Sustainable mobility as a climate adaptation response in protected world heritage areas using Perception of Outstanding Universal Value: The Case of Cosmological Axis of Yogyakarta Indonesia

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Abstract. The Cosmological Axis of Yogyakarta was designated as a UNESCO World Heritage Site in 2023, highlighting its Outstanding Universal Value (OUV). However, rapid urbanization and increased vehicle emissions threaten the area's cultural and environmental sustainability. This study aims to address these challenges by evaluating perceptions of sustainable mobility solutions and their alignment with OUV requirements. Using geospatial analysis, emission modeling, and stakeholder surveys, the research identifies critical traffic patterns and emission hotspots. The findings reveal that while most areas maintain acceptable air quality, zones with high congestion require targeted interventions. The proposed recommendations include enhancing public transportation with low-emission vehicles, expanding pedestrian and cycling infrastructure, and implementing low-emission zones. These measures aim to preserve the cultural and ecological integrity of the Cosmological Axis while fostering environmental and social well-being. This study contributes to sustainable heritage management by providing actionable insights for urban planners and policymakers in managing World Heritage Sites under the pressures of climate adaptation.

1 Introduction

The Cosmological Axis of Yogyakarta (Fig. 1) has been designated as a World Cultural Heritage site (World Heritage Site - WHS) by UNESCO in 2023, according to dossier 1671r 1671 [1]. This recognition has the consequence that the area's management must pay attention to the sustainability of the outstanding universal value (OUV). One form of area management is managing the transportation system and spatial patterns (infrastructure) to protect the OUV. Meanwhile, the Cosmological Axis Area is faced with the problem of congestion due

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to the high growth of private vehicles [2] and the lack of controlled infrastructure growth [3], so transportation movement pattern management is needed that is by the needs of maintaining OUV. OUV can be maintained by attention to the area's traffic movement patterns (transportation systems) and spatial patterns. Transportation and spatial patterns can have a negative impact on the surrounding environment if not controlled.

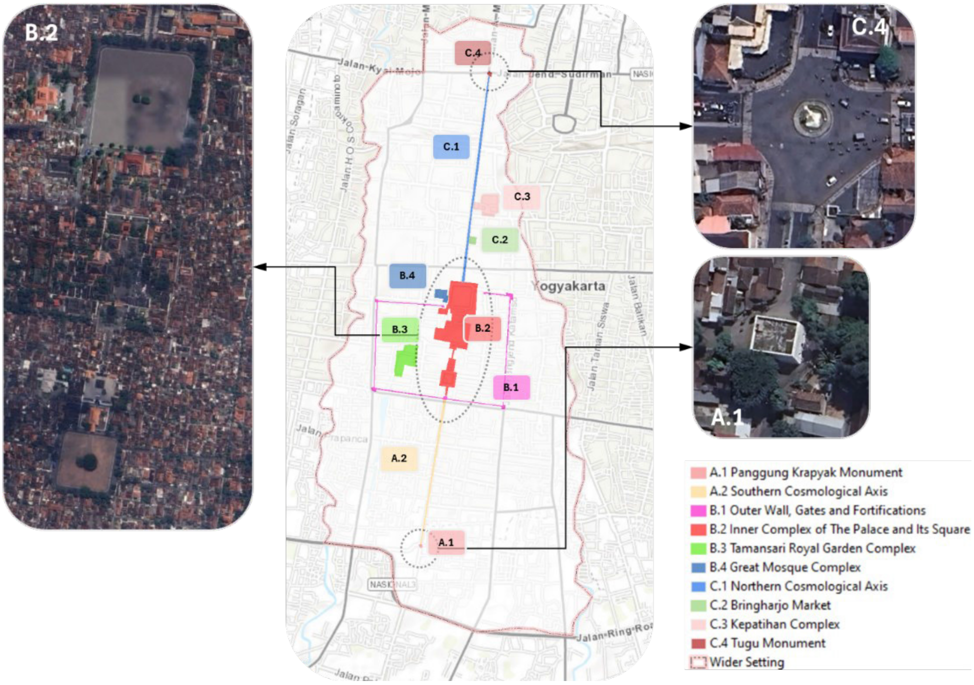


Fig. 1 Cosmological Axis of Yogyakarta area

WHS management must pay attention to OUV [4,5], included in its transportation management, especially land transportation [6]. OUV wants to maintain traditional modes of transportation (pedicabs and andong/dokar) which are low-speed means of transportation. Meanwhile, on the other hand, there is a high growth in vehicle ownership, more than 7% per year [7], that requires enough wiggle room. However, this movement will be hampered by the existence of traditional modes (traffic barriers) which are part of the interest of maintaining the OUV. High traffic growth at WHS is also feared to disrupt OUV.

