

Investment Cost Minimization of Autonomous-Electric Vehicles based on Queueing Model

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Abstract— In this paper, we suggest investment cost minimization of Autonomous-Electric Vehicles (A-EV) for tourist transportation service in tourist spot with consideration for number of A-EVs in charging station. On providing tourist transportation service with A-EVs to tourist, a large number of A-EVs may cause more user satisfaction and require more investment cost. Contrariwise a smaller number of A-EVs may cost little investment cost and less user satisfaction. In other words, there are trade-off relation between user's satisfaction and investment cost. Also, A-EVs which is charging or waiting for charge in the tourist spot's charging station can't serve the transportation service on tourists. Therefore, we applied queueing modeling to minimization investor's investment cost for satisfying tourist's satisfaction by considering tourist's waiting time constraint and the number of A-EVs in charging station. Tour operators and investors of tourist spot can obtain suitable number of A-EVS for their environment by using this minimization.

Keywords—Optimization, Queueing theory, Transportation service, Charging Station, Tourism

I. INTRODUCTION

In automobile manufactures, two megatrends are drastically changing the market. Automation is the source of a shift towards autonomous driving. On the other hand, sustainability is causing the ever-increasing replacement of the combustion engine by the electric motor and is pushing the sector towards eco-friendly mobility [1]. Autonomous technology continues to evolve. Automotive experts anticipate that the transition to autonomous will be gradual. Autonomous vehicles (AV) may change value distribution across the automotive ecosystem [2]. This advance in AV industry is prospected to affect in whole industry [3]. On the one hand, electric vehicle (EV) technology keeps in progress to replace internal combustion engine cars. This advance is bringing cleaner, more responsive and quieter cars [2]. Moreover, introduction of EVs can improve economic benefits of various industries [4].

Impact of advance of AV industry to 33 industries is described in [3]. For example, media and entertainment industry will face paradigm shift. Also, tourism and travel industry that include hotels and airlines will be affected too. On the one hand, economic forecasting model based on economic model of Toyohashi City in Japan shows a result that more active penetration of EVs can cause higher the city GDP in most industries [4].

A role of AVs in tourism is expected to act as 'last-mile solutions' facilitating multi-modality, therefore that may take an important position in moving tourists. Cost and convenience work as important factors while touring. With regard to cost, because AVs need no driver, tourist could reduce travel cost significantly. Whereas, from a viewpoint of a convenience AVs may mitigate inconveniences caused by taking mobility services. For example, AVs may alleviate the inconvenience of renting a vehicle in a foreign environment. Also, that could minimize risk of jet lag, fatigue, misunderstanding new driving rules, and cultures of mobility [5]. Meanwhile, sustainable tourism is shed light on to reduce atmospheric pollution and noise at local scale. Because transport is one of the most important tourism-related factors causing atmospheric pollution, introduction of EVs to tourism is motivated to alleviate these problems. Further, the EV industry effects on hotel and accommodation industry. For example, hotel hosts can attend e-car industry by installing charging station [6].

In most tourist attractions, transportation services exploiting AV and EV technologies have been demonstrating to provide traveling convenience to tourist. For example, in Chatan Town, Okinawa of Japan, with the intention of achieving driverless autonomous driving mobility services. the ministry of economy, trade and industry (METI) pulled together the ministry of land, infrastructure, transport and tourism (MLIT) to advance a demonstration test for technologies and services involving autonomous driving vehicles, making use of a remote-controlled system. On March 31, 2021, METI shown that driverless autonomous driving mobility services by using Yamaha electric carts, which National Institute of Advanced Industrial Science and Technology (AIST) has modified by adding autonomous driving systems, on a seaside course. They provide this service to passengers as free of charge to encourage many tourists to use this service. and they wanted that this service will operate sustainably, acting as model for a tourist targeted business [7].

