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A Systematic Literature Review: Traffic Management for Motorcycles to Improve Urban Road Air Quality

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Abstract

Motorcycles are a popular mode of transportation for many people. Their simple design makes them easier to maneuver than other types of vehicles. However, the increasing ownership of motorcycles has the potential to increase conflicts with other road users, especially in heterogeneous traffic. Motorcycle movements, especially in urban areas, can affect road performance and ultimately lead to higher levels of vehicle emissions. This research paper is a systematic literature review (SLR) examining evidence from studies on motorcycle demand management policies implemented in various countries. The focus is to evaluate the effectiveness of these policies, especially in countries with high motorcycle usage rates. To address the problem of vehicle emissions on roads with significant motorcycle traffic, several policies have been implemented by relevant authorities. These include banning motorcycles from certain areas or time periods, introducing congestion price, electronic motorcycles, using eco- friendly fuels, and promoting mode shift. The research finding is that a combination of congestion/electronic road pricing policies and a mode shift to public transportation is the most effective traffic management strategy for reducing air pollution.

Keywords

motorcycle, traffic management, urban road, air quality

1 Introduction

Motorcycles significantly contribute to air pollution on urban roads due to their high number and the emissions they produce. Studies have shown that motorcycles are a major source of CO, HC, NO_x, and particulate matter, which can cause air pollution and pose health risks to individuals living near urban roadways (Gantina et al., 2024). The high number of motorcycles in cities like Jakarta, where they account for 66% of motorized vehicles, exacerbates this issue (Gantina et al., 2024). Additionally, the increasing number of motorized vehicles and traffic congestion lead to lower traffic speeds, which further increase emissions. Motorcycles in urban areas emit a variety of pollutants, including Carbon Monoxide (CO): Motorcycles emit significantly higher amounts of CO compared to passenger cars. For example, a study found that motorcycles collectively emit three times more CO than passenger cars. Hydrocarbons (HC): Motorcycles emit disproportionately high amounts of hydrocarbons, which are associated with warming and suspected of being carcinogenic (Gantina et al., 2024). Nitrogen Oxides (NO_x): NO_x emissions from motorcycles are substantial, with median values recorded at 2,447 ppm in urban areas. Particulate Matter (PM): Motorcycles contribute to elevated PM levels, particularly in urban centers like Jakarta, where they account for a significant portion of air pollution. Carbon Dioxide (CO_2): CO_2 emissions from motorcycles are also significant, with median values recorded at 13.90% in urban areas (Gantina et al., 2024).

Motorcycle emissions have a significant impact on air quality in densely populated cities, contributing to various environmental and health issues. Motorcycles are a major source of air pollution in urban areas. These pollutants can reduce air quality, leading to eye irritation, respiratory disorders, and other health problems. Ozone Formation: The emissions of HC and NO_x from motorcycles contribute to the formation of ozone (O_3), a major component of smog. This can exacerbate respiratory issues and affect the overall air quality in urban areas. Carbon dioxide (CO_2) emissions from motorcycles also contribute to global warming, which is a significant concern in densely populated cities

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where urban heat islands can intensify the effects of climate change. The high levels of pollutants emitted by motorcycles can lead to increased stress levels among motorcyclists, as well as higher risks of accidents due to poor riding techniques and increased vehicle emissions. The poor maintenance of motorcycles, which is common in many urban areas, further exacerbates the environmental impact as a greater contribution to air pollution (Odunlami et al., 2018).

This research is a literature review, collecting evidence from research studies regarding motorcycle demand management policies in various countries, especially whether these policies are effective in their implementation or not in countries that have high levels of motorcycle use.

To reduce vehicle emissions on roads that have high levels of motorcycles traffic, several policies have been taken by related parties, such as banning motorcycles at certain times or on certain roads, introducing congestion price, and promoting mode shift. Policy management for motorcycles has been implemented by European and American countries starting in 1900. This policy was taken by the governments due to the high rate of traffic accidents by motorcycle users and the level of crime against motorcycle users. Furthermore, several countries are also starting to try the most effective policies to reduce the high level of motorcycle usage.

2 Material

Several studies regarding emission reduction policies related to motorcycle use in several countries. In order to mitigate emission levels on urban roads, an examination of journals that related to Traffic Management for motorcycles was conducted. A comprehensive analysis was carried out using journal articles and proceedings sourced from Scopus, SJR, and Web of Science (Table 1). There were 135 articles collected with publication years from 2014 to 2024. After screening there were 54 articles and 51 articles were reviewed. The remaining articles were not reviewed because they were not published in reputable journals indexed by Scopus-WoS, but in local journals, and were out of topic. The study encompassed a total of 51 articles, each accompanied by its respective journal quartile ranking. Eight articles are listed in the Web of Science database, while thirty-one articles are indexed in Scopus Q1. Additionally, there are three articles indexed in Q2, two articles in Q3, one article in Q4, and six articles in SJR.

Table 1 Number of articles

Indexed by	Total	Percentage (%)
Web of Science	8	16
Q1	31	61
Q2	3	6
Q3	2	4
Q4	1	2
SJR	6	12

The reviewed articles on traffic management policies for motorbikes originated from Indonesia (13 articles), Nigeria (3 articles), Myanmar (1 article), China (16 articles), Vietnam (7 articles), Thailand (4 articles), Singapore (2 articles), Macau (1 article), Malaysia (1 article), Chile (1 article), USA (1 article), England (1 article), other countries (3 articles).

Since 2014, research on motorcycles and their emission impacts has been studied. Furthermore, every year the issue of motorcycles and emissions continues to grow and develop. Until now it has become a very important issue increasing levels of concern for environmental improvement, especially air quality as an impact of motorcycle vehicle activities on road.