The management of World Heritage Sites (WHS) under sustainable mobility frameworks has been widely explored. Hazen (2008) discussed the complexities of balancing development and sustainability in WHS, emphasizing the need to maintain OUV while addressing urbanization challenges [5]. Similarly, Gurira and Ngulube (2016) analyzed the use of contingent valuation in assessing sustainable tourism and conservation strategies at Great Zimbabwe, highlighting the role of sustainable transportation in preserving cultural heritage [4]. Falk and Hagsten (2024) investigated ambiguous factors impacting WHS management, revealing that traditional transportation modes often conflict with modern demands for efficiency [6]. Furthermore, Bajracharya and Bajracharya (2013) presented scenario analyses of transportation energy consumption and greenhouse gas emissions, stressing the importance of low-emission mobility in reducing environmental impacts on WHS [8]. In the context of Indonesia, Kresnanto and Putri (2024) explored subsidies for electric vehicles, offering evidence of their role in promoting green transportation in Yogyakarta [9]. These studies underline the critical role of sustainable transportation policies and practices in balancing conservation and development, providing a foundation for this research on the Cosmological Axis of Yogyakarta.

Using a sustainable mobility approach is the best approach in transportation management that can maintain the Outstanding Universal Value (OUV) of the Cosmological Axis of Yogyakarta City. This approach emphasizes the integration of environmentally friendly, efficient, and inclusive transportation to reduce negative impacts on the environment and maintain the area's cultural characteristics and historical values. Through sustainable mobility, using reliable public transportation, comfortable pedestrian paths, and adequate cycling infrastructure can encourage people to switch from private vehicles to more sustainable modes of transportation [10–12]. Thus, the sustainability of the universal value of the Philosophical Axis of Yogyakarta City can be maintained, along with improving air quality, reducing congestion, and improving the quality of life of the local community.

This paper will discuss and provide recommendations on sustainable transportation management with a sustainable mobility approach in the Cosmological Axis of Yogyakarta City that can reduce environmental impacts and help protect OUV. This research result's contribution is important in helping the DIY government manage cultural heritage recognized as a world cultural heritage.

2 Sustainable mobility as a climate adaptation

Transportation has a significant relationship with sustainability, especially in urban areas [13]. The global contribution of the transportation sector to GHG emissions of approximately 15% - 16,2 % [14] raises many concerns about reducing GHG contributions and pushing transportation initiatives towards sustainability. Transportation is vital in driving the urban economy as a medium that facilitates people's movement in meeting their daily needs. This linkage has consequences for the complexity of transportation arrangements. In the context of this article, the Cosmological Axis of Yogyakarta, Indonesia, is located in the heart of the city, is the economic centre of the city, and is also a busy transportation route. Apart from being located in a densely populated area, this area is also designated as a protected World Heritage by UNESCO, based on the Perception of Outstanding Universal Value. One of the consequences of establishing a protected World Heritage Area by UNESCO is the implementation of sustainable mobility, the main aim of which is to significantly reduce carbon emissions and pollution, to reduce and prevent damage to world-historic assets in the form of historic buildings, areas, including ecological and anthropological communities.

Sustainable mobility have three key element to support sustainable development goals; decarbonizing the transport system, promoting low-emission mobility solutions, and transitioning to renewable and alternative fuels [15]. In order to support the requirements from UNESCO in Cosmological Axis of Yogyakarta, Indonesia, promoting low-emission mobility solutions is the one of element of sustainable mobility that have greater probability to chosen compare with another element. In order to encourage the promotion of low-emission mobility at this location, several critical stages are needed, including an inventory of potential carbon emissions that can be captured through the volume of vehicles passing through the Cosmological Axis of Yogyakarta location and strengthened by the results of previous research on carbon emissions [8], which aims to increase the level awareness about threats to assets in the World Heritage Area caused by carbon emissions. For the initial stage, the calculation of potential carbon emissions can be assumed to use the conversion of medium car type vehicle emissions to gasoline fuel, the largest population currently passing through the Cosmological Axis of the Yogyakarta location.

