new demand as well as any unserved demand on the waiting list. That is, the unserved demand is any demand that had not been met in iterations up to and including the previous one. Demand is generated from a Poisson distribution every minute and is spread over a 24-h period based on the temporal distribution of US NHTS¹⁹⁾ trip-start rates in 2009, as Fig.2 shows.

(2) Assumptions

Before beginning discussion of SAT assignment, the assumptions made in the simulation are listed in this subsection.

- All customers request an AT through a smartphone or website. No manual taxi calls are considered in the system and taxis cannot be hailed at the roadside.
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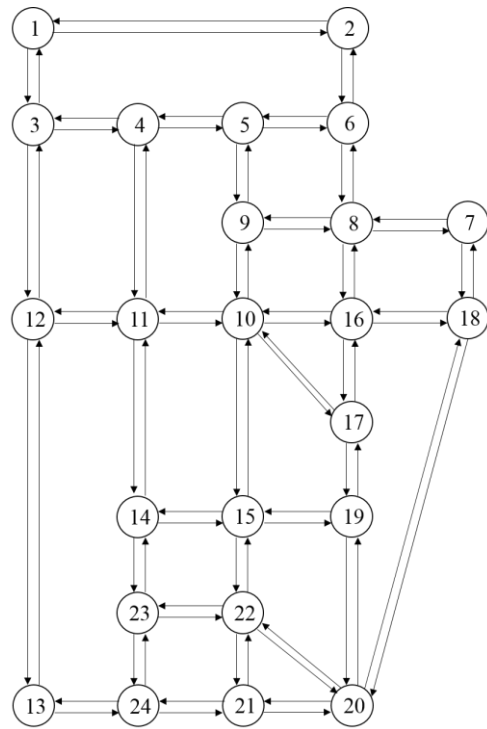


Fig.1 Sioux Falls network

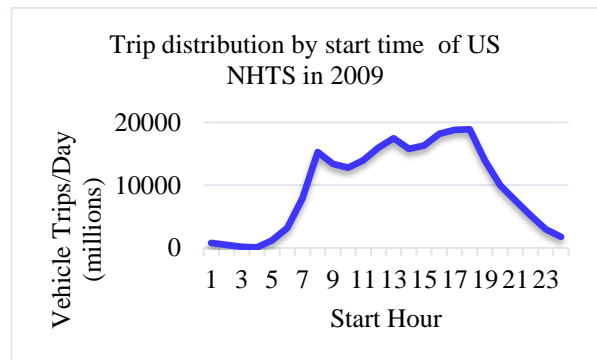


Fig.2 Trip distribution by US NHTS start time in 2009

- A taxi is shared by two customers at maximum.
- The time taken to board the taxi at the pick-up node is taken to be 1 minute.
- The time taken to alight from the taxi at the destination is taken to be 1 minute.
- Every request for a taxi is for a single customer.
- The AT parks at the alighting node of the last customer, if no further request is received.
- An occupied taxi is a taxi with only one customer.
- A full taxi is a taxi which already has two customers.
- An assigned occupied taxi will route to the pick up node of the second customer

from the next node along the first customer's route following assignment.

(3) AT Assignment and Three Simulation Scenarios

The taxis in the SATS are assumed to be connected with each other by wireless communication technology. They are all also connected to a central SATS controller which has information about the real-time location and status of all SATs in the system. The central SATS controller updates the status of SATs and customers, assigns an available SAT to each customer, and plans routes for SATs for the pick up and delivery of customers. The central controller begins work whenever a customer calls a taxi and finishes when all customers have arrived at their destinations.

The outputs of the central SATS controller are the status of SATs and customers. The possible statuses of a SAT include parked, on route to pick up a customer, and on route to a customer's destination. The possible statuses of a customer consist of waiting to be picked up, boarding a SAT, arrival at destination and on the waiting list for the next iteration.

To explore the potential benefits of a SATS, three scenarios are considered in simulation. The first is the base scenario in which one taxi only can serve one customer. When a customer D_i at node N_i at time t requests a taxi, the system will search for the closest unoccupied AT and the closest available occupied AT for D_i . The closest available occupied AT means the occupied taxi that can drop off the customer at his/her destination and then proceed to customer D_i early than any other. The time needed for these two candidate ATs to arrive at D_i from their current nodes are T_1 and T_2 , respectively. The AT searching method is as follows.

