Research on Congestion Pricing in a Multiple-Operator Autonomous-Mobility-on-Demand System

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Abstract

The performance of multiple AMoD operators under congestion pricing strategies remains unexplored. We propose two congestion pricing strategies: Link-based congestion pricing strategy and Delay-based congestion pricing strategy to regulate AMoD services. We aim to demonstrate the effectiveness of such strategies using an agent-based modeling framework in a case study of the city of Hague, the Netherlands. Simulation results suggest that congestion pricing strategies could effectively reduce congestion, and congestion could be significantly reduced even if pricing strategies are in place in a limited area. Moreover, we found that the delay-based pricing scheme is more flexible and more capable of reducing congestion. It is recommended that some road sections may be tolled to reduce delays. Passengers, however, will have to accept higher fares because of the additional congestion fee (as we hypothesized), and the impact needs to be further investigated in future research.

Contents

1. INTRODUCTION

Automated Mobility-on-Demand (AMoD) technology has come a long way in improving the level of transport network management since the rapid development of advanced vehicle and communication technologies, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [1]. Automated Vehicles (AVs) offer a unique opportunity for changing urban mobility in the future. Combining AVs with ride-hailing technology creates the chance for a paradigm shift in urban mobility systems. Automated driving technology will reduce the reaction time and following distance of vehicles compared to human drivers, so the capacity of roads and intersections may eventually increase [2]. Talebpour and Mahmassani used microscopic simulations to demonstrate the impact of AVs on road capacity in high penetration conditions [3]. However, AMoD systems could attract more demand and add more vehicle kilometers travelled. This is because the possibility of performing other activities and varying levels of comfort while driving may affect the travel cost and perceived value of travel time of AMoD users [4]. As a result, congestion in future cities may occur due to added travel [5]. Policies for AMoD services could also influence the use of AMoD services and their effects on cities and people's journey. In the use of AMoD services, there is a trade-off of increased travel demand and improved network travel. Congestion pricing is a scheme of surcharging road users to address air quality and congestion while influencing the choice of travelers. Little is known about the effectiveness of congestion pricing strategies on people's choices of AMoD services and their travel. In this report, we propose and compare two congestion pricing strategies: Link-based congestion pricing strategy and Delay-based congestion pricing strategy in regulating AMoD services. We aim to demonstrate the effectiveness of such strategies using an agent-based modeling framework in a case study of the city of Hague, the Netherlands.

The rest of the paper is organized as follows. The second section describes the impact of the AMoD system on urban traffic and the research status of congestion pricing strategy for AMoD. The third section describes the components and basic principles of the agent-based model. Section 4 describes the case study of the city of The Hague. Section 5 analyzes the results of the case study. The last section summarizes the main conclusions.

2. LITERATURE REVIEW

Congestion pricing (CP) and road tolls are key tools for moderating demand and incentivizing more socially and environmentally optimal travel choices. The idea of pricing road users with marginal external congestion costs related to delays has been extensively studied in the field of traffic engineering in the last century [6]. Over the past 50 years, multiple studies have investigated congestion pricing strategies to determine optimal charging models for infrastructure performance and traveler behavior [7]. Traffic authorities in cities such as London, Milan, Stockholm, Singapore, and Gothenburg have all applied different congestion pricing policies [8]. Most congestion pricing policies are limited to simple and rigid cordon-based or zone-based charges. Their strategy is to mark out congestion areas and charge vehicles entering the areas a fixed fare that does not vary due to congestion. The application of AMoD and the emergence of hybrid scenarios of autonomous vehicles and conventional vehicles have brought new research topics to pricing.

From a practical point of view, the application of high-level communication technology in AV may facilitate the introduction of more flexible pricing strategies. Ideally, changes in congestion pricing should reflect changes in travel costs, depending on the time of day, type of road user, the purpose of travel, real-time traffic conditions, and the availability of alternative modes of transport, such as public transport [9]. However, congestion pricing strategies for traditional vehicles often include facility-based tolls (bridges, tunnels, motorways); cordon-based tolls, which apply when entering an area, such as in London; area-based tolls, which apply when driving within the area, such as Milan. These pricing strategies do not perfectly reflect changes in travel costs.

In the past, research in this area has focused on solutions with a strong analytical framework and unconstrained "best pricing" versus suboptimal but more feasible "suboptimal pricing" [10]. The possibility to exchange traffic and toll information with all AVs in real-time will allow for more flexible pricing strategies that vary dynamically across space, time, and toll levels. In this sense, self-driving technology can almost equalize the congestion externality of a "second-best pricing" system to that of a "first-best pricing" system. In other ways, driverless technology could also facilitate congestion pricing. Due to advanced communication technologies (wireless, GPS), tolling systems may become more feasible and less expensive than current tolling systems based on Dedicated Short-Range Communication and Automatic License Plate Recognition, as these technology do not require additional road infrastructure. In addition, the fact that "smart" self-driving cars could calculate tolls and route options and communicate them to travelers will help keep pricing schemes understandable and transparent. This may ultimately increase public acceptance of congestion pricing [11].

