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Research Article

The Application Study in Solar Energy Technology for Highway Service Area: A Case Study of West Lushan Highway Low-Carbon Service Area in China

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A lot of research works have been made concerning highway service area or solar technology and acquired great achievements. However, unfortunately, few works have been made combining the two topics together of highway service areas and solar energy saving to make a systemic research on solar technology application for highway service area. In this paper, taking West Lushan highway low-carbon service area in Jiangxi Province of China as the case study, the advantages, technical principles, and application methods of solar energy technology for highway service area including solar photoelectric technology and solar water heating technology were discussed based on the analysis of characteristics of highway low-carbon service area; the system types, operation mode, and installing tilt angle of the two kinds of solar systems suitable for highway service areas were confirmed. It was proved that the reduction of the cost by electricity savings of solar system was huge. Taking the investment of the solar systems into account, the payback period of solar photoelectric systems and solar water heating systems was calculated. The economic effect of the solar systems in West Lushan highway service area during the effective operation periods was also calculated and proved very considerable.

1. Introduction

As the renewable and clean energy, solar energy will not cause environmental pollution that is produced by traditional energy like coal, oil, and other fossil fuels during the using process. Development and utilization of green energy are one of the most important energy saving measures. During the past 30 years, many developed industrial countries and some developing countries have attached great importance to the development of solar technology and solar technology has been widely promoted and used in residential areas. The pace of research and application of solar energy in Europe is also very fast and the use of solar heat is more extensive, involving power generation, domestic hot water, heating, local heating water, and so forth. More than 90% of the solar heat is used for residential areas in the EU [1].

China began to use solar energy early in the 1970s, achieving good results in the beacon lights. In the 1990s, solar photovoltaic technology began to be used in road lighting and signals and solar water heating system entered the rural residential areas under the support of China government by the late 20th century. In the 21st century, solar photovoltaic technology has been greatly promoted by the growing attention of government and the improvement of solar cell production technology, meanwhile solar energy applications field also expanded gradually.

Nowadays, solar technology is gradually extended to highway traffic field with the introduction of new traffic lighting devices like solar traffic lights, solar orientation lights, solar street lamps, and so forth. However, few solar energy technologies have been used in highway service area in China. As the basic infrastructure serving for vehicles and passengers, the overall function of highway service area determines the quality and efficiency and the economic benefits of the service. Because of the far location away from urban areas, generally highway service areas have few external energy sources to use, while also consuming more energy. It is relatively closed and independent system. The closeness and independence of highway service area determines its dependence and pressure on resources and environment. The application of solar technology in the construction of highway service area could not only alleviate the scarcity of resources, reduce energy consumption, and improve efficiency of resource and energy, but also reduce environmental pollution, maintain ecological balance, improve highway operational efficiency, and optimize the service quality.

The extensive researches on highway service area began aboard in the early 1990s. American Association of State Highway and Transportation (AASHTO) published the third edition of "expressway service construction guide" in 2001, which stressed the application of green building technology from the aspects of domestic sewage, garbage, and so forth. The studies in the field of highway service facilities in Japan defined the planning layout, architectural forms, design principles, and so on comprehensively, clearly, and in detail. According to "Japan Highway Design Manual" of 1980 version, the design essentials of service rest facilities were defined. The technical standards and design methods of highway new rest facilities are made in "Japanese highway design essentials" in 1991 from more comprehensive aspects. The researches on highway service area were launched relatively late in China. The function, size, and technical requirements of service facilities were simply regulated in "Technical Standards of Highway Construction (JTG B01-2003)" [2], without involving the energy saving technology. Hui and Liu [3] analyzed the space size and parking capacity of highway rest facilities according to the field survey data and theoretical calculations for Shenda Highway service area in Northeast China. Luo [4] made a study in the function, location, spacing control, and architectural design requirements of highway service. Wu [5] proposed the biological disposal method of highway service area sewerage for vegetation watering and toilet flushing. Yang [6] discussed the economic effects of biological contact oxidation treatment technology using highway service area sewage disposal. It could be seen that the researches on highway service area in China focused mainly on the layout and scale of the facilities, the operation way, water supply and sewage treatment, and so forth but few on energy saving technology.