- The central ATS controller searches in order from the closest node to the farthest node on N until an unoccupied AT is found. If an unoccupied AT is found, the controller records T_1 .
- The ATS controller searches for the closest available occupied taxi. If one is found, the controller records T_2 , which includes the total travel time from its current location to the current customer's destination and from that node to D_i 's origin.
- A parameter called acceptable time (T_a) is used as a threshold by which the customer is assigned to the AT or has to continue waiting. If $T_1 \leq T_a$ and $T_1 \leq T_2$, the unoccupied AT will be assigned to the customer; if $T_2 \leq T_a$ and $T_2 < T_1$, the closest available occupied AT will be assigned.
- If there is unoccupied AT and no eligible

closest available occupied AT, the central ATS controller adds D_i to the waiting list. The customer represented by D_i will be assigned a AT before any other demand generated at the same node in the following iteration.

The other two scenarios are designed as SATS, in which taxi sharing by two customers is considered. In these two scenarios, a parameter T_{late} is set for every customer, which represents the latest acceptable arrival time at his or her destination. Sharing can be accepted only when both customers arrive at their destinations before their T_{late} , otherwise it is rejected.

The first SATS scenario considers the non-detour sharing forms shown in Table 1. In this scenario, it is assumed that equal consideration is given to the closest unoccupied SAT, the closest available occupied SAT and the closest sharable SAT. In this case, a sharable SAT means a taxi already occupied with one customer. It is assumed that the first-come SAT is assigned to the customer. The purpose of this design is to minimize customer waiting times. If customer D_i at node N_i at time t requests a taxi, the following sequence of steps is implemented:

- The central SATS controller searches for the closest unoccupied SAT in the same manner as in the base scenario. If such a SAT can be found, the controller records T_1 .
- The central SATS controller searches for the closest available occupied SAT in the same manner as in base scenario. If one is found, T_2 will be recorded.
- Next, the central SATS controller searches for the closest sharable SAT. Not only should such a SAT's route include D_i 's route, but also T_{late} for the current customer should be met. The sharable SAT that can arrive at N_i earliest is chosen. If such a sharable SAT is found, the central SATS controller records T_3 , which is the time from its current location to N_i .
- The central SATS controller compares T_1 , T_2 , and T_3 . If T_1 (T_2 , T_3) is smallest and less than T_a , the unoccupied SAT (or closest available occupied SAT, sharable SAT) will be selected.
- If no eligible SAT is found, the central SATS controller adds D_i to the waiting list.

The second SATS scenario is the detour sharing scenario, in which both detour sharing and non-detour sharing are considered. In this scenario, the first in, first out (FIFO) rule is adopted as a delivery rule.

That is, the first boarding customer should be delivered to his or her destination first, as shown in Fig. 3 (1). However, if the destination of the second customer is located on route to the destination of the first customer, the second customer will be dropped off first, as shown in Fig.3 (2). If customer D_i at node N_i at time t requests a taxi, then the following sequence is followed:

- The central SATS controller searches for an unoccupied SAT in the same manner as in the base scenario; it should be able to deliver the customer to the destination before T_{late} . If such a SAT is found, the central SATS controller records T_1 .
- The central SATS controller searches for the closest available occupied SAT. If one is found, the central SATS controller records T_2 .
- The central SATS controller searches for the closest eligible sharable SAT. First, SATS will check the destination of D_i to determine the potential delivery route. If it is located on route to the destination of the first customer, D_i will be delivered first; otherwise, D_i will be delivered after the first customer. If a SAT can make the T_{late} of both customers be met, the SAT is eligible; otherwise D_i cannot share the SAT. The eligible sharable SAT that can reach D_i earliest is selected as the candidate sharable SAT, and T_3 is recorded.
- The central SATS controller compares T_1 , T_2 , and T_3 , and selects a SAT in the same manner as in the non-detour sharing scenario.
- If no eligible SAT is found, D_i will be added to the waiting list.

(4) AT Generation

A prerequisite for a SAT being assigned to a customer is that there must be a SAT available. Considering that every customer has a maximum waiting time T_{max} , ATs or SATS cannot meet all demand when waiting time T_w is longer than T_{max} . Therefore, an appropriate SAT fleet size is investigated here. Four maximum waiting times are considered in this work: 5 minutes, 10 minutes, 15 minutes, and 20 minutes. Based on this requirement, generation rules for new SATs are defined according to the three scenarios.