To tourists, these tourist transportation services could increase accessibility to tourist spots and improve the travel experience by providing moving convenience to tourists. Consequentially, more this service may attract more travelers to tourist spot. However, from the perspective of tour operators and investors who want to introduce tourist transportation services, it is necessary to take account of

suitable size of number of vehicles, because they have limited capital and investment. For example, the small number of vehicles requires less investment, but it increases tourists' waiting time. Then, travel satisfaction reduces because of the long waiting time. Besides, this long waiting time in these services causes inconvenience to users. Contrariwise, the large number of vehicles increases service satisfaction by providing services in short waiting time. but it requires a large investment cost. According to a study on wait perception, people feel that unoccupied time is longer than occupied time [8]. Thus, tour operators and investors need to consider the tourists' waiting time.

EVs need to be frequently charged. It is a dominant concern of EV users. The EV cannot provide transportation services while the EV waits at the charging station for charging. This waiting time, which is caused in the station, is one of the important consideration factors to enhance the quality-of-service of stations [15]. With consideration for EV's charging characteristics, the size of number of EVs may be determined in more detail.

In this paper, we suggest queueing theory-based investment minimization problem about adopting tourist transportation services with the A-EVs (autonomous-electric vehicle) from the perspective of tour operators or investors. This problem has consideration of a waiting time constraint for taking this service and the number of A-EVs in the charging station. By applying this, tour operators and investors can estimate the least number of AVs that are needed in their business.

The remainder of this paper is organized as follows: Section II presents the several studies applying queueing theory for sizing of number of vehicles in transportation systems. In Section III we suggest sizing optimization of number of vehicles to minimize initial investment considering waiting time constraint of customers and the number of A-EVs at the charging station for charging. In Section IV we present the results of numerical analysis of the proposed sizing optimization problem and in Section V we conclude our work.

II. RELATED WORKS

In this section, we review several studies based on queueing theory for sizing of number of vehicles in transportation systems.

M. P. Fanti et al suggested discrete event system considering electric vehicle utilization in a closed queueing network framework [9]. Their system has a purpose to maximize system revenue by determining the optimal fleet size of electric vehicle sharing systems.

A Mobility-on-demand system that provides one-way vehicle sharing service, consists of a fleet of vehicles and a team of drivers to rebalance such vehicles. Methods for optimizing this system is presented in [10]-[12].

Mobility-on-demand systems for personal transportation in urban areas were investigated by R. Zhang et al. They used a queueing network approach to investigate it. Two coupled closed Jackson networks models with passenger loss are used to estimate the number of vehicles and drivers. Analysis of the

availability of passengers' waiting time was used to optimize the number of vehicles and drivers [10].

J. Alonso-Mora et al. proposed vehicle routing and request-vehicle assignment methods for minimizing passenger costs, taking into consideration expected future demands for reducing passenger travel and waiting time [11].

P. Bazan et al. tackled the optimal rebalancing and fleet sizing problems in order to minimize the number of costly trips with consideration of incentives for rebalancing the system with the help of customers. They provide a simulation model for mobility-on-demand networks with one-way automobile sharing, as well as optimization and queueing network analysis [12].

In networks of stations set, M. P. Fanti et al. suggested a discrete event system in a closed queueing network framework to maximize the network profit by determining the optimal fleet size of electric vehicle sharing systems [13].

J. Alonso-Mora et al.'s vehicle routing and request-vehicle assignment methods do not consider operation cost. However, M. P. Fanti et al.'s two studies have consideration of the operation cost. Also, both two coupled closed Jackson networks models proposed by R. Zhang et al. and the optimal rebalancing and fleet sizing problems of P. Bazan et al. have regard to operating cost. But, investment cost for service introducing is not considered. Therefore, we suggest minimization of initial investment cost.

III. QUEUEING THEORY APPROACH FOR INVESTMENT COST MINIMIZATION OF A-EVS

In this section, our target environment (i.e. tourist spot where want to provide transportation service) and mapping notation to apply queueing theory in the target environment are presented. And, optimal sizing of number of A-EVs to minimize initial investment considering customer's mean waiting time constraint and the number of vehicles in the charging station are followed in the last of this section.