Furthermore, this could be attributed to a growing recognition of the importance of addressing traffic management for motorcycles, as well as advancements in technology and methodologies that have enabled researchers to conduct more comprehensive studies. The findings from these articles are likely to have significant implications for policymakers, urban planners, and transportation authorities looking to improve traffic management strategies for motorcycles. By synthesizing the knowledge and insights gained from these studies, stakeholders can develop more effective policies and interventions to reduce emissions, enhance air quality, and improve overall traffic flow in urban areas. Overall, the data presented in Figs. 1–3 underscore the importance of ongoing research in Motorcycle

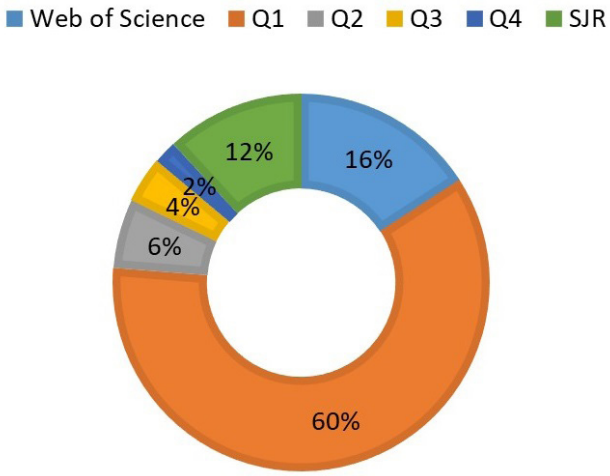

Fig. 1 Percentage of indexed articles

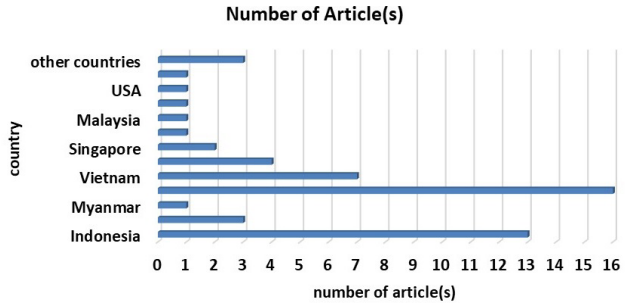

Fig. 2 Number of articles by country

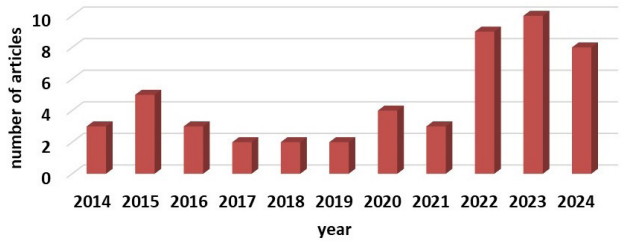

Fig. 3 Number of articles from a given year

Traffic Management and its potential to drive positive change in urban transportation systems.

The issue of use of biofuel in motorcycles has become a concern for several countries, such as Malaysia (2014), China (2015), Nigeria (2022), and Vietnam (2018). The implementation of banning motorcycles from highways has been implemented in several countries, such as China (2015), Nigeria (2016), and Myanmar (2017). The implementation of Congestion pricing for motorcycles has been tested in several countries, namely England (2016), Indonesia (2017), Thailand (2022), and Chile (2023). Mode shift to motorcycles has also become a concern for several countries to be solved, such as Indonesia (2022), Vietnam (2023), and China (2015). Electric motorcycles are a concern for several countries to be addressed, namely China and Indonesia (2020), England (2022), and Thailand (2023).

3 Results

3.1 Banning motorcycles

Several countries have attempted to ban motorcycles from their roads, most notably Myanmar, which banned them from the roads in 2003 and managed to reduce traffic by 18% by 2013 (Inaba and Kato, 2017). China has also introduced the measure in light of a high incidence of motorcycle accidents, including crimes against motorcyclists, as well as increased traffic congestion and air pollution, resulting in reduced CO_2 and NO_x levels, with NO_x recorded as the main cause of haze and photochemical haze pollution in the region (Guo et al., 2020). In addition, the ban on motorcycles, which reduces traffic congestion, is also based on the lack of safety equipment on motorcycles (Chen et al., 2021). On the other hand, however, China's motorcycle ban policy has caused several problems. First, the ban forces motorcyclists to give up this convenient mode of transportation in urban areas where public transportation is inadequate and inconvenient. Second, China's policy has further alienated over 250 million migrant workers who were already considered second-class citizens due to the hukou system and related urban social welfare policies. These migrant workers are exposed to further discrimination because they must register their motorbikes in their hometowns rather than their current urban residences. Third, a total motorcycle ban will have a negative impact on poor urban communities who depend on motorcycle taxis for their livelihoods. Despite these problems, 168 cities in China have implemented various motorcycle ban policies. The most controversial are the total bans in Guangzhou, Shenzhen, and Dongguan in southern China (Xu, 2015). Nigeria banned motorcycles in Lagos due to high crime rates among motorcyclists. The ban significantly reduced the number of road accidents. It was also identified that motorcycles (and okadas) are often used for criminal activities, and the CMO reduced the level of crime using motorcycles (Odugbesan, 2016). Following a proposal from Belgium (Flanders), Vietnam developed a scenario to ban motorcycles from its roads. The model combines heuristic rules and econometric models. Simulation results show that strict control over motorcycle use significantly reduces the number of motorcycle trips and encourages a reorganization of the location and time of daily activities (Linh et al., 2023).