In the next stage, the changes in human behaviour, such as increased use of low-emission transportation and reduced reliance on single-occupancy vehicles, should also be addressed after calculation. Human behaviour now plays a large and essential role in the behaviour of the overall climate system [14], so the choices of low-emission mobility solutions have to be internalized in society's mindset. One of the initiatives that depicted travel behaviour was transport sharing. Transport sharing is an alternative, although several studies [16–18] have found it to be not effective enough in supporting the goal of low-emission mobility. This is a pressing issue, as it requires better multimodal infrastructure [16].

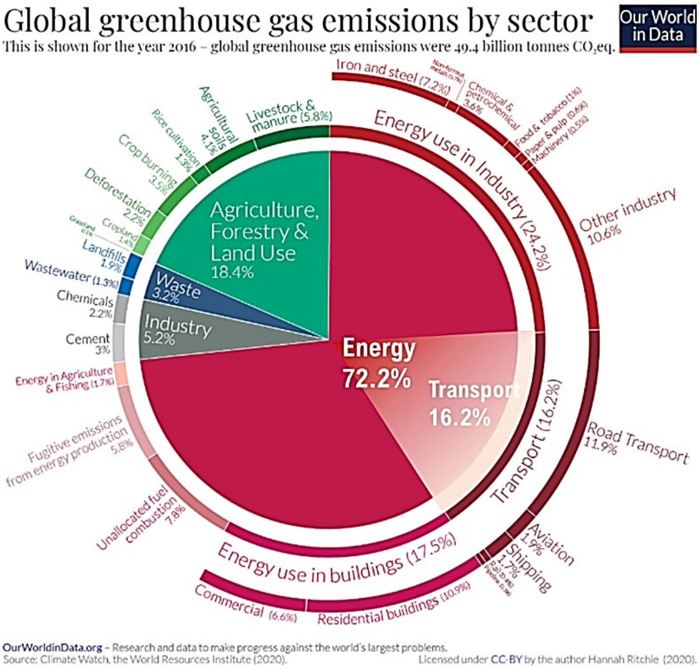
Furthermore, the crucial step that should be followed up is preparing transport policies. These policies are not just guidelines but a powerful catalyst in shaping the mobility transition, particularly in developing countries. A study in Pakistan shows that policies play a crucial role in managing multidimensional low-emission mobility transitions using compressed natural gas/CNG [19]. Transport policies play a crucial role in fostering environmental sustainability and energy efficiency. Promoting low-emission mobility is only possible with policies because society's existing culture is usually based on a command-control approach [9]. However, it's not just about promoting low-emission mobility. Transport policies must also consider the challenges of a sustainable mobility transition, such as the increasing intensity and frequency of rising temperatures and other climate change phenomena, to ensure a comprehensive approach. Incorporating climate change phenomena into transportation planning, urban design frameworks, and transportation policies is essential things to preparing climate adaptation and mitigation [20].

Just mobility plans are essential for managing society and economic growth [21] in the Yogyakarta Cosmological Axis. These plans serve as practical management tools, supporting efforts to promote low-emission mobility. This plan also plays a crucial role in traffic management simulations, which are practical tools for reducing carbon emissions. However, it is equally essential that these plans consider the socio-economic aspects of the people who work, pass, or travel and carry out daily business activities in the area [22]. This balanced approach is critical to Yogyakarta's more sustainable and prosperous future. Therefore, a fairer traffic engineering transition model is needed to achieve this balance by applying multimodal traffic modelling [16].