In the "Congestion Pricing Schemes" section, we propose two congestion pricing strategies that leverage AMoD's advanced computing and communication capabilities to derive pricing that benefits all AMoD operators, road users, and traffic authorities. According to existing studies, the performance of multiple AMoD operators under congestion pricing strategies remains unexplored. Simoni et al. [12] developed several pricing strategies in different scenarios using an intelligent body-based simulation model, MATSim. The traditional calculation is to charge congestion costs by link or distance, e.g., a fixed cost for vehicles passing through congestion-prone roads (tunnels and bridges) during peak hours. Another more advanced congestion pricing scheme is to charge users for delays (at the network level) caused during their time travel based on the time of day and the traffic conditions of the network [13]. Simulation results show that although the effectiveness of pricing schemes varies by scenario, all congestion pricing schemes can significantly reduce the occurrence of congestion and advanced pricing schemes can lead to more economic benefits. Wang et al. [14] proposed a link-based dynamic pricing model in order to improve the performance of the road network system, which uses a heuristic algorithm to calculate the dynamic pricing of each link to avoid blockage occurrence and improve the reliability of travel time and system performance of the AMoD system.

3. MODELING AMOD WITH AN AGENT-BASED MODEL

3.1 General model framework

We model the morning rush hour commute in an urban area. In the study area, three AMoD operators are set up, and they manage fleets that can serve passengers traveling between various service points. The model framework is shown in Figure 1. The congestion pricing strategy model generally has five main components: the traffic management department, the AMoD operators, the travelers, the AMoD network, and the autonomous vehicle.