3.2 Congestion pricing

To effectively solve the traffic congestion problem, many densely populated and highly developed cities around the world have chosen to implement congestion pricing for vehicles entering the city center, and the effectiveness of this congestion pricing policy has been proven.

Nevertheless, the success of a congestion pricing system heavily depends on a thorough understanding of the behavioral responses of urban passengers (Chiou and Fu, 2017). For example, traffic congestion in the city of Yogyakarta, Indonesia, is increasing due to an increase in vehicles, population growth, and urban area expansion. A possible solution to overcome this congestion is to implement congestion pricing. The implementation of a city fee for motorcyclists is expected to: increase vehicle

speeds by 0.42-6.32 km/h, reduce general costs for motorcyclists, in particular, vehicle speeds on Malioboro Street are expected to increase by 1.76 km/h. The general cost for motorbike riders is expected to decrease by IDR 3.63, per trip (Sugiyanto, 2016). In Chile, the introduction of a pricing mechanism for sustainable transport has been shown to have a positive impact on urban traffic congestion, including improving quality of life, reducing pollutant emissions, reducing wear and tear on vehicles caused by traffic congestion, and reducing unnecessary fuel consumption (González-Aliste et al., 2023). In China, traffic congestion increases fuel consumption by up to 80% compared to normal driving conditions, resulting in increased emissions of pollutants into the atmosphere. This exacerbates the air pollution problem in cities and leads to increased energy consumption. Moreover, traffic congestion also leads to increased CO_2 (Zhang et al., 2023). By implementing the motorcycle congestion pricing process, an optimal balance between speed and CO_2 emissions across the road network is achieved when the congestion price is set at 7 yuan, resulting in an increase in the average speed across the road network from 29.64 km/h to 43.31 km/h and a reduction in CO_2 emissions by 852.4 kg (Yang et al., 2023). An analysis of environmental and social costs associated with motorized traffic in Bangkok shows a clear transformation from a city that relied primarily on buses and motorbikes to one dominated by motorized traffic over the past 25 years, making Bangkok one of the most densely populated cities in the world. The study found that total external costs weigh on Bangkok's economy, accounting for around 7% to 10.8% of its Gross Regional Product (GRP), with almost half of the costs due to traffic congestion. A strategic approach to pricing urban transportation services could significantly benefit urban mobility. Specifically, setting the congestion charge at $2.3, the road toll at $2.7, and the inner city parking fee at $3.2 per hour could lead to improved efficiency and quality of life in cities. By implementing a combination of congestion and parking pricing, cities can encourage shared pooled mobility options and maintain transport flexibility, ultimately enhancing the overall urban experience (Ayaragarnchanakul and Creutzig, 2022). Singapore's ERP system is designed to manage traffic congestion by charging vehicles based on the time of day and the road segment used. The ERP system in Singapore has been shown to reduce the generalized cost for motorcycle users by 1.09 to 6.63%. This reduction in cost can encourage motorcycle users to switch to other modes of transportation, such as public transportation or walking. The ERP system in Singapore has also been found to reduce pedestrian traffic and cause retail real estate prices in cordoned CBD areas to decline (Koh and Chin, 2022).

A study found that the sudden removal of road pricing in Milan decreased bike-sharing use by about 5%. This suggests that ERP policies can influence the use of alternative modes of transportation, including motorcycles. The ERP system in Milan aims to reduce traffic congestion by charging vehicles based on their usage. This can lead to reduced traffic congestion and improved air quality, which can benefit motorcycle users by reducing the risk of accidents and improving overall traffic conditions. Another city, Jakarta is planning to implement an ERP system to manage traffic congestion and reduce emissions (Sunitiyoso et al., 2020). The proposed ERP system in Jakarta can lead to a shift in economic activity and potentially affect the motorcycle industry (Sunitiyoso et al., 2020). London has implemented a congestion charge, which charges vehicles entering the city center during peak hours (Croci, 2016). The congestion charge in London can lead to a shift in economic activity and potentially affect the motorcycle industry. The congestion tax in Stockholm has also been found to have a significant economic impact, potentially reducing the number of motorcycles on the road and encouraging the use of public transportation. Dubai has implemented a corridor congestion pricing scheme called Salik, which charges vehicles based on their usage.

3.3 Mode shift

Mode of travel choice depends on travel time, cost, socio-demographic factors, psychological and behavioral aspects, cultural and social identity. Research results from Vietnam show that motorcyclists aged 23 and above value travel time more than those under 23. In contrast, motorcyclists aged 23 and below, as well as female motorcyclists, place more importance on environmentally friendly travel options such as public transportation. However, they do not seek to differentiate themselves from societal norms in terms of motorcycle use (Nguyen et al., 2024a). The shift from the use of motorcycles to the utilization of public transportation in Southeast Asia, with the aim of reducing individual mobility, is a crucial subject that warrants examination (Nguyen et al., 2024b). Many developing Asian cities are contemplating the implementation of a Bus Rapid Transit (BRT) system in their public transport planning due to its advantages, such as lower investment costs and more flexible implementation compared to rail systems. Both