3 Traffic reengineering and carbon accounting

3.1 Emission Factors and Air Quality Index

Transportation contributes more than 16 percent of greenhouse gas emissions (Fig. 2) in many cases [23]. For example, according to the Intergovernmental Panel on Climate Change (IPCC), the transportation sector in Indonesia contributes around 27% of national greenhouse gas emissions, with the majority (around 90%) being generated by the land transportation subsector [24]. These emissions mainly come from exhaust gases produced by various types of motor vehicles, such as cars, buses, trucks, and motorbikes. Harmful gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM_{10}) are released into the air in large quantities, especially in urban areas with high levels of congestion [8]. In addition to contributing to global warming, these emissions from traffic also have a direct impact on public health, causing respiratory problems, heart disease, and other health disorders [25,26]. Therefore, managing and reducing emissions from the transportation sector is key to improving air quality and creating a healthier environment.



Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020). Licensed under CC-BY by the author Hannah Ritchie (2020).

Fig. 2. Global greenhouse gas emissions by sector

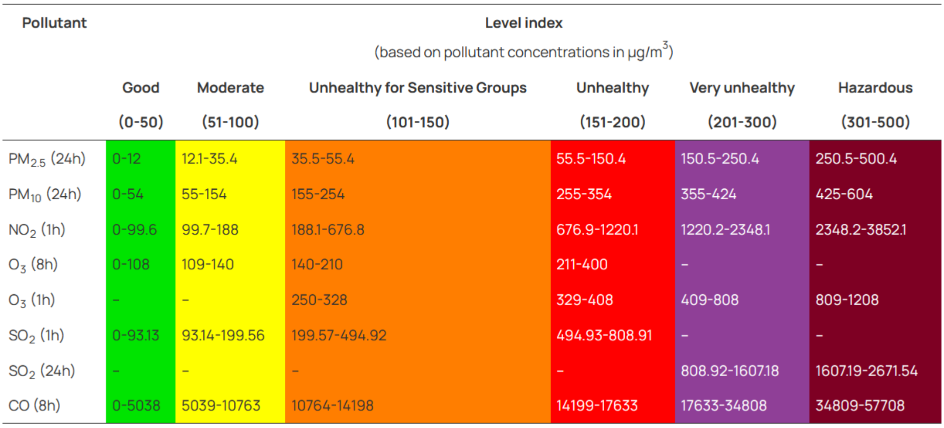
Table 1 shows the emission factors of various types of vehicles based on the type of gas produced, such as CO_2, CO, NO_x, HC, and PM_{10}. Each of these emission gases is measured in different units, such as CO_2 in kg/GJ and other gases in g/km. The types of vehicles listed include buses, minibuses, light duty vehicles, gasoline vehicles, diesel vehicles, and hybrid vehicles. This table provides important information to understand the differences in emission levels of various types of vehicles under certain operating conditions.

Table 1. Emission factors by vehicle type [8]

Vehicle Type	CO (g/km)	Nox (g/km)
Bus	4.9	6.8
Minibus	4.9	6.8
Gasoline car	3.16	0.21
Diesel car	3.16	.26

Air quality can be seen based on the air quality index, this index is based on the concentration of various pollutants in µg/m³ units, which are grouped into several quality categories: Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy, and Hazardous. The pollutants measured include $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO, with different concentration limits for each quality level. For example, for $PM_{2.5}$, concentrations between 0-12 µg/m³ are categorized as "Good," while concentrations of 250.5-500.4 µg/m³ are categorized as "Hazardous." This table helps in interpreting the level of risk to public health based on the concentration of pollutants in the air [27].

Table 2. Air Quality Index (AQI)



Pollutant	Level index (based on pollutant concentrations in $\mu g/m^3$)					
	Good (0-50)	Moderate (51-100)	Unhealthy for Sensitive Groups (101-150)	Unhealthy (151-200)	Very unhealthy (201-300)	Hazardous (301-500)
$PM_{2.5}$ (24h)	0-12	12.1-35.4	35.5-55.4	55.5-150.4	150.5-250.4	250.5-500.4
PM_{10} (24h)	0-54	55-154	155-254	255-354	355-424	425-604
NO_2 (1h)	0-99.6	99.7-188	188.1-676.8	676.9-1220.1	1220.2-2348.1	2348.2-3852.1
O_3 (8h)	0-108	109-140	140-210	211-400	-	-
O_3 (1h)	-	-	250-328	329-408	409-808	809-1208
SO_2 (1h)	0-93.13	93.14-199.56	199.57-494.92	494.93-808.91	-	-
SO_2 (24h)	-	-	-	-	808.92-1607.18	1607.19-2671.54
CO (8h)	0-5038	5039-10763	10764-14198	14199-17633	17633-34808	34809-57708

The colour scheme is provided to give information on the status of the Kunak devices.