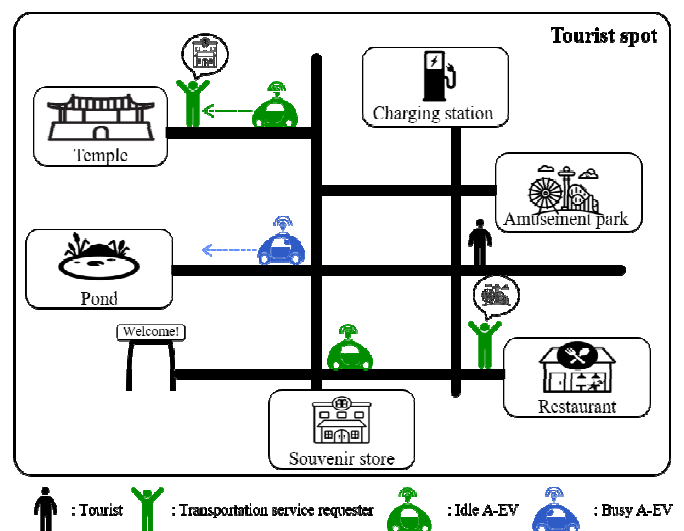


Figure 1. Tourist spot environment with charging station

A. Target Environment

Figure 1 shows tourist spot environment with charging station. It consists of many places to tour (e.g. temple, amusement park, pond, restaurant, souvenir store, etc.), A-EVs that provide transportation service to a tourist's or a tourist group's demand, and a charging station which has one or more electric vehicle charger and waiting area. Tourists can visit a specific place or walk around in the tourist spot. Also, they can take a service providing A-EV by calling it if they need it, and they can take off from the A-EV anywhere in the tourist spot.

B. Applying Queueing Theory Notation

Mapping relationship of target environment with queueing theory is presented in figure 2 and figure 3. In the target environment, tourist transportation service can be regarded as queueing system. Figure 2 depicts this mapping relationship. In the queueing theory, λ (arrival rate) is mean rate of arrival. μ (service rate) is mean service rate. W_q (waiting time in queue) is mean waiting time in queue. N (number of servers) is system serving capacity.

Applying these notations to figure 2, average request rate of transportation service per particular time interval is considered as average arrival rate (noted as λ_s). The transportation service can be requested from a group of tourists or a tourist. Average rate of transportation completion to required destination during a particular time interval is considered as average service rate (noted as μ_s). Average time spent for waiting the service AV is considered as mean waiting time (noted as $W_{s,q}$). The number of service A-EVs for providing transportation service is considered as the number of servers (noted as N).