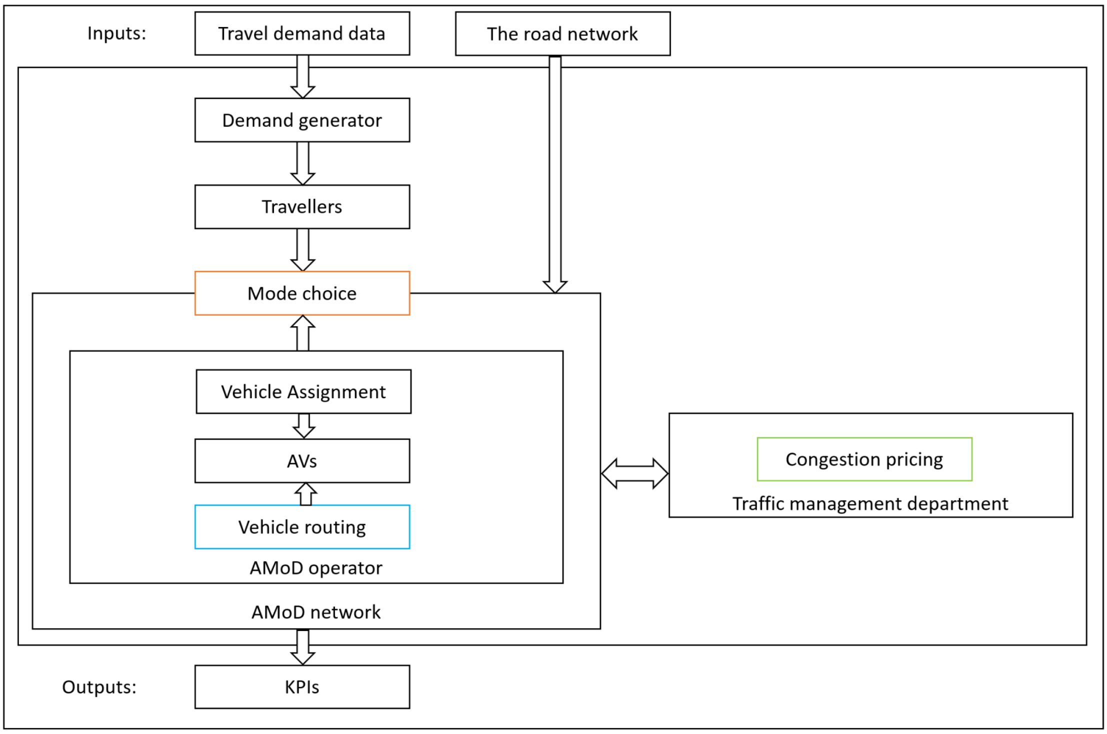

Fig. 1. AMoD Model

As shown in Figure 1, demand generators generate travelers with travel needs between service points based on travel demand data. Corresponding traveler agents will be generated in the model, they have travel demands from one service point to another service point, and these travel demands will be received by all AMoD operators. Based on the traveler's trip request, the AMoD system calculates the passenger's estimated trip time based on road condition information and prices the trip based on the current condition of the autonomous vehicle. When AMoD calculates the ride price, in addition to the ride time, ride distance and other factors, it is also necessary to add the congestion price charged due to road congestion. The congestion price is calculated by the traffic management department according to the road congestion situation, using the congestion pricing strategy to calculate the specific congestion price of the road section. Travelers use mode choice component to choose different AMoD services. The result of mode choice will be determined by the attributes of the trip, including waiting time, travel time, and price etc. If the passenger accepts the price and time of the trip, the AMoD operator assigns the self-driving vehicle to the passenger and updates the route of each vehicle.

3.2 Mode choice component

Demand (travel requests) is determined endogenously for competing AMoD operators[15]. In this model, the travel needs of travelers will be allocated by the mode selection component to different AMoD operators, each operator operating a fleet of AVs. The probability that a traveler selects an AMoD operator is calculated by a multinomial logit model. In the MNL model, probability that passenger k chooses alternative i is described by the logit expression:

$$\Pr(i) = \frac{\exp\left(V_i\right)}{\sum_i^3 \exp\left(V_i\right)}$$

When evaluating the service level of an AMoD operator, the following important aspects are considered: waiting time (including waiting time for allocated vehicles and waiting time for vehicles to arrive), in-vehicle travel time and fare. Therefore, the total utility V_i will be expressed as the linear sum of the three utilities associated with AMoD operator i.
The expected utility V_i of AMoD operator i is expressed as follows:

$$V_i = V(w_i) + V(t_i) + V(f_i)$$

Where,
$V(w_i)$ is the waiting time utility.
$V(t_i)$ is the in-vehicle travelling time utility.
$V(f_i)$ is the fare utility.

Congestion pricing influence the attractiveness of AMoD services this is because the travel time and travel costs might be influenced by the implementation of a congestion pricing. We consider the could influence the travel times and travel costs. The changes in travel cost may be imposed to the services users (i.e., travelers).

3.2.1 Utility of waiting time $V(w_i)$
$V(w_i)$ describes the utility generated by passenger k during the period of time from making a travel request to the AMoD system until boarding. Wait time includes the time a customer waits for a vehicle to be assigned after making a request (assignment time) and the time it takes for the vehicle to arrive at the customer's origin (pickup time). The expected assignment time is calculated by multiplying average single assignment time by the number of passengers in waiting list. The calculation of pickup time is also based on an empirical estimate since the passenger has not been assigned a vehicle.

$$V(w_i) = -\alpha * VOTT_{AMoD} * (p * \varphi) - \alpha * VOTT_{AMoD} * t_{max} * \frac{N_i - n_i}{N_i}$$

Where,
α is a multiplier that reflects the discomfort of waiting time. The comfort level inside the car is usually higher than that outside the car.
$VOTT_{AMoD}$ is the monetary value of AMoD travel time. This parameter allows us to measure AMoD in-car travel time in monetary terms.
φ is average single assignment time.

p is passengers' number in the waiting list. This parameter is multiplied by φ to get the passenger's expected assignment time.
N_i is the vehicle number of operator k.
n_i is the idle vehicle number of operator i.
t_{max} is the maximum pickup time. We set a maximum radius, and only idle vehicles whose distance from the passenger is less than the maximum radius can pick up passenger k. t_{max} is determined by the maximum radius.

3.2.2 Utility of travel time $V(t_i)$

The second component $V(t_i)$ of this utility function models the cost of IVTT in AMoD vehicles. The cost of IVTT depends on the IVTT and VOTT in AMoD vehicles.

$$V(t_i) = -s_{ik} * VOTT_{AMoD}$$

Where,
s_{ik} is the expected travel time for the OD of user k.

3.2.3 Utility of fare

The third component $V(f_i)$ of this utility function regards the fare for the AMoD service. Fare is the out-of-pocket cost of a customer k of the chosen operator i. In this study, the fare is structured by a base fare, a distance-based fare, and a time-based fare for a single ride.

$$V(f_i) = -(c + m * d_{ik} + n * s_{ik} + toll_{ik})$$

Where,
c is base fare of AMoD service.
m is the distance-based fare of AMoD service per kilometer.
n is the time-based fare of AMoD service per hour.
d_{ik} is the expected in-vehicle travel distance of traveler k.
$toll_{ik}$ is the expected total congestion price along the trip of traveler k.