In the meanwhile, many researches were made on the economic effect assessment of solar technology. Maria and Marano [7] discussed the economic analysis methods of solar photovoltaic systems under different climatic conditions and pointed out that the economic analysis methods were related to local policy as well as technical level and climatic conditions. Schröder and Reddemann [8] made an analysis in the economic influence of hot water consumption and energy efficiency on solar collectors in different months and climatic conditions in terms of the German federal government's economic conditions. Zilla and Abraham [9] proved that the economic effects became better with the increase of useful life period, fuel prices, and market demand based on the establishment of a model for the economic practicability of solar hot water systems and also concluded that the effect of series solar collectors is better than that of parallel collectors. Hawlader et al. [10] made the economic evaluation for solar heating water system by using different variables and concluded that the designed collector area is 1000 m^2 for best payback period and internal rate of return. Yi [11] made an analysis in the energy consumption constitution and energy saving way for residential building. It can be seen that solar technology brings very considerable economic benefits as well as reducing environmental pollution.

In summary, a lot of research works have been made related to the two fields of highway service area and solar technology and acquired great achievement. However, unfortunately, few works were made combining the two topics together of highway services and solar energy saving to make a systemic research on solar technology in green highway service area due to the design and construction of the service mainly undertaken by the transport authorities, coupled with the faraway location of the service and its subordinate position in the highway system. In this context, it is quite necessary and urgent for launching the research on solar technology and economic effects of highway service area to promote low-carbon highway service area development and guide solar engineering practice.

2. Objectives

The main objectives of this paper were as follows:

(1) confirming the applicability and advantages of solar technology for highway service;

(2) choosing the suitable type and the best tilt angle of solar photovoltaic system for highway service area based on the location and local climate conditions;

(3) choosing the suitable operation type of solar water heating system, suitable type, and the best installing angle of collectors for highway service area;

(4) calculating the economic effects and environmental effects of solar technologies on highway service area.

3. Methods

3.1. The General Situation of Low-Carbon Highway Service Area. In recent years, with the development of green transportation ideas in China the concept of low-carbon highway service area has been proposed and people are increasingly concerned about the comfort and green level of the service area. Low-carbon highway services generally refer to the services which integrate various measures throughout the entire life cycle of planning, designing, construction, operation, and management to maximize saving resources, protect environment, reduce pollution, and provide people with a safe, healthy, comfortable, and efficient highway service area based on the principle of the virtuous circle of ecosystem in design conception and construction practice. Some highway service areas have begun to employ different energy saving technologies to try establishing low-carbon service areas in China. Green building and clean energy technologies have

FIGURE 1: The aerial view of Lushan highway service area.

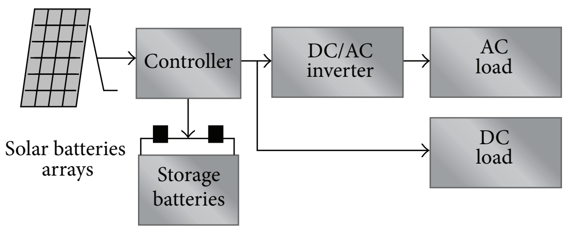

FIGURE 2: The diagrammatic sketch of solar photoelectric technology.

been used in a small number of service areas and achieved good effects [12].

In this paper, utilization technologies and methods of solar photoelectric and water heating technology for highway service area were analyzed according to the natural geographical and climatic conditions of West Lushan scenic area, which would achieve effective operational cost reductions and good energy saving effects.

West Lushan highway is located in northern Lushan Scenic Area in Jiangxi Province of China, with the extremely rich and natural landscape resources along and it is the highway with the highest environmental protection requirements in Jiangxi as seen in Figure 1. The location of West Lushan highway service area is in the southern region and has rich solar energy resources with 4494.35 MJ/m^2 (horizontal) annual radiation and 1700.7 sunshine hours. In the construction of West Lushan service area, solar energy technologies are fully made in use in order to maximize energy savings and environment protection.

3.2. Solar Photoelectric Technology for Highway Service Area

3.2.1. Technical Principles and Constitution. Solar photoelectric technology is based on the photoelectric effect, through the using of solar cells to convert solar energy directly into electricity, as shown in Figure 2. There are two main types of solar photovoltaic systems: independent photovoltaic power generation and grid-connected photovoltaic power generation.