- In the base scenario, a new AT is added to the system when a customer’s waiting time T_w exceeds T_{max} .
- In the non-detour and detour scenarios, if the arrival times of the closest unoccupied

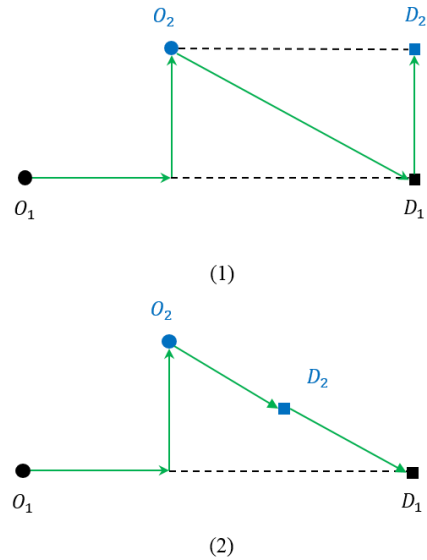


Fig.3 Customer delivery rules in detour sharing scenario

taxi, the closest available occupied taxi and the closest sharable taxi exceed T_{max} , a new SAT is generated.

4. CASE STUDY AND RESULTS

To explore whether a SATS enables the taxi fleet size to be reduced, the minimum required fleet size able to cover the demand for each waiting time is investigated for each of the above three scenarios. Then, to evaluate the potential benefits of SATS in terms of service level, the minimum fleet size needed among the three scenarios when the maximum waiting time is 10 minutes is applied to all three scenarios. Based on these simulations, taxi utilization, sharing ratio, operational costs and profit, and emissions are analyzed. Since the Sioux Falls network is much smaller than the total road network of the US, and the number of links is less than 0.1% of the road network of the US, 0.1% trips of US NHTS are applied to the simulation. T_a is set to 20 minutes in all simulation experiments. The T_{late} of every customer is set to 10 minutes.

(1) Fleet Size

Fig.4 shows the minimum fleet size needed in the three scenarios with different maximum waiting times. It can be seen that the fleet size in the non-detour sharing scenario is 81.01% of that in base scenario on average. The detour sharing scenario requires 73.42% of the fleet required in the base scenario (and 90.63% of that in the non-detour sharing

scenario). As maximum waiting time is increased, the required fleet sizes for all scenarios fall. The reduced fleet size in the two shared scenarios indicates that SATS can achieve efficient utilization of autonomous taxis. Compared with the non-detour sharing scenario, allowing detours improves the likelihood of sharing.

(2) Service Level

One purpose of SATS is to provide a more efficient service to customers. Each scenario is set to have 168 ATs so as to analyze the service level that SATS offers. The results are shown in Table 2. The satisfaction ratio denotes the ratio of customers whose waiting time is less than 10 minutes; it can be seen that it is only 76.48% in the base scenario. In the non-detour sharing and detour sharing scenarios, it is 96.44% and 100%, respectively. It can be seen that the average waiting time in the detour sharing scenario is 1.08 minutes, while it is 2.37 minutes in the non-detour sharing scenario. The base scenario figure is 6.18 minutes, which is about six times as long as in the detour sharing scenario. Total customer travel time is the time elapsed from the taxi request until arrival at

the destination. The average total travel time of the base scenario is 23.73 minutes, and it decreases by 15.59% in the non-detour sharing scenario and by 18.33% in the detour sharing scenario, respectively. These results verify that SATS is able to offer better service to customers than ATS when the supply of taxis is the same.

(3) Utilization of Autonomous Taxis

Table 3 shows the average driving time while empty, average driving time while occupied, and average parked time of all SATs. This result is obtained by simulating peak hour (16:00-19:00) trips with a minimum fleet when the waiting time is 10 minutes. In the two sharing scenarios, occupied travel time is twice as much as actual driving time, if the taxi is shared by two customers. The results show that the average occupied travel times in the detour sharing scenario (203.70 minutes) and non-detour sharing scenario (159.77 minutes) are greater than in the base scenario (143.22 minutes), which implies that the time in service of a SAT is longer than that of an AT so SATS improves the utilization of ATs.