3.3 Vehicle routing

There are two functions of the vehicle routing component. In the mode choice component, the vehicle routing component will estimate the route of the AMoD service provided by each operator. These travel itineraries will be used to estimate travel distances, travel times, and costs incurred during travel for AMoD service es offered by various operators. Another feature is planning travel routes for the operator's self-driving taxis. It is worth noting that due to the time difference between the execution of these two functions, the road conditions may change, so the estimated route used in the mode choice may not necessarily occur in practice.

Considering that AMoD operators usually serve as many travel needs as possible, we use the Dijkstra algorithm to develop a cost-based routing algorithm to find the least cost route in time rather than the shortest distance in space between OD pairs. Different from the traditional Dijkstra algorithm, the cost-based routing algorithm uses the link feature not distance when finding the shortest path, but the sum of the the congestion price and the monetized travel time.

$$C_r = s_r * VOTT_{AMoD} + toll_r$$

Where,
C_r is the cost of road segment r.
s_r is the travel time of road segment r.
$toll_r$ is the toll for road segment r.

In addition, since the congested road section will lead to extra travel time and the traffic management department will charge the congestion fare, we have improved it based on the Dijkstra algorithm. When there are congested road sections in the road network, The congestion-avoiding routing algorithm will give priority to using the non-congested road. Segments make up a route. The congestion-avoiding routing algorithm will use the congested road segments only when the set of non-congested road segments cannot form a feasible route between ODs.

3.4 Congestion pricing strategy

1. Link-based congestion pricing strategy

Facility-based congestion pricing is one of the most common forms of congestion pricing because it is easily understood by drivers and simple to implement. Facility-based congestion pricing strategies mainly target bridges, tunnels, and road facilities because these road segments are congestion-prone. Congestion pricing is uniform for all selected road segments, regardless of congestion level and road characteristics.

$$toll_r = \beta$$

Where,
β is basic fare for congestion road segment.

Another traditional congestion pricing strategy is the distance-based congestion pricing strategy. Distance-based congestion pricing strategies vary only with distance traveled. Toll road segments are selected from the road network based on whether the volume/capacity (V/C) ratio of each road segment in the network exceeds a certain threshold.

$$toll_r = \gamma * l_r$$

Where,
γ is distance-based fare for congestion road segment.
l_r is the length of road segment r.

However, both congestion pricing strategies have their drawbacks. The disadvantage of facility-based toll is that, since all congested sections are charged the same regardless of length, vehicles will tend to pass through those longer sections, which may result in still severe congestion on long sections. And distance-based toll also has disadvantages. Since pricing based on the length of the road section may cause motor vehicles to tend to pass through those road sections with shorter lengths, there are still serious congestion in some short-circuit sections. Therefore, this paper will combine these two congestion pricing strategies to design a new congestion pricing strategy: link-based congestion pricing strategy.

The fare will consist of two parts, fixed fare and distance-based fare.

$$toll_r = \beta + \gamma * l_r$$

According to Fundamental Graph (FD), before the flow q (veh/h) on a link reaches capacity, the speed u of the motor vehicle on the link will be maintained at free flow speed, at this time the density of the link is less than critical density. When the flow reaches capacity, the speed of the motor vehicle on the link will be equal to the free flow speed and link density will be equal to the critical density. When the outflow flow of the road is less than the inflow flow, the density of the link will continue to increase, and the link will be in a congested state. As the density continues to increase, the speed on this link will also decrease until the density reaches jam density and the speed decreases to zero. However, in a real environment, the speed cannot be maintained at free flow speed for a long time while the traffic reaches capacity. When a critical density is reached, traffic flow becomes erratic and vehicle speeds can easily drop below the critical speed unexpectedly. Research by John C. Falcocchio[20] has shown that as the volume of traffic in a highway increases, the speed generally decreases until a critical speed is reached and the throughput reaches its maximum value (V/C = 1.0). When the ratio of volume to capacity is less than 0.60, the speed change is not obvious. As the volume-to-capacity ratio increases, the speed drops off dramatically. Therefore, we will regard the link whose volume reaches 60% of the capacity as a congestion link to implement the pricing strategy.

2. Delay-based pricing strategy

However, there are certain limitations to pricing by road section. When the traffic on a road exceeds the threshold, the road segment will be set toll. However, when the inflow of the link continues to be greater than the outflow, the degree of congestion increases and the vehicle speed decreases, but the toll will not increase. When the vehicle chooses a route, it may choose the more congested but shorter road among the two congested routes, which is obviously not conducive to reducing the degree of congestion. In order to enhance the congestion pricing strategy to reduce congestion, we design a delay-based congestion pricing strategy. Road sections with different congestion states have different speeds and cause different delays.

Therefore, the delay caused by a congested link can be calculated according to the link speed:

$$\tau_{rt} = \frac{l_r}{u_{rt}} - \frac{l_r}{u_{rf}}$$

Where,

τ_{rt} is the delay on road section r at time t.

u_{rf} is the free flow speed on road segment r.

u_{rt} is the average travel speed on road section r at time t.

