A novel method of island port's transport: Automatic guided vehicle approach

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***Abstract*—The Shanghai Yangshan Port, which is an island port with limited area, is only connected to the Shanghai's inland by Donghai Bridge whose condition cannot lay railways trucks. Meanwhile, empty-load backhaul and empty container balancing waste amount of transport resources. All these limit the port's future development and overall transport efficiency. This paper proposed a novel method that used the electric AGVs fleet to transport containers between island port and inland port (Luchao port), and reduced the empty-load transportation by using one AGV to carry an empty-load AGV. Hence, the inland port could be served as the second yard and the sea-rail intermodal hub of the Yangshan Port to promote the sea-rail combined transportation and expand the port's hinterland area. Then, exhaust emission, energy consumption and cost were analyzed. The results showed that using AGVs can reduce 50% of the total energy cost and 87% of the total CO2 emissions. Meanwhile, an AGV's total monthly costs were equivalent to a container truck when transporting 10 containers per day.**

Keywords- Island port; automatic guided vehicle; combined transport; empty-load transportation; CO2 emission;

I. INTRODUCTION

After the trial operation of the fully-automated container terminal of the Shanghai Yangshan Port in December 2017. Yangshan Port, as part of Shanghai Port, has become the world's biggest deep-water port. This terminal has boosted Shanghai port's standing as the busiest container port in the world. However, the Yangshan Port was reported to suffer a heavy congestion lasted for a month starting from the April 2017 [1]. Reasons for this severe congestion are as follows. Firstly, Yangshan Port was built on 10 percent land mass and with the remaining 90 percent as reclaimed land. Thus, limited yard areas will restrict the future development of the port. Secondly, Yangshan port is only connected to the mainland through a 31.5 kilometers cross-sea bridge—Donghai Bridge, a long, narrow speedway with 4 lanes. Cargos transported into/out of the port by land transportation must cross the sea through the Donghai Bridge. Hence, Donghai Bridge can be regarded as a bottleneck road, which was considered as one of the key factors for road congestion [2] in the port's transport networks. Meanwhile, heavy traffics and bad weather usually cause traffic accidents and congestion in the bridge [1]. Thirdly, the railway cannot be built in Donghai Bridge because of the steep slope in a 40-meters-high section which is built for ship navigation. Hence, the direct the sea-rail combined transportation, which is proved to be more cost efficient and environment friendly than road transport, is not feasible in Yangshan Port, which makes the traffic condition between the port and mainland even worse. Furthermore, as all port's transportation faced, the empty-load backhaul causes the waste of transportation resources. Meanwhile, the balancing of empty container, which is an important part of the transportation, cannot be omitted entirely, and the unbalancing of that will also cause delays in the whole logistics links.

In addition to the transport efficiency, sustainability is also significant for the port's future development [3]. Shanghai port had led to a switch from oil to electricity, and the first step was the application of "electricity instead of oil" technology to the lifting equipment [4]. Automatic Guided Vehicle (AGV), which is intelligent, high efficient and environment friendly compared to diesel truck, is used in Yangshan Port's automatic wharf transportation [5]. What' s more, with the completion of the Donghai Offshore Wind Farm which yields about 267 million Kw·h electricity annually, a cleaner energy can be provided for the Yangshan Port.

With the upgrading of the lifting equipment, some lifting equipment can lift 2 containers at the same time, in this the efficiency of vertical operation has been improved greatly. Hence, the horizontal transport efficiency has become a bottleneck that restricting the overall operation efficiency of the terminal [6]. Since AGVs' transport efficiency is critical for the productivity of the container terminal [7], many researchers studied the AGVs' dispatching [8], scheduling [9] and routing [10]. Choe et al. [11] proposed an online preference learning algorithm that dynamically adapted the policy for dispatching AGVs to change situations in an automated container terminal. Angcloudis & Bell [12] proposed a real-time scheduling method for AGVs, and the experimental results were better than the results of heuristic algorithm. In order to increase container carrier's transport efficient, the dual-load AGV which can carry two containers at a time has already been taken into consideration [13]. While, few researches focused on the technology that can decrease the waste of transport resources caused by the empty-load backhaul and empty container balancing problem.