3.2 Traffic Carbon Emission in Cosmological Axis

The analysis method for assessing pollution in the Cosmological Axis Region involves a geospatial data-based approach and air quality modeling:

1. The first step is to collect vehicle emission data from various types of vehicles passing through the main roads in the region, such as traffic volume data, vehicle types, and emission factors from each vehicle. Calculation of vehicle emissions in the Cosmological Axis area is carried out using a simple but effective formula, namely the number of vehicles in passenger car units (gasoline cars) multiplied by the appropriate emission factor for each type of vehicle, then multiplied by the length of the road traveled **Table 1**. This formula can be formulated as follows:

   $$Emissions = (Number\ of\ Vehicles).(Emission\ Factors).(Road\ Length) \quad (1)$$

   With this approach, we can obtain an estimate of the total exhaust emissions, such as CO and NO_x, produced by vehicles passing along a particular road.
2. This data is then integrated with geospatial data using a Geographic Information System (GIS) to map the distribution of pollutants on each road section based on

3. **Table 2**. Air quality modeling using special software helps predict the concentration of pollutants such as NOx, and CO at various points along the Cosmological Axis.
4. The result of this analysis is a pollution map that shows the level of emissions on each road, so that areas with poor air quality can be identified. Based on the results of the pollution map, recommendations for sustainable mobility can be made, such as improving pedestrian infrastructure, developing bicycle lanes, restricting motorized vehicles at sensitive points, and increasing access to low-emission public transportation, all of which aim to reduce the negative impacts of pollution and maintain the sustainability of the Outstanding Universal Value (OUV) in this region.

Based on the calculation of vehicle emission gas passing through the roads in the Sumbu Cosmologi Area of Yogyakarta City, most areas are still in the good and moderate air quality categories (**Fig. 3** dan **Fig. 4**). This shows that most routes in the area have relatively low pollutant concentrations, so that the risk to public health is still relatively safe. The use of more environmentally friendly vehicles and the implementation of sustainable mobility policies have helped reduce emission levels on several roads, so that air quality is maintained around areas that have Outstanding Universal Value (OUV).

Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

(a) CO emissions (gr/km) (b) Nox emissions (gr/km)

Fig. 3. CO dan NOx emission map of Cosmoslogical Axis Area

However, several points require special attention, such as Jalan HOS Cokroaminoto and the area around the Yogyakarta Palace. In these locations, emission levels tend to be higher than in other areas, which the high volume of vehicle traffic and frequent congestion can cause. Emissions from vehicles in these two locations have the potential to increase the concentration of pollutants such as NO_2 and $PM_{2.5}$, which can reduce air quality and pose a risk to sensitive groups. Mitigation measures are needed to maintain the sustainability of OUV in the Cosmological Axis Region, such as increasing the use of public transportation, better traffic management, and regular air quality monitoring at these points.