For sections of road with severe delays and a density close to jam density, inflow traffic needs to be reduced as soon as possible to eliminate congestion this morning. Therefore, the main method of Delay-based pricing strategy is to describe the congestion price as a linear function of delay:

$$toll_r = \beta + \rho * \tau_{rt}$$

Where,

ρ is time-based fare for congestion road segment.

For the passenger, the price of the AMoD service he needs to pay includes the congestion price of all the links included in this trip. The criteria for determining whether a link is charged is the same as the link-based congestion pricing strategy. In the model, we will monitor the flow of each road segment every six seconds to update the state of the road segment (density, speed and congestion price).

4. SIMULATION SCENARIOS, THE CASE STUDY OF THE HAGUE

4.1 The road networks

Figure 2 shows the road network in the Hague region. Since driverless taxis are not widely used in practice, it is difficult to obtain road parameters (capacity, speed limit) related to driverless cars. We used the relevant road parameters in a manned vehicle scenario. Correcting road properties in autonomous driving scenarios can be a future research work. Figure 2 also shows the distribution of service points of the AMoD system. The role of these green spots is as a traveller's travel origin and travel destination.

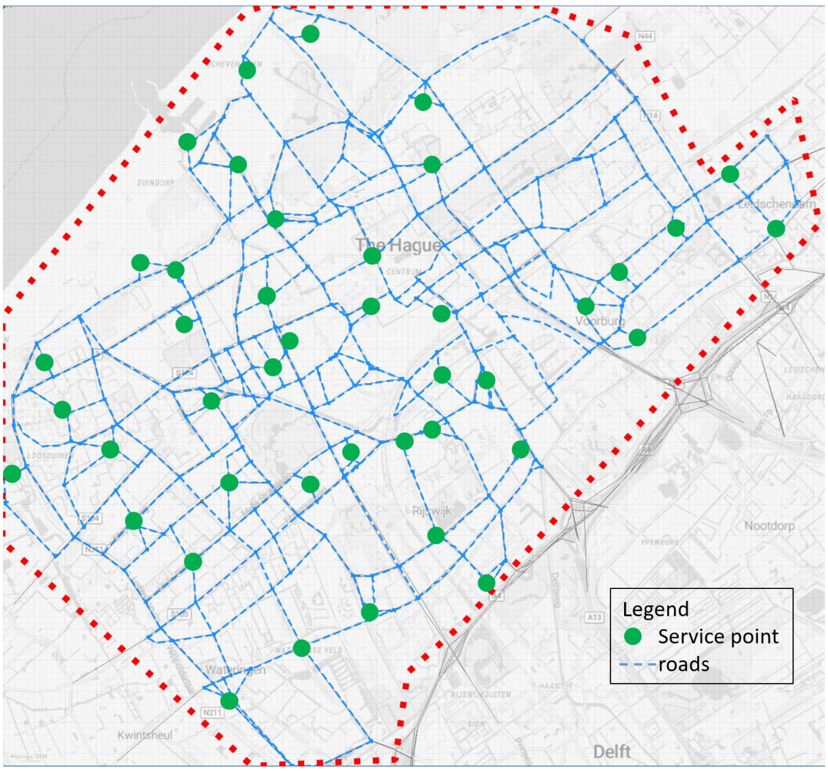

Fig. 2. The road network of The Hague

The total traffic demand in The Hague during the morning rush hour (5:30AM-10:00AM) is 38,700 trips. These requirements are distributed among 49 traffic analysis zones, so the OD matrix contains 2401 OD pairs. The aggregation of travel demand is not uniformly distributed in the time dimension but is generated at 15-minute intervals. Figure 3 shows the departure time distribution of traffic demand. A number of trips are intra-regional trips, which do not use AMoD services. For the three AMoD operators, 255 idle automated taxis will be generated for each operator in each traffic analysis zone at the start of the simulation.