In order to meet the requirement of building a green port, improve transport efficiency and solve the others problems of the Yanshan Port, this paper introduced a novel transportation mode by using the electric AGVs to commute between Yangshan Port and Luchao Port, which is near the other end of the Donghai bridge. In this novel mode, a AGV was connected with another AGV horizontally or carrying another empty-load AGV vertically, which was used to replace the diesel-powered trucks for transportation. Then, energy consumption and the cost were compared between using traditional container trucks and using the proposed novel transportation mode.

The rest of the paper is organized as follows: Section 2 introduces the novel transportation mode. Section 3 describes the seasonal forecasting method, the energy consumption model, the emission model and the cost model. Section 4 describes the data set and discusses the evaluation results of the exhausted emission and cost. The article is summarized in Section 5.

II. NOVEL ELECTRIC AGVS' TRANSPORTATION MODE

As shown in Fig. 1, the Luchao Port is connected with Yangshan Port by the Donghai bridge. Luchao Port has sufficient supply of the lands for container's storage, while there are limited yard areas in Yanshan Port. Hence, the Luchao Port could be served as the second yard for the Yanshan Port.

Figure 1. Study area of Yangshan Port (30.63N, 122.06E), Donghai Bridge and Luchao Port (30.88N, 121.84E), The map is from Google Map.

As the railway cannot be set in the bridge and the Luochao Port has already had a trail station, setting the Luchao Port as the sea-railway combined transportation hub for the Yanshan Port is feasible. Through Luchao Port's railway, the Yanshan Port's cargos can be transport in the lower cost and the hinterland areas can be expanded, which leads to the increase of the freight volume.

The proposed novel electric AGVs' transportation mode is as follows. The AGVs were connected into teams horizontally and pass through the Donghai Bridge to transport cargos between Yangshan Port and Luchao Port. With the merit of automatic guided and optimal path planning, the AGVs are more efficient than traditional trucks [14]. What's more, vehicles' headway could be decreased with the automatic guiding technology. Therefore, using AGVs is a good method to ease the traffic congestion and improve the efficiency in the Yangshan Port and Donghai Bridge. Meanwhile, energy consumption might be reduced as the traction and pushing effect between AGVs. The transport cost could also be decreased by saving the driving cost and reducing the energy cost. Furthermore, the connecting device can also help AGVs to remove the malfunction AGVs, so problems caused by the vehicle malfunction, such as traffic congestion and occupying the emergency lane, can be solved more quickly.

Regarding the empty-load backhaul and empty container balancing problem, this paper used an empty-load AGV to carry another empty-load AGV plus one empty container. In this way, emission and the cost of the empty-load transportation caused by the asymmetric transportation can be well reduced. Under this circumstance, an AGV loaded with an empty container is approximately to the situation of the empty-load, while an AGV loaded with another AGV is approximately to the situation of carrying a heavy-load standard container.

The abovementioned AGV combined transportation mode realizes the utilization of transport resources horizontally and vertically. It provides a new solution for building green and intelligent ports, solves the problems of yard area limitation and achieves the sea-railway combined transportation.

III. METHODOLOGY

In this paper, ARIMA model was first used to forecast the container throughput data with seasonal fluctuation characteristics. Then emission model and cost functions were introduced to evaluate this novel electric AGVs' transportation mode.

A. *ARIMA Model*

Autoregressive Integrated Moving Average Model (ARIMA) is a famous time sequence prediction method proposed by Box et al. [15], which is widely used in time series data and has high forecast accuracy. As the container throughput data introduced in this paper is time series with periodical features, this paper used ARIMA(p,d,q) (P, D, Q)s model which is used for time series with seasonal and tendency features, and it can be mathematically written by:

$$\phi_P(B^S)\cdot\varphi(B)\cdot\nabla_S^D\cdot\nabla^d\cdot x_t = \Theta_Q(B^S)\cdot\theta(B)\cdot w_t \quad (1)$$

where, p is the order of the autoregressive process. d is the order of the differencing. q is the order of the moving-average process. P is the order of the seasonal autoregressive process. D is the order of the seasonal differencing. Q is the order of the seasonal moving-average process. w_t is the non-stationary time series, w_t is the usual Gaussian white noise process, and S is the period of the time series. The ordinary autoregressive and moving average components are denoted by polynomials $\varphi(B)$and $\theta(B)$of orders p and q. The seasonal autoregressive and moving average components are $\phi_P(B^S)$ and $\Theta_Q(B^S)$ of orders of P and Q. ∇^d and ∇_S^D are ordinary and seasonal difference components. B is the backshift operator. More details and explanations on the seasonal ARIMA equations can be found in [16].