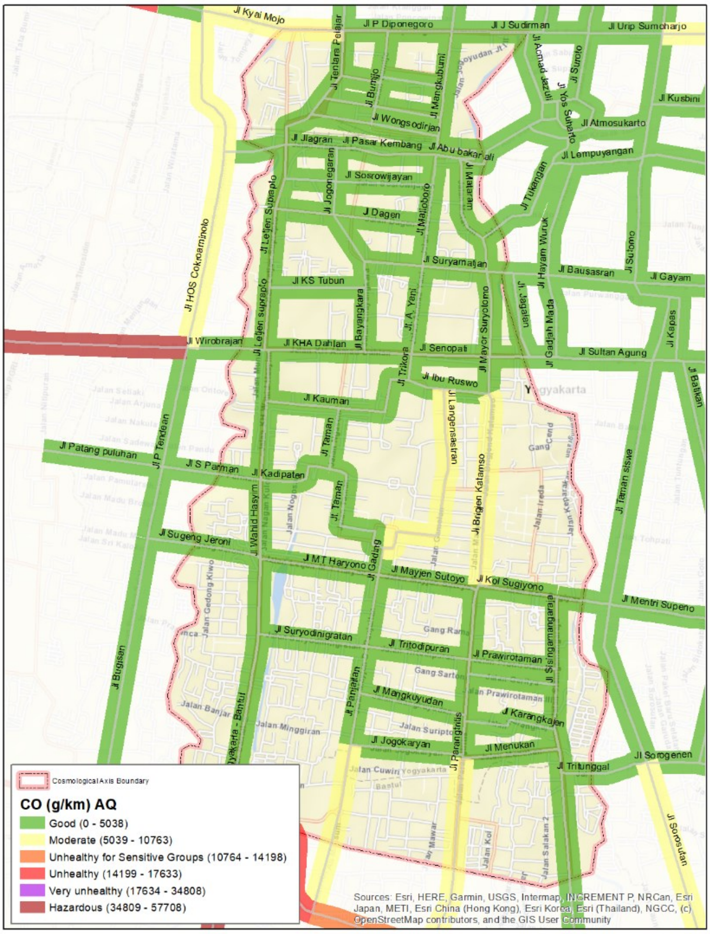


Fig. 4. Air quality index map of Cosmoslogical Axis Area

3.3 Traffic reengineering based on sustainable mobility

Sustainable mobility recommendations for the Cosmological Axis Area to protect Outstanding Universal Value (OUV) include developing and improving access to environmentally friendly public transportation, such as electric buses or renewable energy-based vehicles, which can reduce exhaust emissions from private vehicles. In addition, restrictions on motorized vehicle traffic in specific areas, such as around the Keraton and Jalan HOS Cokroaminoto, need to be implemented, especially during peak hours, to reduce air pollution. The construction of comfortable and safe bicycle and pedestrian paths also needs to be strengthened to encourage people to use more environmentally friendly modes of transportation. Implementing low-emission zones at specific points along the Cosmological Axis can be a strategic step to reduce the number of vehicles that produce high emissions. In addition, it is crucial to launch educational campaigns to encourage people to use more sustainable transportation and to enforce restrictions on fossil fuel vehicles. These measures are not only about maintaining air quality and protecting the environment but also about preserving this area's historical and cultural values, a responsibility we all share.

Table 3. Recommendations of traffic reengineering for Handling Cosmological Axis Areas paying attention to OUVs based on sustainable mobility

Recommendations	Types Of Activities	Sustainable Goals
Improvement of Transit Routes and Bus Stop	Addition of Bus Stops/Stops (Addition of the number of Trans Jogja stops with a maximum distance of 400 meters)	Development and improvement of access to environmentally friendly public transportation
	Re-route Transit (Changes in the Trans Jogja route due to the enactment of traffic engineering management)	
	Public Transport Signage	
	Public Transport Information System	
	City Tour Bus	
	Route integration to other tourist sites	
CBD Traffic Demand Management	Cordon Pricing	Restrictions on motorized vehicle traffic in sensitive areas
	Smart Parking System	
Improvement of Traditional Transport	Rickshaw/Andong Park	Encouraged to use more environmentally friendly modes of transportation
	Rickshaw /Andong Route	
	Signage for Traditional Transport	

4 Conclusions

The Cosmological Axis of Yogyakarta, as a World Heritage Site, is responsible for maintaining and protecting its Outstanding Universal Value (OUV). This OUV value can be threatened by dense and congested traffic conditions, potentially increasing pollutant emissions and damaging air quality in the area. Therefore, a sustainable mobility approach is needed to manage transportation in this area and reduce these negative impacts. Steps that can be taken include increasing access and quality of environmentally friendly public transportation, such as electric buses or renewable energy-based vehicles, and encouraging the use of non-motorized modes of transportation, such as bicycles and traditional modes, such as pedicabs (becak) and horse carts (andong). In addition, implementing low-emission zones in certain areas also needs to be carried out to limit the number of motorized vehicles that produce high emissions. Through this strategy, the sustainability of OUV can be maintained, along with improving environmental quality and the welfare of the local community.

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