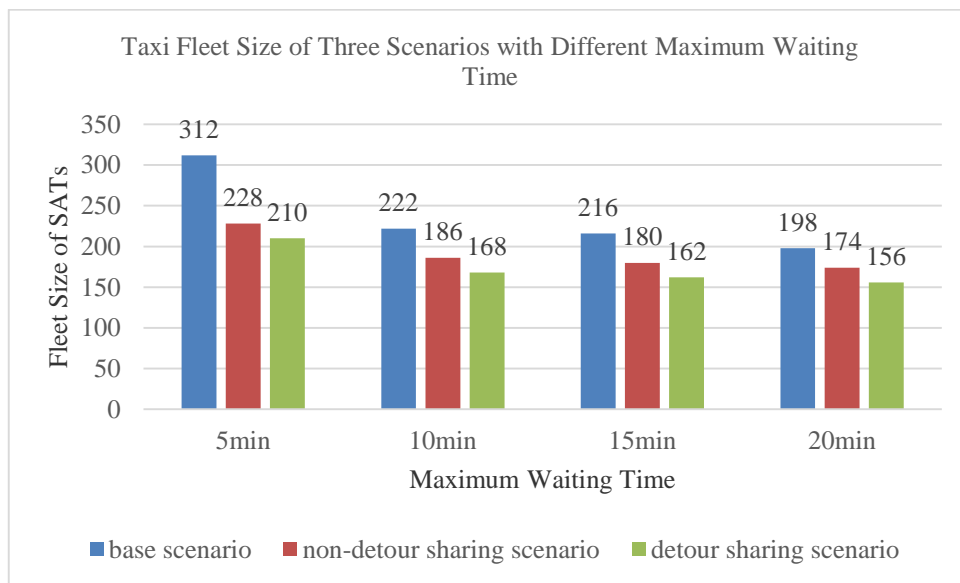


Fig.4 Minimum taxi fleet size required in the three scenarios with different maximum waiting times

Table 2 Service level offered by the three scenarios with fleet of 168 taxis

Scenario	Satisfaction ratio	Average waiting time	Average total travel time
Base scenario	76.48%	6.18 minutes	23.73 minutes
Non-detour sharing scenario	96.44%	2.37 minutes	20.03 minutes
Detour sharing scenario	100%	1.08 minutes	19.38 minutes

Table 3 Utilization of SATs during peak hours with minimum taxi fleet supply (minutes)

Scenarios	base scenario	non-detour sharing scenario	detour sharing scenario
Average empty driving time	7.63	8.91	4.76
Average occupied travel time	143.22	159.77	203.70
Average parked time	29.15	37.76	20.30

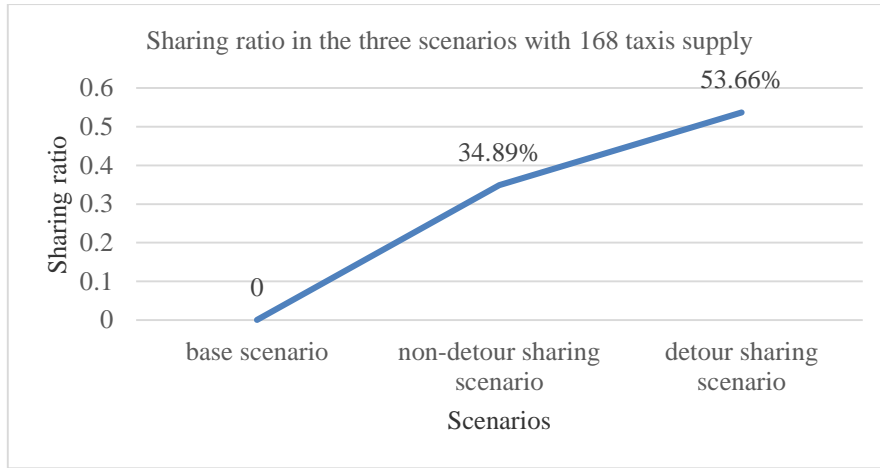


Fig.5 Sharing ratio in the three scenarios with fleet of 168 taxis

(4) Sharing Ratio

Sharing ratio is the ratio of number of customers taking sharing taxis to the total number of customers. Fig.5 shows the sharing ratio in the three scenarios over 24 hours of operation with the same fleet size (168 taxis). Since there is no sharing in the base scenario, the sharing ratio is 0 for this case. The sharing ratio in the detour sharing scenario is 53.66% and that in the non-detour sharing scenario is 34.89%. This indicates that detouring can improve the sharing ratio, which indirectly reduces the required fleet size.

(5) Operational Costs and Profit

In an autonomous taxi system, there are no salaries to pay to drivers. In this study, it is hypothesized that the cost of each AT is \$50,000 and can work for twenty years, which is regarded as an operational cost. Based on taxi fares in New York City²⁰⁾, fares are set at \$5 per mile in this study and the average profit per SAT is calculated. The calculation assumes an average speed of 30 mile/h and VMT of peak hour

accounts for 24% of the whole day. Fig.6 exhibits the operational costs and average profit of running the minimum fleet every year. To supply enough ATs, companies in the base scenario need to spend \$135,000 more than a company operating the detour sharing scenario, and \$90,000 more compared to the non-detour sharing scenario. The average profit among taxis is \$544,534.4 in the base scenario, which is 89.64% of that in the non-detour sharing scenario and 70.31% of the detour scenario. It can be concluded that SATS is beneficial to companies in terms of costs and profit.