In order to obtain stationary data, this paper conducted the first-order differential to extract the trend features of the data, and then extracted periodic features by twelve-step periodic difference. The equation of the twelve-order periodic difference can be shown as follows:

$$D(TP,1,12) = \Delta(TP) - \Delta^{12}(TP) \quad (2)$$

Where, TP is the container throughputs. Δ is the first-order difference and Δ^{12} is the twelve-order difference.

B. Emission model

The energy-related emissions method (EREM), which calculated emissions from the fuel consumption which can also be used to calculate energy consumption and energy cost in next part of the paper, was introduced in this paper [17]. Meanwhile, the emissions within the semi-life cycle that include fuel combustion emission and production emission (which means "*How much CO2 emissions are generated when 1 kg of diesel is extracted, refined, and transported before it is used for freight transportation*" [18]) were calculated in this paper. The semi-life cycle EREM is calculated as follows:

$$K_j = L \cdot E_j + L \cdot P_j \quad (3)$$

Where K_j represents the type of the exhaust emissions, g, j = 1,2,3,4 represents CO, NO_x, PM, CO_2 respectively. L is the fuel consumption of the container truck, L. E_j is the combustion emission factor (see Table 1). P_j is the production emission factor, g of CO2/L (see Table 1).

The fuel consumption equation, which has a better performance of calculating trucks' emissions in a China's highway than other forms of fuel consumption equations [19], can be shown as follows:

$$L = a + b \cdot V + c \cdot V^2 + d \cdot IRI + e \cdot H \quad (4)$$

Where L is the container trucks' fuel consumption per hundred kilometers, L/100km. a, b, c, d and e are the regression parameters (see Table 1). V is the average vehicle speed, km/h. IRI is the international roughness index, m/km. H is the longitudinal slope, %, where uphill is positive and downhill is negative. Considering the symmetry of the Donghai Bridge, the slope effects can be offset.

Although there has no direct-emissions from the electric AGVs, emissions from the generation of electricity still need to be considered. Electric AGV's power consumption was calculated based on the equivalent energy method [20], and the amount of carbon emissions are calculated by emission factor method. The formula is as follows:

$$E_e = E_d / (\eta_1 \cdot \eta_2) \quad (5)$$

$$\eta_1 = E_1 / E_2 \quad (6)$$

$$E_d = L \cdot \lambda_1 \cdot \varphi_1 \cdot \eta_3 \quad (7)$$

Where E_e is the energy consumption of the AGV for 100 kilometers, MJ/100km. E_d is the energy consumption per 100 km for a diesel engine truck, MJ/100km. η_1 is the battery recycling efficiency. η_2 is the energy conversion efficiency of the electric motor. λ_1 is the density of diesel, kg/L. E_1 is the discharge power, MJ. E_2 is the charge power, MJ. L is the energy consumption per 100 kilometer of container trucks, L/100km. φ_1 is the energy per kilogram of diesel, MJ/kg. η_3 is the thermal efficiency of diesel engine.

$$K_e = \varphi_e \cdot E_e \cdot S / 360 \quad (8)$$

Where, K_e is the carbon emission of electric AGV power consumption, g. φ_e is the electricity production's carbon emission factor, g of CO2/kW·h. S is the driving distance, km.

C. Cost model

This paper mainly compared the monthly cost between AGVs and traditional container trucks. The monthly cost included energy consumption costs, labor costs and vehicle depreciation costs. The isokinetic depreciation formula was used to calculate the vehicle depreciation, and the depreciation rate was assumed to be constant. The management costs were not included in the total cost as management costs of two different transport modes were approximately equal. In practice, there are three transportation situations: heavy-load, empty-load, empty-box load. And there must have a single trip to load a container (heavy or empty) in a round trip. Meanwhile, the energy consumption of the empty-box load situation was regarded as empty-load transport situation.

The monthly costs of container truck transportation mainly included the cost of diesel consumption, the labor cost and depreciation cost. Its cost formula is as follows:

$$C_1 = L_s \cdot S \cdot (M_H + \beta_1 \cdot M_E) \cdot P_d / 100 + [P_l + (1 - Y_1) \cdot P_c / T_m] \cdot N_c \quad (9)$$

Where, C_1 is the monthly cost of container truck transportation, yuan. L_s is the container truck's oil consumption for one hundred kilometers, L/100km. S is the driving distance, km. M_H is monthly number of the transported heavy-load containers. M_E is monthly number of the empty container plus empty-load transport. β_1 is the conversion coefficient for empty-load's energy consumption. P_d is the price of the diesel, yuan/L. P_l is the salary of the driver, yuan. Y_1 is the residuals rate. T_m is the number of the months for depreciation. P_c is the original price for the vehicle, yuan. N_c is the number of the container trucks.