Photovoltaic power generation system consists of three major components of solar panels, controller, and inverter. Solar panel is the core part of the system and its role is to convert solar radiation to electrical energy stored in batteries or generated. Solar controller is to control the working status of the entire system and make an overcharge or overdischarge protection for battery [13]. The role of the inverter is to convert DC (direct current) solar power into AC (alternating current) power, directly transmitting 12 VDC, 24 VDC, and 48 VDC solar energy to provide 220 VAC electrical power [14].

3.2.2. Advantages of Solar Photovoltaic (PV) System for Highway Service Area. They are as follows

(1) small size, light weight, and small occupational space like building integrated photovoltaic (BIPV);

(2) long useful life period: the life of PV systems can reach 20 to 50 years;

(3) zero pollution emissions: PV consumes no fuel with no noise and no pollution to the service area;

(4) power generation without water: PV systems can be applied for highway service area in the uninhabited areas.

3.2.3. The Selection of Solar Photovoltaic System Type for Highway Service Area. Highway service area is usually to use independent photovoltaic systems, with the appropriate choice of voltage levels and the number of phases in accordance with electricity requirements, as shown in Table 1 [15].

3.2.4. The Determination of the Tilt Angle of Solar Photovoltaic Systems for Highway Service Area. In the photovoltaic system, the solar radiation received by PV arrays differs according to its tilt angle. For a fixed PV array, if the designed inclined plane is not rational, there may be a waste of more solar modules to meet the power or causes of the unreasonable capacity of battery, which makes the cost of the entire system higher. For determining the best angle of PV arrays, the nature of the load, local weather, and geographical conditions should be taken into account. There are three kinds of load of PV systems including balanced, seasonal, and temporary load. Balanced load refers to the daily electricity for production and life. Air conditioning is the seasonal load and temporary load is generally for the unexpected emergency electrical events. In general, the tilt angle of PV system is determined by application amount of the balanced load and the specific load condition should also be considered. The basic principle is to reach the best tilt angle, reduce the instability of the solar radiation throughout the year, and make the solar radiation amount more evenly for the entire year received by inclined planes.

Research [15] has showed that the designed installing tilt angle of photovoltaic panels equals the local latitude $\pm 15^{\circ}$. Considering the average amount of electricity use throughout the year, the tilt angle = local latitude; considering the amount of electricity use in summer months (April to September), the tilt angle = local latitude $- 15^{\circ}$; considering the amount of electricity use in winter months (October to March), the tilt angle = local latitude $+ 15^{\circ}$. And the specific azimuth and tilt angle should be considered together for the actual situation of the buildings in service areas.

Table 1: Design and selection of solar photovoltaic system.

System type	Type of current	Whether it has the energy storage device	Application scope
Stand-alone photovoltaic system	Direct current (DC)	Yes	Remote areas with no power, DC power load equipment, and high power continuity requirements for power supply
		No	Remote areas with no power, DC power load equipment, and no continuity requirements for power supply
	Alternating current (AC)	Yes	Remote areas with no power, AC power load equipment, and high power continuity requirements for power supply
		No	Remote areas with no power, AC power load equipment, and no continuity requirements for power supply

3.3. Solar Water Heating Technology for Highway Service Area

3.3.1. Technical Principles and Characteristics. Solar heating water system is the system converting solar radiation into thermal energy to heat water and delivering to each user and typically includes a solar collector, heat storage, circulation pumps, pipe connections, brackets, and other components. The system constitutional diagram is shown in Figure 3.

There are three types of solar water heating system including natural circulation systems, DC systems, and forced circulation system. According to the presence or absence of heat exchanger, solar water heating systems are divided into two types of direct and indirect systems. According to hot water providing range, solar water heating systems are divided into three types of centralized heating water systems, centralized-decentralized heating water systems and decentralized water heating systems.

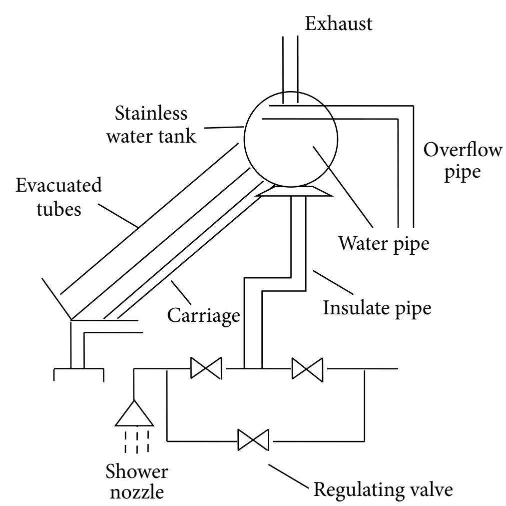

Figure 3: The constitutional diagram of solar heating water system.