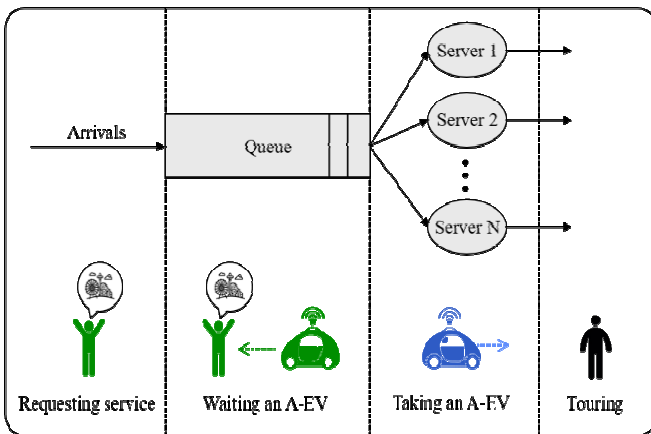


Figure 2. Queueing model of a service in the target environment

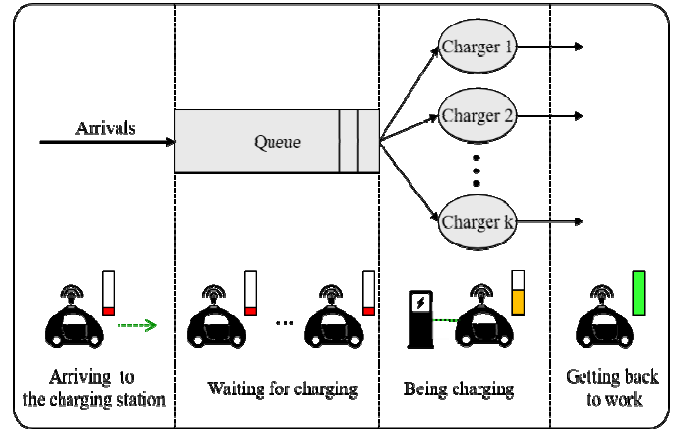


Figure 3. Queueing model of a charging station in the target environment

In the same manner, figure 3 is analyzed follows. A-EV's average arrival rate to a charging station is noted as λ_c . charger's average service(charging) rate is noted as μ_c . The number of chargers is noted as k . Waiting time in the charging station for the charging service is noted as $W_{c,q}$. Time spent in the charging station is noted as W_c . The number of A-EV in the charging station's queue is noted as $L_{c,q}$. The number of A-EV in the charging station is noted as L_c .

In our target environment, the tourist transportation service is regarded as M/M/N queueing system following Kendall's notation. In this notation, the first 'M' means that the arrival process is Poisson or random process. The midst 'M' means that the service process is exponential service time. Because transportation service A-EVs are called by tourist's on demand, so arrival process is random. The rides in the amusement park have a fixed service time. However, most queue have probabilistic service time in outside of the entertainment arena [14]. And tourists can get off from the A-EV if they want anywhere in tourist spot. Thus, service process is noted as 'M'. In this environment, many A-EVs are operated to satisfy tourist's waiting time constraint. So, the number of servers is noted as 'N'.

We refer to assumptions of charging station in [15]. In the reference model, a charging station is considered as M/G/k queueing system. A-EV arrival to a charging station follows a Poisson arrival process. Hence, A-EV inter-arrival time to a charging station is Markovian and follows the exponential distribution. Charger's service time is regarded as generic service time by considering A-EV's battery capacity, initial state of charge (SoC) and requested SoC. So, charging process is general service process. Finally, some charging stations are equipped with multiple charging outlets. The number of service capacity is noted as 'k'.

C. Optimal sizing of number of A-EVs for investment minimization considering tourist's waiting time and the number of A-EVs in charging station

The optimization problem to minimize initial investment considering waiting time of service requester and the number of A-EVs in the charging station is formed as equation (1). A investment cost is determined by multiplying sum of the number of A-EVs by the unit price (noted as I_{unit}). N is suitable number of A-EVs to satisfy tourist's waiting time constraint. And L_c is the number of A-EVs in the charging station.

$$\text{minimize } I_{unit} \times (N + L_c) \quad (1)$$

$$\text{subject to } W_{s,q} \leq \varepsilon$$

Because the waiting time constraint, noted as ' ε ', is decided depending on characteristics of objective environment, the suitable values for the system must be regarded.

According to [16], process to obtain the customer's waiting time, W_q , is as followed

$$\rho_s = \frac{\lambda_s}{N\mu_s} \quad (2)$$

$$P_{s,0} = \left[\sum_{n=0}^{N-1} \frac{(N\rho_s)^n}{n!} + \frac{(N\rho_s)^N}{N!(1-\rho_s)} \right]^{-1} \quad (3)$$

$$L_{s,q} = \frac{P_{s,0} \left(\frac{\lambda_s}{\mu_s} \right)^N \rho_s}{N!(1-\rho_s)^2} \quad (4)$$

$$W_{s,q} = \frac{L_{s,q}}{\lambda_s} \quad (5)$$

In equation (2), where ρ_s is utilization of the transportation service. In equation (3), $P_{s,0}$ is a probability that there is no waiting tourist in tourist spot. And, $L_{s,q}$ of equation (4) is mean number of customers in the transportation service queue. Equation (5) means that, tourist's mean waiting time in service queue is estimated by applying little's law.