travel time and travel cost impact mode selection, with travel time having a highly significant effect on passenger car users' decision to use BRT, while travel cost has a highly significant effect on motorcyclists' choice. Additionally, certain socioeconomic factors, such as gender, age, possession of a driving license, and residential location, also influence the choice to use BRT (Satiennam et al., 2016). The Jakarta metropolitan area in Indonesia introduced bus rapid transit (BRT) in 2004, but motorcycle ownership continued to grow even after that. Since the modal share (proportion of total trips) of bus rapid transit (BRT) systems is still low, transport policies in cities where motorcycles are the dominant mode of transportation and BRT systems are present could increase the use of BRT by raising the relative costs of using private motorcycles, such as through higher parking fees; reducing the relative travel time of the BRT system by increasing service frequency and improving travel speeds; enhancing the user-friendliness of the first and last mile connections to the BRT system (Chiu, 2022). Another research in Indonesia says that implementing policies to reduce privace vehicle use and integrate public transportation can reduce fuel consumption and road emission by about 34% (Sukarno et al., 2016). Motorcycles are found to emit higher levels of CO_2 and other pollutants (CO_2: 53.8%, CH_4: 91.4%, CO: 90.8%, HC: 98.7%, NO_x: 85%, PM: 93.3%, SO_2: 65%) compared to buses, microbuses, taxis, and cars on the road. The 70:30 split between private and public transport was the sweet spot for fuel use and emissions. In the forecast of fuel consumption and emission levels, there are several policies to be implemented by governments in order to reduce fuel consumption from road transport. Important variables to be delivered effectively in a future context are thus reducing the usage private vehicle and motivating people for moving on to public transport. In Padang, a policy option as reformation of Bus Rapid Transit (BRT) system is installation of converter kits for public vehicles and improvement of emissions standards that need to adopted. However, a policy evaluation is necessary to assess whether the policies have contributed significantly in reducing fuel consumption and emission levels (Sukarno et al., 2016). Vietnam has a long entrenched background in motorcycle use throughout the cities, successfully dealing with popularity: motorcycles possess characteristics that appeal to inhabitants and can satisfy the basic mobility needs of almost everyone. But they are not safe at all, and there is no fresh air on them (Tong et al., 2024). Among the 1,159 short journeys considered eligible for substitution, it was found that active modes of travel could feasibly supplant 62% of short motorcycle trips, amounting to 41% of all trips. Consequently, this measure led to a decrease of 0.23 kg CO_2 per person per day, translating to an almost 18% reduction in greenhouse gas emissions. Should biking and walking be utilized for all shopping trips typically undertaken on motorcycles, the potential replacement of short-distance trips would rise to 84%, resulting in a 22% reduction in motorcycle-related GHG emissions (Tong et al., 2024; Ngoc et al., 2022).

3.4 Electric motorcycles

A study utilized an electric motorcycle as a mode of transportation for daily ride-sharing purposes. Furthermore, the rider frequently operated a motorcycle powered by an internal combustion engine. The electric motorcycle, in contrast, was more eco-friendly and had a lower environmental impact due to the lack of CO_2 emissions. Furthermore, the vehicle had virtually no maintenance costs during the trial period. Additionally, the total energy expenditure required to operate the electric motorcycle per kilometer was significantly decreased by 89% (Suwignjo et al., 2023). Additionally, the perceived noise produced by motorcycles is significantly greater than most other vehicles. At speeds above 30 mph, the noise from motorcycles is roughly double that of automobiles, and at speeds over 50 mph it even exceeds the noise levels of medium-sized trucks and buses. In fact, the noise from motorcycles at high speeds surpasses the 80 decibel limit set by the US standard (Hernandez et al., 2019). Electrification can address these problems, although the current limitations in range and high costs are hindering widespread acceptance. To achieve these environmental advantages, it is crucial that the transition to electrification is accompanied by a concurrent shift away from coal as a primary energy source. Additionally, more stringent emission regulations and stronger enforcement of existing restrictions on specific types of vehicle modifications could also help reduce the outlier status of gasoline-powered motorcycles (Hernandez et al., 2019).

The number of motorcycles in Indonesia has experienced a very significant increase over the past 10 years, reaching a staggering 300%. Consequently, this dramatic rise in the number of motorcycles is bound to lead to a corresponding increase in carbon pollution levels within Indonesia. The conversion of motorcycles to electric power involves the incorporation of new and still highly advanced technology. It is crucial for the government to prioritize this transition, ensuring that Indonesia does not fall behind other countries

in this regard. Extensive public awareness campaigns should be conducted to educate the populace about electric motorcycle conversion, enabling them to understand the benefits of this drive system. Additionally, the Indonesian government must accelerate the development of necessary infrastructure, such as fast charging technology, public electric charging stations, and battery swap technology. Providing tax deductions for companies involved in this industry can also help to accelerate its growth. Furthermore, the Indonesian National Standards (SNI) for electric motorcycle conversion must be formalized and implemented without delay (Habibie and Sutopo, 2020; Balijepalli et al., 2023). Providing green alternatives, such as electric motorcycles, for drivers and passengers can be a solution to reduce carbon emissions and promote sustainable environmental development in an eco-friendly manner. Motorcyclists' attitudes towards environmental policy motivate them to adopt electric motorcycles. Based on this, the Macau government is planning to implement appropriate environmental policies to promote the use of electric motorcycles. For instance, the government could build more charging stations in public parking areas, and require that all new properties be "electric car ready" by including charging stations (Balijepalli et al., 2023). Additionally, the government could install solar-powered charging systems in open-air parking lots. The results also indicate that motorcyclists' perceptions regarding the pollution reduction and energy-saving capabilities of electric motorcycles can influence their attitudes towards adopting this technology (Balijepalli et al., 2023).

Another research examined the impact of various factors on the energy utilization and carbon emissions associated with the entire energy supply chain for three types of electric motorcycles in four Southeast Asia countries: those with a home charging system, those using a battery swapping system, and those with both battery swapping and photovoltaic systems. The use of electric motorcycles with battery swapping systems is only viable when the main energy sources for electricity generation are sufficiently clean, or when the battery swapping stations are equipped with a 3 kW photovoltaic system. In these four specific countries, electric motorcycles with battery swapping capabilities have the potential to accelerate the transition towards a net-zero carbon emission society by reducing CO_2 emissions by approximately 2.6–3.0 Mt-CO_2 per year, provided the right conditions are in place (Charoen-amornkitt et al., 2023).