The monthly cost of electric AGV transportation mainly considered the cost of energy consumption and depreciation cost. Its cost formula is as follows:

$$C_2 = E_e \cdot S \cdot (M_H + \beta_1 \cdot M_E) \cdot P_e / 100 + (1 - Y_2) \cdot P_A \cdot N_A / T_m \quad (10)$$

Where, C_2 is the monthly transportation cost of the electric AGV, yuan. E_e is the power consumption of the AGV per 100 kilometers, MJ/100 km. L/100km. P_e is the electricity price, yuan/kW·h. Y_2 is the AGV's residuals rate. T_m is the number of the depreciation time. P_A is the primary price of the AGV, yuan. N_A is the number of the AGVs' motorcade.

IV. CASE STUDY

A. Data description

The container throughput data was collected form the open database of Shanghai International Port Co. Ltd [21]. A total 134-month container throughput data of Shanghai Port (homeport) from January 2007 to December 2017 was collected, which is shown in Fig. 2. The container throughputs of Yangshan port is 41% of that of Shanghai Port in 2017 [21]. As there will not be a big change for Shanghai Port's infrastructure in the next few years, this article predicted Yangshan Port's container throughputs by considering a fixed 41% of the forecasted Shanghai Port's container throughputs.

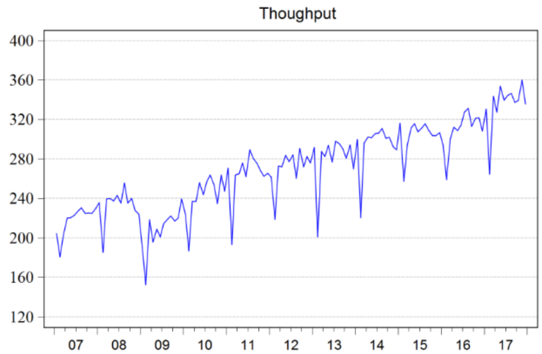

Figure 2. Shanghai Port's container throughputs

In the part of CO_2 emission, the AGV mentioned in this article has an average speed of 68 km/h, the heavy-load is 34.35 t and the empty-load is 16.2 t [22]. The distance between Yangshan Port and Luchao Port is 34 km, the Donghai Bridge's average *IRI* is 1.35. The (3)'s emission factors and (4)'s parameter regression results [19] are showed in Table 1.

TABLE I. COEFFICIENT OF FUEL EMISSION AND REGRESSION RESULTS

Combustion Emission E_j (g/L)	CO	NOx	PM	CO_2	Production Emission P_j (g/L)	CO_2
Heavy-load Truck	33.96	50.5	1.71	2468.94		247.88
Regression Results	*a*	*b*	*c*	*d*	*e*	R^2
Heavy-load Truck	165.49	-4.73	0.04	5.64	5.11	0.74

The truck in the study uses 0 # diesel, the 0 # diesel's density is 0.835 kg/L and its combustion energy is 42.652 MJ/kg. The battery recycling efficiency η_1=90%, the motor 's energy conversion efficiency η_2=90% and the diesel engine's thermal efficiency η_3=40% [23]. The Shanghai's electricity production's carbon emission factor φ_e=624.1 g of CO_2/kW·h [24].

In the part of the cost model, the 0 # diesel's price is 6.63 yuan/L in Shanghai. The salary of the truck driver is 8000 yuan per month. The truck's price is 5×10^5 yuan, its residuals rate is 5% and depreciation time are 180 months. Meanwhile, the electricity's commercial price is 0.849 yuan/kWh in Shanghai, the AGV's price is 5×10^6 yuan, its residuals rate is 10% and depreciation time are 240 months.

According to the Shanghai Port's container throughput data from 2016 to 2017 [21], the proportion of empty-box load is about 24.6%, and the average proportion of balance transport is about 3.19% which calculated through the minus between the import and export. When the truck's load increased 10 tons, the truck's fuel consumption per 100 kilometers will increase 6 L in the speed of 60 km/h [25]. In this case, according to the (4), we can obtain that the fuel consumption per 100 kilometers of the empty-load is 57% of the heavy-load.