3.3.2. The Selection of Solar Water Heating Systems for Service. Separation system is preferred from architectural aesthetic considerations; indirect system is preferred from water sanitation considerations; from water and energy saving considerations, the insulation measures must be taken into account according to the different forms of buildings.

Solar heating water system operation mode generally is determined by the user basic conditions, the relative needs of the user, the installation location of collector and storage tank, and other factors [16]. The recommended mode is shown in Table 2. The type of collector is based on the operation time of solar heating water system, the minimum temperature, and other factors.

By the comparison of flat plate collector and evacuated tubular collector, it can be seen that the economical efficiency, operation environment, useful life period, and stability of evacuated tube collector are all better than those of flat plate solar collector. Therefore all-glass evacuated tube collector is preferred for highway service. Solar water heating system should be installed in residential buildings, shower room, kitchen, and other building roofs or exterior for providing hot water for the service areas. The area of solar collector should also be designed based on the demand of hot water. When collector is installed on the roof, the designed tilt angle of collector is based on local solar elevation angle and the general criterion for the optimum tilt angle of solar collector is the local latitude plus 10 degrees [16].

4. Results

4.1. The Application of Solar Photovoltaic Technology for Highway Service Area

4.1.1. Location and System Selection. The solar photovoltaic systems in West Lushan service were installed on the Northeast logistics building floor roof terrace, with the capacity of 20.24 kWp, medium-sized photovoltaic systems. In terms of the natural and geographical conditions and the demand for electricity of West Lushan service area, the independent DC with energy storage device solar photovoltaic power generation system was chosen as seen in Figures 5 and 6.

Table 2: The comparison of recommended operating mode of solar heating water system for highway service area.

Operating conditions	Operating mode		
	Natural circulation	Direct circulation	Forced circulation
Instability water pressure	Available	Unavailable (1)	Available
Insufficient power supply	Available	Unavailable (2)	Unavailable (3)
Instant hot water	Unavailable	Available	Unavailable
The relative installation location of collector and storage tank			
High collector	Unavailable	Available	Available
High storage tank	Available	Available	Available
Operating temperature			
Above 0°C	Available	Available	Available
Below 0°C	Available with antifreezing measures		

(1) Available with thermostat control pump.
(2) Available with thermostatic valve.
(3) Available with DC pump under photoelectric cell.

Figure 4: The solar panels of solar photovoltaic systems in West Lushan highway service area.

Figure 5: The solar controller of solar photovoltaic systems in West Lushan highway service area.

4.1.2. The Determination of Solar Panel Type and Installing Angle. The model of solar panel was S-220D (230 Wp), a total of 88 with a 220 V, 100 A solar controller as well as a 220 VDC/220 VAC 5 kVA separate inverter, which could meet the power supply for 3 consecutive rainy days as shown in Figure 4.

Considering the average amount of electricity use throughout the year, the tilt angle equalled the local latitude. The local latitude of West Lushan was 28.67 degrees, so the tilt angle was set as 28 degrees.

Figure 6: Solar photovoltaic power generation storage batteries of solar photovoltaic systems in West Lushan highway service area.

4.2. The Application of Solar Water Heating Technology for Highway Service Area

4.2.1. Selection of System Type and Installing Angle. Solar water heating systems were installed in the buildings of West Lushan highway service area for hand washing, showers, and other hot water needs like Lushan West Visitor Centre, dining lounge, logistics building, service stations, and maintenance station.

The direct system was chosen and the control mode was set with three modes of constant temperature control, difference temperature control, and timing control by freedom choice. The operation mode was forced circulation and the collector type was evacuated tubular collector based on the comparison analysis of flat plate collector and evacuated tubular collector for highway service area, as illustrated in Table 3.

According to the local solar elevation angle, the tilt angle of solar collector was the local latitude plus 10 degrees, which was 38 degrees.