In China, on average, shared electric bicycles have been found to reduce carbon emissions by 108 to 120 grams per kilometer. Interestingly, this reduction effect is even more pronounced in less developed, non-central regions that have lower population densities, less diverse land use, poorer accessibility, and lower economic activity levels (Li et al., 2023).

In England, by estimating the distance individuals can travel by e-bike and the extent to which they are willing to replace travel by private car, the maximum potential to reduce CO_2 emissions by replacing car travel with e-bike use is 24.4 million metric tons of CO_2 per year. The CO_2 reduction capability per person and per small geographical area is greatest (over 750 kg CO_2 per person per year) for residents of rural areas and the rural-urban interface. In contrast, major urban centers can achieve more modest per-person CO_2 savings through e-bike adoption (Philips et al., 2022).

3.5 Eco-friendly fuel

Motorcycles and scooters are responsible for over 32% of global pollution. Specifically, the idling and revving of motorcycle engines in urban areas lead to significant emissions and environmental pollution. Motorcycle engines typically run in a state of incomplete combustion, and they also have less effective emission control and aftertreatment technologies. As a result, motorcycles tend to emit more pollutants per mile traveled compared to cars, despite having smaller engine displacements than cars (Fu et al., 2020). Forecasts indicate that there will be approximately 75 million motorcycles in circulation by the year 2025. This is the same year that Vietnam plans to begin implementing exhaust gas testing for motorcycles, based on the Vietnamese National Standard "TCVN 643:2018" (Kieu et al., 2023). This standard represents the maximum permitted limits for exhaust emissions from road vehicles in Vietnam. However, it is expected to be challenging for older motorcycle models to meet these requirements. As a result, alternative fuel sources will likely need to be explored as a solution. The performance and emissions data were evaluated for both gasoline and LPG through experimentation and simulation. The findings indicate that the performance of the LPG-powered system decreases compared to gasoline-powered ones. Nonetheless, the exhaust emissions and fuel efficiency are enhanced. This system does not necessitate modifications to the fuel injection system or the engine, has low manufacturing costs, and can be easily implemented in the current context of motorcycles in Vietnam (Tuan and Dong, 2022). The test vehicle fueled by LPG exhibited a significant reduction in the exhaust emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) compared to gasoline. Specifically, the

reductions were 69.94%, 47.89%, and 46.48%, respectively. Additionally, the average fuel consumption in kg/100 km and energy consumption in MJ/100 km were reduced by 14.78% and 12.84%, respectively. However, the average fuel consumption in l/100 km increased by 11.10%. The study also observed a degradation in engine performance, with the best brake power at the wheel being reduced by an average of 19.42%. Despite these performance impacts, the developed bi-fuel system could be a feasible solution for environmental protection, fuel economy, and ensuring the longevity of currently used motorcycles in the context of Vietnam (Duy et al., 2021). In the world, Vietnam is one of the countries with a large number of motorcycles, which have been considered a significant source of environmental pollution. Starting in 2018, E5-biogasoline was officially introduced in the nationwide market, replacing the conventional fossil gasoline RON92 and RON95. The study reported an increase in engine power ranging from approximately 2.3% to 7.1%. Additionally, there was an increase in NO_x and CO_2 emissions, ranging from 1.6% to 2.2%, and 3% to 6.7%, respectively. Conversely, the study also found a reduction in fuel consumption of around 2% to 4%, a decrease in CO emissions of 1.6% to 5.2%, and a decrease in HC emissions of 5.4% to 13.7% when the test motorcycle was fueled with E10-biogasoline, compared to fossil gasoline-RON95 and E5-biogasoline (Hoang et al., 2019). Motorcycle engines typically employ either two-stroke or four-stroke internal combustion engines. The exhaust emissions from internal combustion (IC) gasoline-powered engines are a major contributor to air pollution and global climate change. An engine's operation relies on the combination of air, fuel, and a spark to generate power. Optimizing the engine's performance requires the proper air-fuel mixture. For a gasoline-powered engine, the emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) are significantly influenced by the air-fuel ratio. There is no single air-fuel mixture that can minimize the emissions of all three exhaust gas components simultaneously (Odunlami et al., 2022). The emission factors of total hydrocarbons (THC) and carbon monoxide (CO) from motorcycles using E10 fuel were reduced by 26% to 45% and 63% to 73%, respectively, compared to motorcycles using gasoline. In contrast, the emission factor of nitrogen oxides (NO_x) increased by 36% to 54% for motorcycles using E10 fuel compared to those using gasoline (Li et al., 2015). A retrofit fuel injection system (FIS) is a system that is designed to completely replace the traditional carburetor system. This is done to enhance the fuel efficiency and exhaust emissions, offering a more economical option in an attempt to lower fuel expenses and air pollution (Muslim et al., 2014). Of the three vehicle types, heavy-duty vehicles (HDVs) displayed the highest emission factors for particulate matter (PM2.5) and elemental black carbon (eBC), while light-duty vehicles (LDVs) and motorcycles (MCs) had relatively higher levels of carbon monoxide (CO) and carbon dioxide (CO_2) emission (Ting et al., 2023). The total emission factor of polycyclic aromatic hydrocarbons (p-PAHs) from ten in-use motorcycles was measured to be 676.3 μg/km, with an average of 67.6 ± 13.6 μg/km. Naphthalene (Nap) had the highest emission factor, followed by phenanthrene (PA) and fluoranthene (FL). The mileage of the motorcycles showed a strong positive correlation (Rsp = 0.681) with carbon monoxide (CO) emissions. CO emissions are associated with cumulative mileage, leading to poor combustion efficiency, which in turn resulted in a moderate to high correlation between total p-PAHs (Rsp = 0.388), PM2.5 (Rsp = 0.680), and NO_x (Rsp = 0.799). Both PM2.5 and total p-PAHs are typically generated through incomplete combustion, and the results showed a moderate to high correlation (Rsp = 0.578, 0.898) with NO_x. Considering high-mileage motorcycles (30,001–50,000 km), the toxic equivalent of carcinogenicity and mutagenicity in the exhaust were found to be about 4.67 and 1.99 times higher, respectively, than those of low (10,001–20,000 km) and middle (20,001–30,000 km) cumulative mileages. The emission factor for lower carcinogenicity and mutagenicity was found in motorcycles with lower cumulative mileages. However, the impact increases with motorcycles that have higher cumulative mileages (Lin et al., 2019).