B. Results and discussion

The sample data of the ARIMA model is from 2007 to 2016, and monthly container throughputs during 2017 were predicted. The results showed that the residual terms of the AR (1,12) and MA (1,12) models are not white noise, which mean that the information extracted by the model is insufficient. In this case, the ARMA (1,1) $(0,0,1)_{12}$ model was chosen. The results in Table 2 showed that the residuals of the model are white noise sequences, and parameters are all significant. The model is calculated as the following formula:

$$(1-B)\times(1-B^{12})\times Ln(TP)=(1+0.2772B)/(1+0.4871B)\times(1+0.8905B^{12})\varepsilon \quad (11)$$

Where, B is back operators, $B^iTP_t=TP_{t-i}$. TP is the throughputs. ε is the error terms.

TABLE II. RESULTS OF DIFFERENT ARIMA MODEL

Model	Stationarity	Adjusted R-squared	Sig.	AIC value	SC value	Res. Stationarity	Res. Q Test	Estimation Method
AR(1,12) with intercept	Steady	0.422	C	8.143	8.224	-	-	OLS
AR(1,12)	Steady	0.427	Sig.	8.124	8.178	Steady	Failed	OLS
MA(1,12) with intercept	Steady	0.506	C	8.070	8.026	-	-	OLS
MA(1,12)	Steady	0.513	Sig.	7.970	8.020	Steady	Failed	OLS
ARMA(1,1) ×$(1,0,1)_{12}$	Steady	0.720	Sar(12)	-3.580	-3.472	Steady	Pass	OLS
ARMA(1,1) ×$(0,0,1)_{12}$	Steady	0.676	Sog.	7.565	7.596	Steady	Pass	OLS

The predicted mean absolute percentage error of the 2017 throughput is 2.24%, which means that the forecasting result is reliable. In this case, the model was used to predict the data for the next three years from 2018 to 2020, shown in the Fig.3.

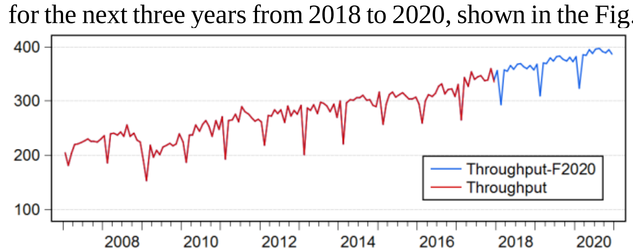

Figure 3. Prediction curve of TP from 2018 to 2020

According to (3), we can obtain the one-hundred-kilometer fuel consumption of container trucks in heavy-load and empty-load conditions, and the corresponding single trip (from Yangshan Port to Luchao Port) fuel consumption. According to the (2), the four main kinds of exhaust emissions produced by 1 L diesel were calculated, and exhaust emissions generated in a single trip were calculated. According to the (4-6), the electricity consumption per hundred kilometers of the electric AGV and the power consumption per single-trip can be obtained. In this case, the CO_2 emissions were calculated according to (7).

As shown in Fig. 4, the electric AGVs' CO_2 emission in a round trip (2 single trips) is 13% of the container trucks'. Fig. 5 shows five kinds of air pollutants produced by the container trucks, when the AGV uses clean wind power generated from the Donghai Offshore Wind Farm, the amount of emissions of CO_2, NO_x, CO, and PM reduced by AGV equals to the value produced by the container truck.

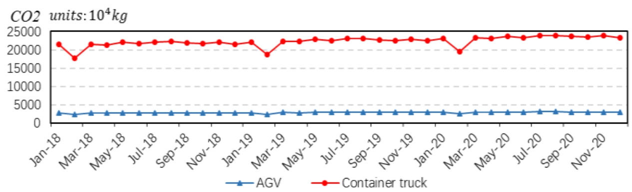

Figure 4. CO_2 emission of using electric AGVs and container trucks

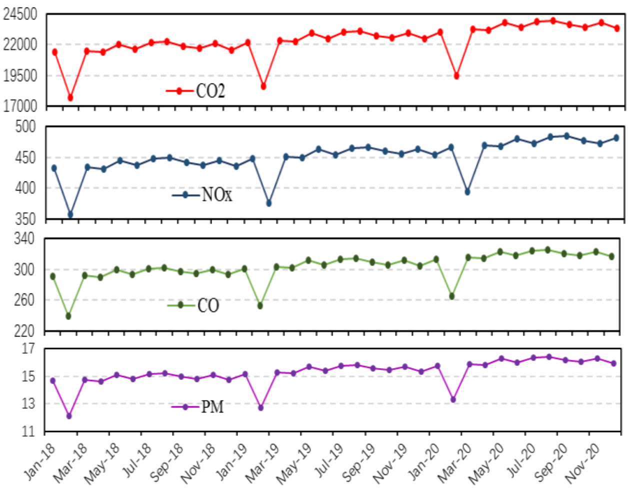

Figure 5. Emissions produced by the container truck (units:10^4kg).