Table 3: The comparison of flat plate collector and evacuated tubular collector for highway service area.

Features	Flat plate solar collector	Evacuated tubular solar collector
System efficiency	About 50% (summer) About 20% (winter)	About 50% (summer) About 40% (winter)
Useful life period	5 years	15 years
Operation temperature	Above 0°C	Above −40°C
Manufacturing cost	Low	Low
Key component efficiency	Fast heat absorption and fast heat release	Fast heat absorption and slow heat release
Efficiency in wet or rainy day	Low	High

Table 4: List of installed solar collectors in West Lushan highway service area.

Installation location	Visitor centre	Dining lounge	Logistics building	Service station	Maintenance station	Total
Number of collectors	64	24	48	24	1	161
Size (each piece)			15 × Φ47 × 1500 mm			
Collecting area (m^2)	120	45	90	45	1.875	301.875

4.2.2. The Solar Collector Installation Condition. The solar collector installation condition in West Lushan highway service area was shown in Table 4.

4.3. Economic Effects Analysis of Solar Energy Technology in West Lushan Highway Low-Carbon Service

4.3.1. The Power Generation Capacity of Solar Photovoltaic System. We can get the power generation capacity of solar photovoltaic system in West Lushan highway low-carbon service according to the following formula [17]:

$$G_{pv} = A_c \cdot J_r \cdot T \cdot n_b \cdot n_s, \quad (1)$$

where A_c is the effective area of photovoltaic cells m^2, J_r is the solar radiation intensity under the best tilt angle per year kw/m^2, T is the effective hours of sunshine per year h, n_b is the component efficiency, and n_s is the system efficiency.

The parameters of solar water photovoltaic system in West Lushan service were as follows: the effective area of photovoltaic cells was about 140 m^2 in terms of the capacity of 20.24 kWp; the solar radiation intensity per year under the best tilt angle 28 degrees in West Lushan district was 1330 kw/m^2; The effective hours of sunshine per year was 1700.7; the component efficiency of silicon battery was generally set 15%; and the system efficiency was generally set 75%.

So the power generation capacity of solar photovoltaic system per year in West Lushan highway low-carbon service was 35625.41 kW·h.

4.3.2. Energy Saving Capacity of Solar Water Heating System. The total collecting area of solar water heating system in West Lushan highway service area was 301.875 m^2, which was calculated in terms of the following formula:

$$\Delta Q_{\text{save}} = A_c \cdot J_t \cdot (1 - \eta_c) \cdot \eta_{cd}, \quad (2)$$

where A_c is the solar collecting area of direct system m^2, J_t is the solar radiation of collecting surface per year MJ/m^2, η_c is the heat loss of pipeline and water tank, η_{cd} is the thermal efficiency in full daytime of solar collector %, and d is the number of days.

The parameters of solar water heating system in West Lushan service were as follows: the total solar collecting area in the service A_c was 301.875 m^2, solar radiation per year J_t was 4494.35 MJ/m^2, set η_c was 0.1, and set η_{cd} was 0.5.

So the amount of saving energy of solar water heating system in West Lushan service per year was 610530 MJ.

If the energy was generated by electricity heating, the consuming electricity was determined in terms of the following formula:

$$G = \frac{\Delta Q_{\text{save}}}{n_d q_0}, \quad (3)$$

where n_d is the efficiency of electricity heating and q_0 is the calorific value of electricity kJ/kW·h.

Generally, n_d is 0.9 and q_0 is 3595 kJ/kW·h.

So the electricity saving by the energy saving of solar water heating system per year is 188697.26 kW·h.

4.3.3. Economic Profit of Solar Energy Technology in West Lushan Highway Low-Carbon Service. Taking the investment of the solar water heating systems into account, the payback period of the investment of solar system was calculated according to the following formula:

$$T = \frac{y}{n_0}, \quad (4)$$

where Y is the investment of the system and n_0 is the cost saving of the system.

According to the current electricity price of 0.60 RMB/kW·h in Jiangxi Province, the reduction of the cost by electricity savings of solar photovoltaic system in West Lushan highway service area was 21.38 thousand RMB per year. The cost of solar photovoltaic system per square meter was around 1300 RMB, so the total investment of solar photovoltaic system was 182 thousand RMB. Therefore, the payback period of the investment of solar photovoltaic system was 8.5 years. As we know the useful life period of solar photovoltaic system was at least 25 years, so economic profits of solar photovoltaic system were relatively high.