4. Discussion

4.1. Banning motorcycles

Banning motorcycles can reduce the number of vehicles on the road, leading to less congestion and smoother traffic flow. This is particularly evident in urban areas where motorcycles are a significant contributor to traffic jams. By reducing the number of motorcycles on the road, the risk of accidents and injuries can be minimized. This is especially important in areas where motorcycle accidents are common and often result in severe injuries or fatalities. When motorcycles are banned, people may be forced to use public transportation, which can lead to increased use of buses and trains. This can help reduce the reliance on private vehicles and improve overall transportation efficiency. Banning motorcycles can contribute

to reduced air pollution and noise pollution, as there will be fewer vehicles emitting pollutants. Two-wheeled motor vehicle emissions contribute greatly to air pollution problems in big cities, thus regulations to reduce the use of fossil motorbikes can help reduce air pollution levels.

However, it is important to note that banning motorcycles can also have negative impacts, such as increased traffic on other roads, economic hardship for motorcycle users, and potential resistance from the public. Therefore, any ban should be carefully considered and implemented with adequate infrastructure and public transport alternatives in place.

While banning motorcycles can reduce air pollution and noise, it can also lead to increased use of other vehicles that may have higher emissions. This needs to be carefully considered in the context of overall environmental impact. In some cultures, motorcycles are an integral part of social and economic life. Banning them can disrupt traditional practices and social structures, leading to resistance and non-compliance. Ensuring that public transportation infrastructure is maintained and accessible is crucial. Without this, banning motorcycles can lead to increased costs and logistical challenges for public transport providers. Implementing and enforcing motorcycle bans require significant regulatory and administrative resources. This can be a challenge, especially in areas with limited administrative capacity. The public must be educated and supportive of the ban for it to be effective. Resistance and non-compliance can occur if the public does not understand the rationale behind the ban or if it is perceived as unfair.

4.2. Electric motorcycles

Electric motorcycles produce no local emissions, which means they do not contribute to air pollution or climate change. This is a major benefit compared to traditional motorcycles that rely on internal combustion engines. By not emitting pollutants, electric motorcycles help reduce air pollution, which is a significant concern in urban areas. This improves air quality and reduces the risk of respiratory problems and other health issues. Electric motorcycles are silent, which means they do not contribute to noise pollution. This is particularly beneficial in urban areas where noise pollution can be a significant issue. Electric motorcycles can be powered by renewable energy sources such as solar, wind, or hydroelectric power. This makes them a more sustainable option compared to traditional motorcycles that rely on fossil fuels. Electric motorcycles have fewer moving parts and require less maintenance compared to traditional motorcycles. This reduces the environmental impact of maintenance activities and saves owners money.

The main barriers to adopting electric motorcycles in developing countries include high purchase price. The high cost of electric motorcycles compared to traditional internal combustion engine (ICE) motorcycles is a significant barrier to adoption. This is particularly challenging for low-income individuals and small businesses that rely on motorcycles for their livelihoods. Lack of charging infrastructure: The availability and accessibility of charging infrastructure are crucial for the adoption of electric motorcycles. In many developing countries, the infrastructure for charging electric vehicles is limited, making it difficult for potential users to charge their motorcycles. Driving range concerns: Consumers are often concerned about the driving range of electric motorcycles, which can be limited compared to traditional motorcycles. This uncertainty about the distance they can travel on a single charge can deter potential users (Rahmawati et al., 2022). Public awareness and acceptance: The lack of public awareness and acceptance of electric motorcycles can also hinder their adoption. Many people may not be familiar with the technology or may have concerns about its performance and reliability (Murtiningrum et al., 2022; Rahmawati et al., 2022).

Technological and infrastructural factors: The technological and infrastructural factors related to electric motorcycles, such as the complexity of the technology and the need for specialized maintenance, can be barriers to adoption. These factors can make the motorcycles seem less appealing or more difficult to maintain public awareness and acceptance. User considerations of non-electric motorcycles regarding electric motorcycle that the battery charging process for electric motorcycle takes longer than motorcycle that use fuel (Aqmarina et al., 2024). The lack of supportive government policies and incentives can also slow down the adoption of electric motorcycles. Governments need to provide policies and incentives that encourage the adoption of electric vehicles, including tax breaks, subsidies, and other financial incentives (Aqmarina et al., 2024; Murtiningrum et al., 2022; Rahmawati et al., 2022).

Meanwhile, in developing countries, there is not much education and outreach regarding the use of electric motorcycles.