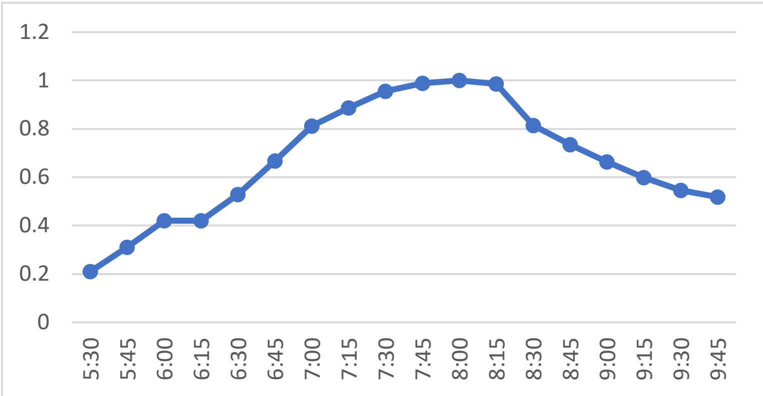

Fig.3. The departure time distribution of traffic demand

4.2 Simulation Parameters

Table 1 lists the model parameters and some model features used in the simulation scenario, and the relevant parameters used in the mode choice component are also included. The literature shows [16] that the monetary value of the time outside vehicle is greater than the monetary value of the travel time in the vehicle, so we use the multiplier α to describe the multiple relationship between the monetary value of the waiting time outside the vehicle and the monetary value of the travel time. In Netherlands, the multiplier for out-of-vehicle waiting times is 1.6 to 2.2 times that of travel time, so the multiplier α is set to 2 in this study. The literature [17] suggests that VOTT inside an AMoD vehicle should be less than in a private vehicle, since passengers in an autonomous vehicle can do leisure activities but not driving a private car. The study by Kouwenhoven et al. [18] pointed out that the value of travel time of traditional cars should be 9.25 Euros/hour, and in this study, the VOTT of AMoD vehicles was 6.01 Euros per hour. The toll rate of congestion pricing refers to the research of Ubbels et al [19]. No matter the degree of congestion and road network feature, the basic fare of all selected road sections is set to 0.5 euros/link, and the distance-based fare is set to 0.2 euros/km. The setting of Time-based fare refers to the research of Michele D. Simoni et al [12]. It is set to be the same as the value of travel time, 6.01 Euro/hour.

Table 1 Value of Simulation Parameters

Parameter	Value
Road nodes	510
Road segments	836
Total travel requests	25800 trips
Service points	49
Operators	3
VOTT	6.01euros/hour
α	2
Vehicle assignment Time interval	20 s
n	0.26 euros/min
m	1.2 euros/km
c	1.4 euros
number of vehicles per centroid	57 per operator
β	0.5 euros per link
ρ	6.01euros per hour
γ	0.2 euros/km
The vehicle assignment search radius	6 km

5. RESULTS

The service level of AMoD can be studied in terms of travel time, waiting time and cost. The level of service will determine which AMoD operator a traveler chooses. In terms of the scope of the congestion pricing strategy, we designed two scenarios. In the first scenario, two congestion pricing strategies are applied to all road segments. In the second scenario, we selected some road segments that are more prone to congestion, and only applied the congestion pricing strategy on these road segments. In addition, the vehicle routing algorithm of AMoD operator 1 is set as the congestion-avoiding routing algorithm, while the vehicle routing algorithms of AMoD operator 2 and AMoD operator 3 are set as the cost-based routing algorithm. Our goal is to study congestion pricing strategy, the effect of vehicle routing strategy and application scope of pricing strategy on the service level and overall network performance of AMoD operators.

5.1 AMoD Operators Performance in all links with congestion price

In this scenario, two congestion pricing strategies are applied to all road segments. Under different pricing strategies, Table 3 and Table 4 show the performance of three AMoD operators. For comparison, Table 2 shows the performance of AMoD operators when no pricing strategy is applied. Tables 3 and 4 except for the performance of the three AMoD operators are also appended with the percentage increase or decrease relative to the case where no pricing policy is applied.

Table 2 No congestion pricing strategy scenario

Operator	Operator 1	Operator 2	Operator 3	Overall
Demand share	8558	8535	8242	27456
Average waiting time	3.36	3.57	3.50	3.47
Served requests	8472	8442	8127	24041
Average Travel time	12.85	12.67	12.50	12.68
Average Trip length	4.79	4.79	4.74	4.77
Average Delay (min)	4.24	4.08	4.02	4.12
Average Fare (euro)	7.20	7.20	7.14	7.18
Average Tolls (euro)	0	0	0	0
Congestion Level	0.39	0.39	0.37	0.38

Table 3 Link-based congestion pricing strategy scenario

Operator	Operator 1	Operator 2	Operator 3	Overall
Demand share	8137(-4.92%)	8503(-0.37%)	8674(5.24%)	27456(0%)
Average waiting time	2.86(-14.66%)	3.23(-9.50%)	3.20(-8.54%)	3.01(-
Served requests	8058(-4.89%)	8419(-0.27%)	8602(5.84%)	25079(0.15%
Average Travel time	11.53(-10.27%)	11.38(-	11.21(-	11.37(-
Average Trip length (km)	4.87(1.73%)	4.76(-0.75%)	4.71(-0.53%)	4.78(0.1%)
Average Delay (min)	2.80(-34.07%)	2.84(-30.47%)	2.78(-	2.81(-
Average Fare (euro)	7.53(4.68%)	7.51(4.35%)	7.44(4.23%)	7.51(4.67%)
Average Tolls (euro)	0.00	0.35	0.34	0.24
Congestion Level	0.25(-37.15%)	0.27(-32.14%)	0.26(-	0.26(-