(6) Emissions

Sections 4.1 and 4.2 demonstrate that, compared with ATS, fewer taxis are needed in a SATS, and vehicle miles traveled are less than in the base scenario. Yearly emissions in the three scenarios are analyzed according to Li²¹⁾ et al., as Table 4 shows. The emissions in SATS are only 83.04% of those in the base scenario on average, which implies SATS can save energy and is more environmentally friendly than ATS.

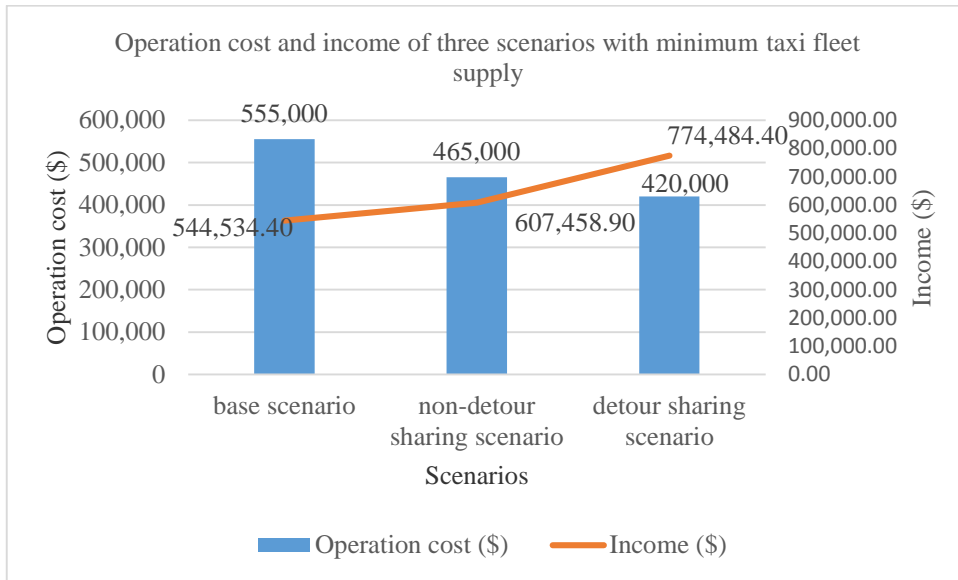


Fig.6 Operational costs and income in the three scenarios with the minimum taxi fleet (\$)

Table 4 Yearly emissions in the three scenarios with the minimum taxi fleet

Scenario	Base scenario	Non-detour sharing scenario	Detour sharing scenario
Emissions (CO ₂ , kg)	1.1355E10	9.5847E9	9.2737E9

5. CONCLUSIONS AND FUTURE WORK

This study proposes two sharing strategies for shared autonomous taxi systems and evaluates their potential benefits in comparison to a non-sharing taxi system. In the non-detour sharing strategy, taxis may not make detours to pick up sharing customers; the candidate taxis include the closest available occupied and unoccupied taxis, and one is assigned to the customer request depending on arrival time. In the detour sharing strategy, both non-detour and detour situations are incorporated. We design the route for picking up the subsequent customer and the delivery sequence according to the destinations and latest arrival times of the customers.

An agent-based simulation is developed for evaluating the performance of the proposed sharing strategies. Several of the important findings are outlined below.

The minimum taxi fleet size for a specified customer demand is much smaller with SATS as compared to a non-sharing strategy, a result that is consistent with the conclusions found in the literature. SATS can, on average, reduce the fleet size needed in a non-shared situation by 22.79%.

Simulation results show that the average waiting time is respectively 2.37 minutes and 1.08 minutes in the non-detour and detour sharing scenarios, while it is 6.18 minutes in the base scenario (non-sharing). The satisfaction ratio deteriorates (only 76.48%) if

the fleet size is set as the same as in the detour sharing scenario.

Sharing also improves the utilization of autonomous taxis, as seen by comparing the time occupied of all taxis in the three scenarios with the parked time and the empty driving time.

Another finding is that the sharing ratio sharply improves if detour sharing is introduced. It can also be said that sharing has economic and environmental advantages. All of this evidence indicates that a SATS can provide a more efficient service to customers, improve the utilization of autonomous taxis, save costs and bring more income for the operator, save energy and favor the environment.

Potential directions for future study include more complicated sharing schemes and an analysis of the effect of road network type on sharing performance. With the aim of offering a better level of service, another suggestion for study is the relocation of autonomous taxis during unoccupied periods, because this may reduce the average waiting time for customers and balance travel demand and shared autonomous taxi supply.

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