4.3 Mode shift

The policy most intensively implemented by developing countries is mode shift or the use of public transportation (such as buses). However, it is also necessary to pay attention to several challenges that need to be addressed by the

government related to shifting modes, namely improving infrastructure, comfort, safety in public transportation, improving service quality, integrated public transportation. The advantages of shifting mode are reduced emissions and increased road capacity. Shifting from motorcycles to public transportation can have significant advantages in terms of emissions. Public transport vehicles, such as buses and trains, emit significantly fewer pollutants compared to motorcycles. This reduces the overall air pollution and environmental impact of transportation (Risdiyanto et al., 2022). By reducing the number of motorcycles on the road, public transportation can help improve air quality in urban areas. This is particularly important in densely populated cities where air pollution is a major concern (Jou and Chen, 2014; Risdiyanto et al., 2022). Public transportation is more environmentally friendly than motorcycles. Buses and trains use cleaner fuels and have more efficient engines, resulting in lower emissions per passenger. Public transportation systems are designed to be more sustainable, with a focus on reducing emissions and promoting a greener environment. This aligns with the goals of many cities and governments to reduce their carbon footprint (Risdiyanto et al., 2022). Public transportation infrastructure is designed to be more efficient, with dedicated lanes and optimized routes. This reduces congestion and the need for multiple vehicles to travel the same route, further reducing emissions (Jou and Chen, 2014; Risdiyanto et al., 2022). Many governments provide incentives and subsidies for the use of public transportation, making it a more attractive and cost-effective option for commuters. This support can further encourage the shift from motorcycles to public transportation.

The challenges of shifting from motorcycles to public transportation from emission point of view include:

Infrastructure and Maintenance: Ensuring that public transportation infrastructure is maintained and accessible is crucial. Without this, banning motorcycles can lead to increased costs and logistical challenges for public transport providers. Public Transport Alternatives: Providing adequate public transportation alternatives is essential. Without these alternatives, banning motorcycles can lead to increased congestion on other roads and a lack of mobility for those who cannot afford or access public transport (Risdiyanto et al., 2022). Economic Impact: Banning motorcycles can have a significant economic impact, especially on low-income individuals and small businesses that rely on motorcycles for their livelihoods. This can lead to economic hardship and reduced mobility for certain segments of the population (Risdiyanto et al., 2022). Government Support and Policies: The lack of supportive government policies and incentives can slow down the adoption of public transportation. Governments need to provide policies and incentives that encourage the adoption of public transport, including tax breaks, subsidies, and other financial incentives. Public Awareness and Acceptance: The lack of public awareness and acceptance of public transportation can hinder its adoption. Many people may not be familiar with the system or may have concerns about its performance and reliability. Technological and Infrastructural Factors: The technological and infrastructural factors related to public transportation, such as the complexity of the technology and the need for specialized maintenance, can be barriers to adoption. These factors can make public transportation seem less appealing or more difficult to maintain compared to motorcycles (Risdiyanto et al., 2022).

4.4 Congestion pricing

By reducing the number of motorcycles on the road, higher taxes and charging prices can contribute to reduced emissions and improved air quality.

Congestion price for motorcycles, also known as e-road pricing, is a system where motorcycles are charged for using roads based on distance traveled, time spent on the road, or other metrics. This system aims to manage traffic congestion, reduce emissions, and generate revenue for road maintenance and infrastructure development. Electronic road pricing can help manage traffic congestion by encouraging motorcycles to use less congested routes or times of day.

Electronic road pricing can generate revenue for road maintenance and infrastructure development, which can help improve the overall quality of roads and transportation systems. The system can help ensure that roads are used efficiently by charging motorcycles based on their usage, thereby reducing the likelihood of unnecessary or excessive use of roads.

Implementing congestion price for motorcycles requires significant infrastructure and technology investments, including the installation of sensors, toll gates, and payment systems. The public may need to be educated about the benefits and necessity of electronic road pricing, as there may be initial resistance to the system. Ensuring compliance with electronic road pricing can be challenging, particularly in areas with limited law enforcement resources. The system must be designed to ensure that it does not disproportionately affect low-income individuals or those who rely heavily on motorcycles for transportation.

Electronic road pricing systems typically use sensors to detect the passage of motorcycles and calculate the distance traveled or time spent on the road (Asian Development Bank, 2022). Motorcycles can be equipped with devices that allow their owner to pay for road usage, either through a dedicated account or by using a credit card (Asian Development Bank, 2022). In some cases, toll gates may be installed at strategic locations to collect fees from motorcycles. The implementation of electronic road pricing often requires government policies and regulations to ensure compliance and revenue collection.

A study found that the implementation of congestion pricing can decrease the generalized cost for motorcycle users by 1.09 to 6.63% (Agarwal and Koo, 2015). Another study on the influence of pricing on mode choice decision in Jakarta found that the implementation of congestion pricing can affect the likelihood of switching from motorcycles to other modes of transportation. A study on the operational cost of electric motorcycles (e-motorcycles) in Indonesia showed that e-motorcycles are more financially efficient than fuel-powered motorcycles. The average operating cost of an e-motorcycle is Rp 46,952 (US$3.08) per month, which is four times more efficient than the operational cost of a fuel-powered motorcycle (Agarwal and Koo, 2015). Congestion pricing policies can have different impacts on motorcycles across various cities due to the unique characteristics of each city's transportation system, traffic congestion, and economic conditions (Feng et al., 2023). The implementation of electronic road pricing can control vehicle volume which directly reduces motor vehicle emissions such as nitrogen oxide (NO_x) and PM10 particles.