Table 4 Delay-based congestion pricing strategy scenario

Operator	Operator 1	Operator 2	Operator 3	Overall
Demand share	8413(-1.69%)	8399(-1.59%)	8428(2.26%)	27456(0%)
Average waiting time	2.69(-19.85%)	2.85(-20.24%)	2.95(-	2.83(-
Served requests	8327(-1.71%)	8314(-1.52%)	8344(2.67%)	24985(-
Average Travel time	10.74(-16.36%)	10.82(-	10.81(-	10.79(-
Average Trip length (km)	4.84(1.04%)	4.75(-1.00%)	4.78(0.87%)	4.79(0.34%)
Average Delay (min)	2.19(-48.27%)	2.39(-41.49%)	2.35(-	2.31(-
Average Fare (euro)	7.50(4.18%)	7.44(3.43%)	7.50(5.01%)	7.48(4.26%)
Average Tolls (euro)	0.00	0.31	0.31	0.21
Congestion Level	0.19(-51.40%)	0.22(-43.37%)	0.23(-	0.21(-

Overall, the application of the two pricing strategies and the two vehicle routing algorithms has little effect on the passenger's mode choice results. The application of the Link-based congestion pricing strategy makes the total average waiting time slightly decreased, while the travel time is significantly reduced, and the total average travel time is reduced by about 10%. The performance of the two vehicle routing algorithms is close. From perspective of average travel length, the congestion-avoiding routing algorithm leads to a small increase in the average travel length of AMoD operator 1, while the average travel length of AMoD operator 2 and AMoD operator 3 using the cost-based routing algorithm has a small change. This is as expected, since the congestion-avoiding routing algorithm will prioritize routes without congestion, it will have to detour further in some cases. The average delay shows that the pricing strategy reduces the time loss caused by congestion. Average fare means the fare paid by passengers to AMoD operators, which includes time-based fare, distance-based fare, basic fare and congestion price generated during travel. The average fare has increased slightly, which may be caused by the congestion pricing strategy. Finally, we use the congestion level parameter to describe the impact of the toll policy on the overall road network congestion level. 0.21 means that compared with the travel time using free flow speed for the whole journey, the travel time needs to be 21% more on average. Link-based congestion pricing strategy reduces congestion by about 26%.

The application of the Delay-based congestion pricing strategy makes the waiting time slightly reduced, while the average travel time is significantly reduced. From the perspective of the average fare, the AMoD price increases caused by the two pricing strategies are similar, but the delay-based congestion pricing strategy reduces the delay more, lowers the congestion level, and is much more effective in dealing with congestion.

Comparing the performance of the three AMoD operators, it can be found that operator 1 has a smaller average delay and a lower congestion level, but the average fare is the highest among the three AMoD operators. Although operator 1 avoids most road sections where congestion pricing occurs, passengers taking operator 1 do not need to pay congestion pricing, but these passengers need to endure longer travel time and travel distance.

5.2 AMoD Operators Performance in Potentially Congested links with congestion price

In this section, we will narrow down the application of congestion pricing strategy to some high-congestion road segments. Under the condition that the non-congestion pricing policy is applied, the time when the traffic of each road segment exceeds the threshold is counted. We selected road segments with time greater than zero as potential congested road segments to apply congestion pricing strategy on these road segments. Other road segments are no longer subject to congestion pricing, even if they are congested. Figure 4 shows where these road segments are located. Most of these road sections are distributed in the urban center area.