Taking 25 years as the effective operation period, the economic profit of the solar photovoltaic system in West Lushan highway service area would reach 352.5 thousand RMB.

The reduction of the cost by electricity savings of solar water heating system in West Lushan highway service area was 113.22 thousand RMB according to the current electricity price of 0.60 RMB/kW·h in Jiangxi Province. Because one piece of solar evacuated tubular collector was about 4000 RMB, the total investment of 161 pieces of solar evacuated tubular collector was 644 thousand RMB. Therefore, the payback period of the investment of solar water heating system was 5.69 years. As we know the useful life period of solar photovoltaic system was at least 15 years, so economic profits of solar photovoltaic system were very high.

Taking 15 years as the operation period, the economic profit of the solar photovoltaic system in West Lushan highway service area would reach 1.05 million RMB.

4.4. Environmental Benefits Analysis of Solar Energy Technology in West Lushan Highway Low-Carbon Service. The statistics from National Development and Reform Commission of China reveals that every saving of 1 kwh electricity equaled the consumption of 0.4 kg standard coal and also equaled a decrease of standard coal combustion producing 0.997 kg carbon dioxide (CO_2), 0.03 kg sulfur dioxide (SO_2), 0.015 kg nitrogen oxides (NO_x), 0.272 kg smoke, and other pollutants.

The energy saving of the solar technology in West Lushan highway service area equaled the reduction of 89.73 tons standard coal, also 233.65 tons CO_2, 6.73 tons SO_2, 3.36 tons NO_x, and 61.02 tons smoke. It could be seen that the solar technology of West Lushan highway service area would make great contributions to the reduction of environment pollution.

5. Conclusion

(1) The closeness and independence of highway service area determined its dependence and pressure on resources and environment. The application of solar technology for highway service area could not only reduce energy consumption and improve energy efficiency, but also reduce air pollution and protect ecological environment.

(2) Solar photovoltaic (PV) system was quite suitable for highway service area based on its advantages of small size and occupational room, long useful life period, zero pollution emissions, and generation of power without water.

(3) Based on the comparison analysis of solar photovoltaic systems and the natural and geographical conditions of West Lushan in Jiangxi Province, independent photovoltaic system with energy storage device was chosen for West Lushan highway service. And considering the average amount of electricity use throughout the year, the tilt angle of solar panel equalled the local latitude, set as 28 degrees according to the local latitude of West Lushan of 28.67 degrees.

(4) It was proved that evacuated tubular collector and the operation mode of forced circulation were preferred for West Lushan highway service area by the comparison analysis. The selection of designed tilt angle of collector was based on local solar elevation angle and the tilt angle of solar collector in West Lushan highway service area was the local latitude plus 10 degrees, which was 38 degrees.

(5) The power generation capacity of solar photovoltaic system per year in West Lushan highway low-carbon service was 35625.41 kW·h by calculation analysis. The reduction of the cost by electricity savings of solar photovoltaic system in West Lushan highway service area was 21.38 thousand RMB per year according to the current electricity price of 0.60 RMB/kW·h in Jiangxi Province.

Taking the investment of the solar water heating systems into account, the payback period of the investment of solar photovoltaic system was 8.5 years.

Taking 25 years as the effective operation period, the economic benefits of the solar photovoltaic system in West Lushan highway service area would reach 352.5 thousand RMB.

(6) The electricity saving by the saving energy of solar water heating system per year was 188697.26 kW·h. The reduction of the cost by electricity savings of solar water heating system in West Lushan highway service area was 113.22 thousand RMB per year.

Taking the investment into account, the payback period of the investment of solar water heating system was 5.69 years.

Taking 15 years as the operation period, the economic effect of the solar photovoltaic system in West Lushan highway service area would reach 1.05 million RMB.

(7) The energy saving of the solar technology in West Lushan highway service area equalled the reduction of 89.73 tons standard coal, also 233.65 tons CO_2, 6.73 tons SO_2, 3.36 tons NO_x, and 61.02 tons smoke. It could be seen that the solar technology of West Lushan highway service area would make great contributions to the reduction of environment pollution.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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