According to charging station of reference model, charging station provide charging service to randomly arrival A-EVs in generic service time. The expectation ($E[t]$) and variance ($V[t]$) of the charging time model are derived as equation (6), (7) respectively.

$$E[t] = \int_{X_{\min}}^{X_{\max}} \int_{Y_{\min}}^{Y_{\max}} \int_{Z_{\min}}^c f_X(x) f_Y(y) f_Z(z) G_1(x, y, z) dx dy dz + \int_{X_{\min}}^{X_{\max}} \int_{Y_{\min}}^{Y_{\max}} \int_c^{Z_{\max}} f_X(x) f_Y(y) f_Z(z) G_2(x, y, z) dx dy dz \quad (6)$$

$$V[t] = \int_{X_{\min}}^{X_{\max}} \int_{Y_{\min}}^{Y_{\max}} \int_{Z_{\min}}^c f_X(x) f_Y(y) f_Z(z) H_1(x, y, z) dx dy dz$$

$$+ \int_{X_{\min}}^{X_{\max}} \int_{Y_{\min}}^{Y_{\max}} \int_c^{Z_{\max}} f_X(x) f_Y(y) f_Z(z) H_2(x, y, z) dx dy dz \quad (7)$$

where

$$G_1(x, y, z) = \frac{(Z - Y) \cdot X}{P_{\max}}$$

$$G_2(x, y, z) = \frac{(c - Y) \cdot X}{P_{\max}} + \frac{(1 - c) \log(1 - c)}{P_{\max}} \cdot X - \frac{(1 - c) \log(1 - Z)}{P_{\max}} \cdot X \quad (8)$$

$$H_1(x, y, z) = (G_1(x, y, z) - E[t])^2$$

$$H_2(x, y, z) = (G_2(x, y, z) - E[t])^2 \quad (9)$$

In equation (8) and (9), X , Y and Z denote the random variables characterizing the battery capacity, the initial SoC and the requested SoC, respectively. And, these follow a truncated normal distribution (i.e. their probability density function is normal distribution). Where c is the threshold SoC value.

The mean number of A-EVs in the charging station is estimated by utilizing $E[t]$ and $V[t]$ derived from charging time t . The equation (10) through (15) express process to approximate the average number of A-EV in the charging station. As we noted above notation, utilization of the charging station is formed as bellow:

$$\rho_c = \frac{\lambda_c}{k\mu_c} \quad (10)$$

$$\text{Where } \mu_c \text{ is } \frac{1}{E[t]}.$$

For the M/M/k queue, the mean number of customers (A-EVs) in the waiting line

$$L_{c,q} = \frac{P_{c,0} \left(\frac{\lambda_c}{\mu_c} \right)^k \rho_c}{k!(1-\rho_c)^2} \quad (11)$$

Where

$$P_{c,0} = \left[\sum_{i=0}^{k-1} \frac{(k\rho_c)^i}{i!} + \frac{(k\rho_c)^k}{k!(1-\rho_c)} \right]^{-1} \quad (12)$$

$P_{c,0}$ denotes the probability that there are no A-EVs in the charging station.

The mean waiting time in the queue, $W_{c,q}^{M/M/k}$, is obtained by using $L_{c,q}$ and λ_c (little's rule). Then, for the G/G/k queue, we apply the Whitt, 1976 and Medhi, 2003 approximation for the mean queueing time using (13). Because inter-arrival time is Poisson distribution, the squared coefficient of variation of the arrival time, C_a^2 , is 1. On the other hand, the squared coefficient of variation of the service time, C_s^2 , is $\sigma_s^2 \times \left(\frac{1}{\mu_c} \right)^{-2}$, where $\sigma_s^2 = V[t]$.