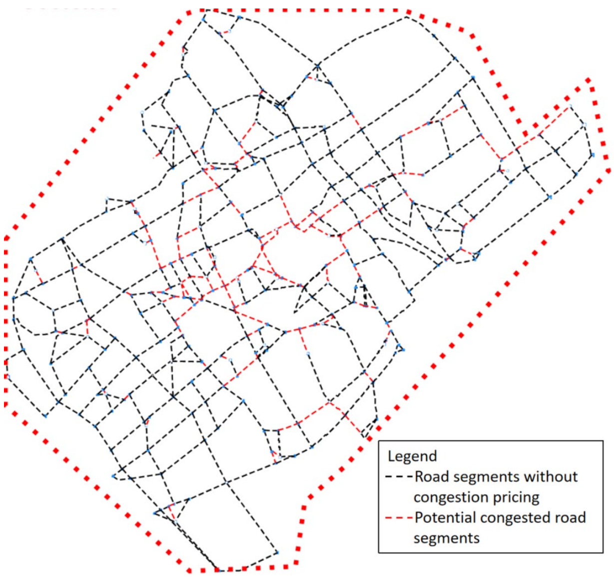

Fig.4. Distribution of Potential congested road segments

Table 5 Link-based congestion pricing strategy scenario

Operator	Operator 1	Operator 2	Operator 3	Overall
Demand share	8364(-2,27%)	8391(-1.69%)	8602(4.37%)	27456(0%)
Average waiting time	3.06(-8.55%)	3.98(11.83%)	3.61(3.14%)	3.55(2.39%)
Served requests	8257(-2.54%)	8276(-1.97%)	8486(4.42%)	25019(-
Average Travel time	12.26(-4.49%)	11.09(-	12.051(-	12.07(-
Average Trip length (km)	4.89(2.17%)	4.73(-1.13%)	4.75(0.38%)	4.79(0.44%)
Average Delay (min)	3.55(-16.10%)	3.45(-15.33%)	3.57(-	3.53(-
Average Fare (euro)	7.58(5.38%)	7.45(3.56%)	7.46(4.52%)	7.50(4.5%)
Average Tolls (euro)	0	0.314	0.304	0.20
Congestion Level	0.31(-20.36%)	0.32(-16.58%)	0.34(-8.82%)	0.33(-

Table 6 Delay-based congestion pricing strategy scenario

Operator	Operator 1	Operator 2	Operator 3	Overall
Demand share	8636(0.91%)	8380(-	8248(0.07%)	27456(0%)
Average waiting time	3.16(5.75%)	3.60(0.81%)	3.32(-5.23%)	3.36(-3.4%)
Served requests	8566(1.11%)	8252(-	8147(0.25%)	24965(-
Average Travel time	11.73(-8.67%)	11.72(-	11.44(-	11.63(-
Average Trip length (km)	4.78(-0.08%)	4.78(-0.25%)	4.71(0.59%)	4.79(0.34%)
Average Delay (min)	3.09(-27.16%)	3.25(-	3.13(-	3.16(-
Average Fare (euro)	7.54(4.84%)	7.51(4.36%)	7.41(3.70%)	7.49(4.39%)
Average Tolls (euro)	0.00	0.32	0.30	0.21
Congestion Level	0.27(-30.79%)	0.31(-	0.29(-	0.29(24.35%

Tables 5 and 6 show the changes in the performance of the three AMoD operators caused by two tolling strategies in a scenario where only some road sections are applied with congestion pricing strategies. The performance of the Link-based congestion pricing strategy is worse than that of applying the pricing strategy to all road segments. The average waiting time not only did not decrease, but increased slightly. The decline in average travel time has also become smaller, shrinking to about 5%. Changes in average travel distances have been small. The increase of the average fare is similar to the case of applying the pricing strategy to all road segments, but the decrease of delay and congestion level is much smaller. The congestion level of the overall network has only decreased by about 15%.

The performance of the Delay-based congestion pricing strategy has also deteriorated a bit. There are small decreases in wait times and travel times, and only small changes in average travel distances. The average fare is similar to the case where the pricing strategy is applied to all road segments, but the decrease in delay and congestion level is much smaller. The congestion level of the overall network has only decreased by about 24%. This level of congestion is still four percentage points lower than the performance of the congestion pricing strategy, which shows the advantage of the delay-based congestion pricing strategy. In the case where the pricing strategy is applied to all road segments, this gap is five percentage points, which means that the gap between the two pricing strategies is decreasing as the number of links where pricing strategy applied decreases.

Comparing the performance of the three AMoD operators, the delay caused by operator 1 is still less than the other two operators, and the service price of the operator is also the highest among the three. However, the performance of operator 1 is closer to the average value than when the pricing strategy is applied to all road segments, which is also in line with expectations.

6. SUMMARY AND CONCLUSIONS

AMoD will affect people's mobility and community's traffic conditions. Congestion pricing schemes represent an opportunity to internalize the negative costs of traffic congestion. The evolving transportation landscape, eventually characterized by higher automation and connectivity, enables the implementation of relatively advanced CP strategies.

This research employs an agent-based model to study the effect of the city of The Hague using a congestion pricing strategy to regulate road congestion after the widespread adoption of AMoD services in the future. In the two simulated scenarios analyzed, road network congestion levels and traffic delays are reduced by road congestion pricing strategies.

From a transportation perspective, all congestion pricing strategies are efficacious in reducing congestion, and congestion can be significantly reduced even if the scope of application of pricing strategies is reduced. The delay-based pricing scheme is more flexible and more capable of reducing congestion. For the AMoD operator, avoiding road sections that may be tolled is a good strategy, which can effectively reduce delays. Passengers, however, need to bear higher prices, and the impact of this needs to be further discovered in future research.

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