4.5 Eco-friendly fuel

Sustainable fuel oils, such as biofuels, do not generate carbon dioxide emissions, which helps reduce air pollution and promote a cleaner environment (Darmanijati et al., 2024; Kusalaphirom et al., 2022): These fuels do not require combustion, meaning they produce no noise pollution, making them a quieter alternative to traditional fuel-powered motorcycles. Biofuels are derived from renewable sources like agricultural waste, reducing the demand for non-renewable fossil fuels and supporting sustainability. Electric motorcycles, which use rechargeable batteries, require less maintenance and fewer part replacements, decreasing the demand on natural resources like crude oil. Electric motorcycles offer immediate torque and power, providing a smooth and efficient riding experience. Electric motorcycles do not produce vibrations or heat, making them a more comfortable ride for both the driver and passenger (Halder et al., 2024). Using renewable energy sources to charge electric motorcycles supports environmental protection initiatives and reduces the carbon footprint.

Challenges of using environmentally friendly fuel oil for motorbikes are higher purchase cost: Electric motorcycles and other alternative fuel-powered motorcycles are often more expensive due to their advanced technology and features. Safety concerns: The complex technologies used in alternative fuel motorcycles are not as thoroughly tested, which can raise safety concerns. Higher maintenance costs: Motorcycles with eco-friendly fuel-powered engine require specialized maintenance and may have higher costs for accessories and chargers, demand extensive maintenance, and incur high repair expenses (Wagino et al., 2024). The use of these environmentally friendly fuels helps reduce emissions of harmful pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and greenhouse gases. Furthermore, these fuels also play a role in reducing dependence on finite fossil fuels and providing a more sustainable energy alternative for transportation.

The relationship between motorcycle growth and the level of air pollution in a city is very close and significant. A high growth in the number of motorcycles leads to an increase in fossil fuel consumption, which results in increased emissions of harmful exhaust gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and fine particulate matter. These emissions directly degrade urban air quality and are a major source of air pollution in large cities.

Measures frequently attempted by governments to reduce emissions and environmental impacts caused by motorcycles in urban areas include the use of free public transportation, paying subsidies to switch household fuels, and charging congestion fees on main roads during peak traffic hours. This statement is also supported by previous research (Jonidi Jafari et al., 2021). In addition to the above, another strategy is speed limitation (Tang et al., 2020), age restrictions for motorcycles in operation, regular motorcycle emission routine checks, and the provision of dedicated lanes for motorcycles.

The policy prohibiting motorcycles on highways takes quite a long time to be accepted and implemented by motorcycle riders. This policy depends on the cultural factors of each region. For example, in countries with the highest number of motorcycle riders, this policy will be difficult to enforce. Even if this policy is implemented, it only applies in the short term to reduce the number of trips.

The negative impact of this policy is the paradox of emission reduction, the concentrated movement of motorcycles in certain locations, resulting in more traffic congestion, traffic conflicts, and negative environmental effects.

The use of eco-friendly fuel-powered and electric motorcycles also has negative impacts, namely in countries with limited natural resources for environmentally friendly fuels and electricity, where fuel prices will be more expensive compared to existing fuels. In addition, not all areas are equipped with environmentally friendly fuel refilling points and electric charging stations or public electric charging stations. Financial risk perception also influences consumer decisions. The uncertain maintenance costs of electric vehicles and the possibility of expensive repairs are deterrent factors. These concerns are reinforced by the lack of widespread charging infrastructure and the perceived risk of limited driving range for daily use. Used batteries also pose environmental problems in terms of waste management. Although the use of environmentally friendly fuels and electricity in motorcycles reduces the impact of air pollution, it does not solve the problem of reduced road capacity due to the volume of motorcycles.

There needs to be a combination of traffic management policies for motorcycles concerning the reduction of emissions and air pollution. This includes the use of free and affordable public transportation available to all locations and congestion pricing to limit the movement of private vehicles. This statement is supported by previous research showing that a combination of public transportation use and vehicle restrictions can reduce traffic congestion by 29.13%, decrease air pollution by 52.63%, and improve the air quality health index by 54.63% (Chen et al., 2022).

5 Conclusion

The traffic management policies adopted by developed countries often involve banning motorcycles on roads and promoting the use of electric motorcycles instead. While this approach can have significant drawbacks, developing countries have an opportunity to facilitate the adoption of electric motorcycles and work towards a more sustainable transportation sector. Banning motorcycles from roads can lead to various challenges, such as economic impacts, limited public transport alternatives, safety and accessibility concerns, enforcement difficulties, environmental consequences, social and cultural implications, infrastructure and maintenance issues, regulatory hurdles, and public resistance. Developing countries can play a pivotal role in encouraging the transition to electric motorcycles. Governments and transportation authorities can incentivize this shift, reducing emissions and improving air quality in urban areas. Increasing taxes and charges on traditional motorcycles can discourage their use and drive the adoption of electric alternatives, though this must be accompanied by adequate public transportation options and supportive policies. Electronic road pricing for motorcycles can be a valuable tool for managing traffic congestion, reducing emissions, and generating revenue for infrastructure development. However, its implementation requires significant investments in technology and infrastructure, as well as public acceptance and effective enforcement mechanisms. The successful adoption of electric motorcycles in developing countries can contribute to a more sustainable and environmentally friendly transportation sector, but it necessitates a careful consideration of the various challenges and the implementation of comprehensive, supportive policies. A combination of congestion/road pricing policies and a mode shift to public transportation is the most effective traffic management strategy for reducing air pollution caused by the high volume of motorcycle use. Congestion pricing funds can be used to support the development and operation of more effective and environmentally friendly public transportation.

This study is limited to the number of articles reviewed. It is expected that in future studies, the number of articles reviewed can be increased, where the articles are indexed with international reputation (Scopus and WoS), and other policies in an effort to reduce motorcycle vehicle emissions, especially in countries with a large number of motorcycle users, can be studied.

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