$$W_{c,q}^{G/G/k} \approx W_{c,q}^{M/M/k} \cdot \frac{C_a^2 + C_s^2}{2} \quad (13)$$

Finally, we can get the mean waiting time including charging time and waiting time in the charging station by equation (14). On the same manner, the number of A-EVs in the charging station is calculated applying Little's rule.

$$W_c = W_{c,q}^{G/G/k} + \frac{1}{\mu_c} \quad (14)$$

$$L_c = \lambda_c W_c \quad (15)$$

IV. NUMERICAL ANALYSIS

In this chapter, we provide numerical analyses on optimization problem of our target environment where tour operators or investors want to introduce tourist transportation service with A-EV considering tourist's waiting time and the number of A-EVs in the charging station in tourist spot.

Each tourist spot has its sightseeing time and tourist arrival rate. Also, their charging station has its own characteristics of A-EV's average arrival rate to a charging station, charger's average service(charging) rate, and the number of charging poles. Thus, to offer transportation services in a tourist spot, parameters have to be determined properly. Hence, we perform numerical analysis with given parameters assumption. In this assumption, the average rate of requesting transportation service per particular time interval and the average rate of transportation completion to required destination during a particular time interval are given. To assume characteristics of the charging station, we reproduced $E[t]$ and $V[t]$ of our reference model with its simulation parameters and obtained $E[t]$ as 0.669 and $V[t]$ as 0.065. Because our purpose is not analysis about queueing system of charging station, so we assume that expectation and variance of charging time is given. Especially $V[t]$ is determined as 10% of the applied average charging rate. Also, each average rate of requesting transportation service per particular time interval and A-EV's average arrival rate to a charging station vary keeping its utilization factor below 1 considering its service rate and the number of servers.

In the analysis conducted on the waiting time of tourists, the relationship between the average waiting time of tourists for transportation service and utilization of transportation service on static service rate is presented in figure 4. The service rate (the average rate of transportation completion to required destination during a particular time interval) is set as 1 and the arrival rate (the average rate of requesting transportation service per particular time interval) is set suitably according to the number of A-EVs to envelope the transportation service utilization in between 0 to 1. This result shows that growth of utilization makes the average waiting time increase exponentially. Especially, when utilization approaches 1, the waiting time is getting longer. Also, arranging more A-EVs reduces the average waiting time dramatically. In the frame of the tour operator's context, they can get information of minimum number of A-EVs to provide

transportation service with in tourist's waiting time threshold. Further, they could obtain information on the extra number of A-EVs for coping peak arrival rate.