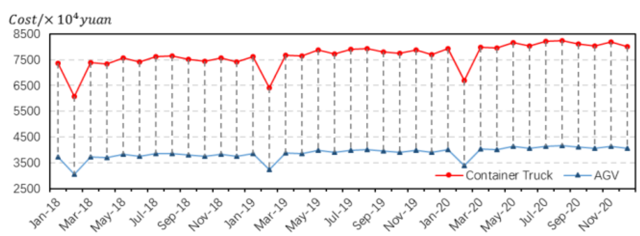

Figure 6. The monthly energy cost of container trucks and AGVs

The costs mainly include the energy cost, labor cost and depreciation cost. The area between two curves shown in Fig. 6 is the cumulative reduced energy cost. The analysis of each individual emission and cost are as follows.

- In the case of empty-load, an empty-load AGV's CO_2 emissions are 21% of an empty-load truck's. In the case of heavy load, the combined AGVs transport mode's CO_2 emissions were only 12% of container trucks'. Regarding to the empty-load backhaul, the combined transport mode that used one AGV to carry another empty-load AGV (equals to one heavy-load AGV) was compared to the situation that used two empty trucks. The results showed that the combined AGVs transport mode's CO_2 emissions were 18.45% of container trucks'.
- Regarding to the novel AGVs' transport mode, The AGVs' average annual CO_2 emissions are 3.42×10^5 kg, while, the trucks' average annual CO_2 emissions are 2.64×10^6 kg. This means that the total annual CO_2 emissions of using electric AGVs is 13% of using the container trucks. When replacing all trucks by AGVs, the annual reduction of CO_2 emissions is about 2.30×10^6 kg. When AGVs are using the electricity generated by the Donghai Offshore Wind Farm, there would be no more CO_2 emissions during the energy generation and consumption process.
- For the energy cost of a single-trip transportation, the AGV's energy cost is 50.67% of the container truck's. Regarding to the empty-load backhaul, the combined transport mode's energy costs is 44.45% of container trucks'.
- Considering the total energy cost and the depreciation cost of vehicle, the monthly depreciation cost of an AGV is about 18750 yuan, which is 1.76 times higher than the monthly depreciation cost of a truck plus the monthly salary of a driver. Considering the energy cost in heavy-load situation, the monthly total costs of an AGV are equivalent to a container truck when transporting 298 containers per month (about 10 containers per day), in this case, using AGVs to take place of the trucks is feasible in practice.

V. Conclusions

This paper presented a novel method that using AGVs to communicate between inland port (Luchao port) and island port (Yangshan Port). With the proposed combined transport mode, the electric AGVs could increase the transport efficiency and traffic safety significantly, and reduce the empty-load backhaul transportation by carrying empty-load AGV by AGV. With the electricity replace fossil fuel and without the need of drivers, the electric AGVs could reduce 87% of the total CO2 emissions, 50% of the total energy cost and operation cost comparing to trucks. Regarding to the empty-load backhaul condition, 82% of the CO2 emissions can be reduced, Meanwhile, an AGV's total monthly costs were equivalent to a container truck when transporting 10 containers per day. What's more, the electric AGVs could work in anytime and in some poor weather conditions which are not suitable for humans. Under this novel electric AGVs' transportation mode, the inland port could be used as the second yard and the sea-rail intermodal hub of the island port. In this way, more cargos would be delivered by the sea-rail combined transport mode which is more cost efficient than road transport, and the port's hinterland area would be expended.

The present study is in the interest of enterprises, government departments and researches because it provides useful insights of the new transport mode that will allow them to make informed decisions. Future studies could consider more factors in the emission models, the total emissions could be expanded into life cycle assessment considering the emissions from vehicles' manufacturing and scrapping process, and AGV's transport mode could be further improved for higher transport efficiency.

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