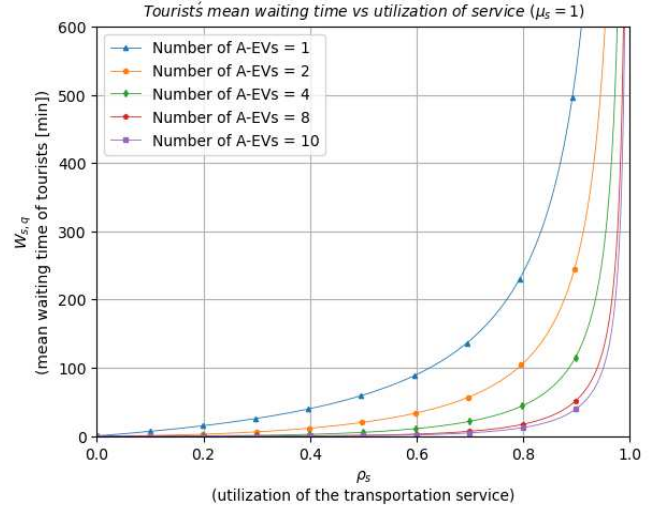
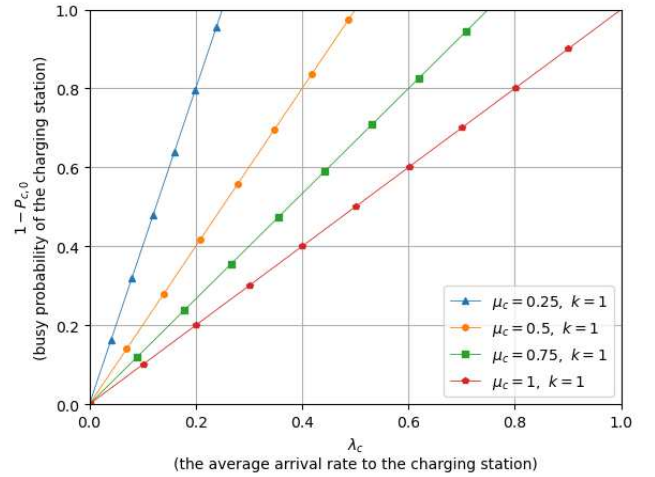
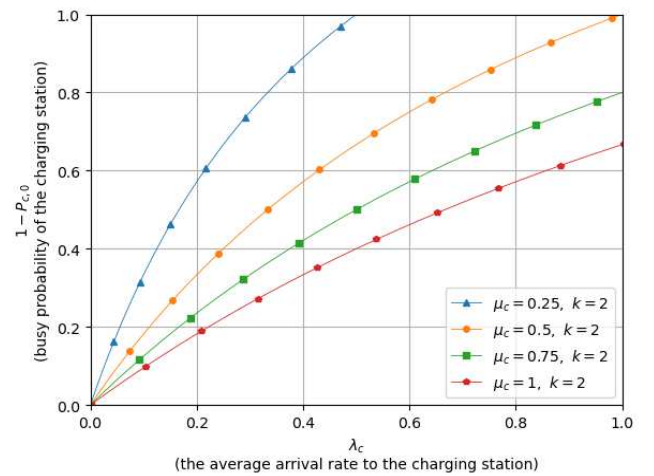


Figure 4. Mean waiting time versus utilization of service on the number of A-EVs



(a)



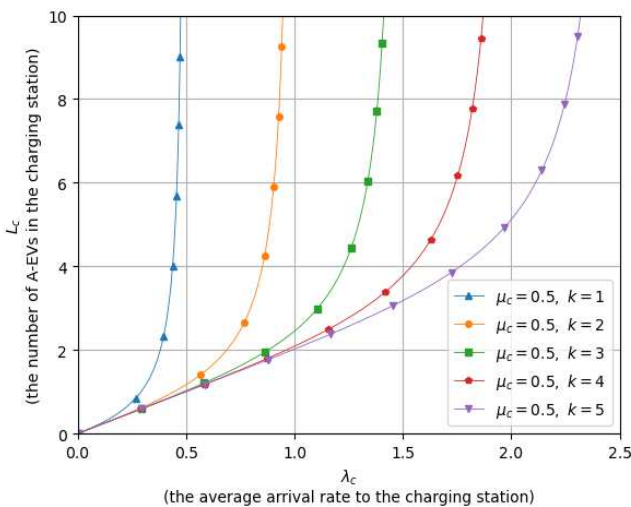
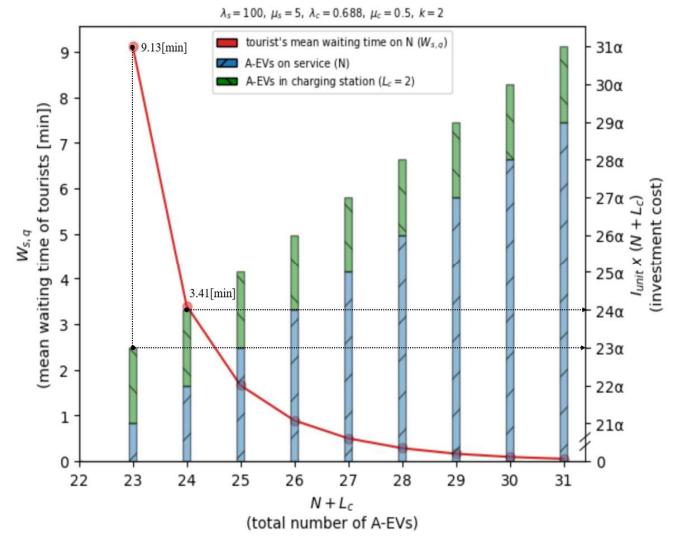
(b)

Figure 5. Busy probability of the charging station versus arrival rate to the charging station

For more detailed sizing of number of A-EVs in addition to the tourist's waiting time constraints, we estimated the number of A-EVs at the charging station through the M/G/k queuing model analysis for the charging station. Figure 5 shows the busy probability that A-EVs exist at the charging station versus various arrival rates which in different charging service rates and different number of charging poles. On the curve of the charging station's service rate at 0.25 in figure 5-(a), the charging station is busy with an 80% chance at 0.2 arrival rate to the charging station with a charging pole. By the way in figure 5-(b), an additional charging pole can reduce this probability to 60% with the same arrival rate and same service rate. The better charging performance increases idle state probability which means no A-EVs in the charging station. A high charging rate may reduce investment cost of A-EV by enhancing service availability of A-EVs which provide tourist transportation service.

Figure 6 depicts the relationship between charging station's arrival rate and the number of A-EVs in various number of charging poles with same charging rate. The arrival rate of each curve is enveloped in a range of below utilization 1 about given parameters. If A-EVs request charging frequently, the number of A-EVs in the charging station increase exponentially. When utilization of charging station closes to 1, almost every A-EV will be in the charging station. In summary, we can know that it is necessary to consider characteristic of tourist spot's charging station to reserve the number of A-EVs for providing tourist transportation service within tourist's waiting time threshold.

Sizing of number of A-EVs for providing transportation service in tourist spot is affected by characteristics of tourist spot and its charging station. These characteristics include arrival rate to it, service rate of it, and number of servers. Therefore, it is necessary to consider appropriate these values for providing transportation service within tourist's waiting time threshold.

**Figure 6.** The number of A-EVs in the charging station versus arrival rate to the charging station**Figure 7.** Investment cost on mean waiting time versus the number of A-EVs

The figure 7 indicates investment cost obtained by multiplying A-EV's unit investment cost by number of A-EVs. It's average tourist's arrival rate and average A-EV's service rate are specified as 100 requests per hour and 5 services per hour respectively. And, according to a curve which k is 2 in the figure 6, its charging station's arrival rate is set as 0.688. Therefore, the number of A-EVs in the charging station is determined as 2. In this result, if tour operators want to provide transportation service under average waiting time of 5 minutes, they need to have 24 A-EVs at least. When the unit price of A-EV is I_{unit} , their investment cost is calculated as multiplication I_{unit} by 24.

V. CONCLUSION

In automobile manufactures, Automation and sustainability are two megatrends. autonomous driving and eco-friendly mobility are not only changing the market drastically but also affecting many industries. Especially in tourism, the vehicle's automation is expected to act as 'last-mile solutions' facilitating multi-modality in transportation tourists. On the other hand, sustainable tourism is shed light on to reduce atmospheric pollution and noise causing by transport. There are many ongoing studies that optimize operation costs about sizing of number of vehicles on transportation systems with queueing analysis. However, research on initial investment cost minimization is lacking. Therefore, we suggest queueing theory-based investment cost minimization problem about adopting tourist transportation services from the perspective of tour operators or investors in the tourist spot. Also, we consider the tourist's waiting time constraint for taking this service and the number of A-EVs in the charging station. This

research may bring proliferation of AVs and EVs in tourism to the table by providing investment information. Further, it could be applied to similar circumstance or system.

Not only the tourism industry but also various industries effort to introduce AV and EV. Accommodations are participating in the EV industry by setting up charging poles. So, we will research on methods to optimize accommodations' investment cost and profit.

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