International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Sustainable Development and Planning
Vol. 19, No. 12, December, 2024, pp. 4623-4634
Journal homepage: http://iieta.org/journals/ijsdp

Leveraging Battery Electric Vehicles (BEV) and Policy Interventions to Mitigate Jakarta's Traffic and Pollution Crisis: A System Dynamic Analysis

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https://doi.org/10.18280/ijsdp.191211

Received: 1 November 2024
Revised: 9 December 2024
Accepted: 19 December 2024
Available online: 30 December 2024

Keywords:
ineffectiveness of Odd Even policy, excessive use of ICE, air pollution, traffic congestion

ABSTRACT

The Jakarta Regional Government has been implementing an odd-even traffic policy for over 20 years. This regulation aims to mitigate negative impacts in the transportation sector, such as excessive reliance on Internal Combustion Engine (ICE) vehicles, high air pollution levels, and severe traffic congestion. Currently, the policy's effectiveness has diminished, prompting the need to identify factors that could lead to more effective solutions. A dynamic system analysis is proposed to determine the variables that influence the use of ICE vehicles. Key factors to be examined include the effects of road segments designated solely for Battery Electric Vehicles (BEVs), fluctuations in fuel and charging prices, and restrictions on ICE vehicles to decrease emissions and alleviate traffic congestion. Through this analysis, simulations indicate that air pollution from the transportation sector could be reduced by over 26.9% annually over the next 12 years, while effectively addressing traffic congestion. Reducing the number of ICE vehicles could improve the road service level to 'Level A,' which would increase the average speed from 21 km/h to 55 km/h.

1. INTRODUCTION

Indonesia's commitment to achieving the Paris Agreement targets has highlighted the need for transformative policies in the transportation sector. As one of the primary contributors to greenhouse gas emissions, the sector requires urgent interventions to address its environmental and social impacts. Jakarta, as a microcosm of Indonesia's urban transportation challenges, provides a compelling case study for exploring the dynamics of vehicle ownership, emissions, and traffic congestion.

Despite the implementation of progressive policies such as the odd-even road scheme and exemptions for Battery Electric Vehicles (BEVs), Jakarta continues to grapple with rising Internal Combustion Engine (ICE) vehicles ownership and associated emissions. Research indicates that government policy exemptions alone are insufficient to drive substantial changes in vehicle adoption patterns. While BEVs offer a promising alternative, their success depends on comprehensive strategies that combine financial incentives, infrastructure development, and complementary policies such as investments in public transportation. Evidence from low emission zones (LEZs) in other regions suggests that such approaches can reduce traffic, phase out older vehicles, and encourage the transition to zero-emission vehicles.

In this context, the study aims to examine the interplay between mandatory BEV policies, ICE vehicle ownership, air pollution, traffic congestion, and charging infrastructure development in Jakarta. Employing a dynamic systems analysis, the research seeks to answer the question: How does the mandatory BEV policy influence the adoption of ICE vehicles, emission levels, and traffic congestion? By addressing this question, the study aims to contribute to the development of integrated, evidence-based strategies for achieving sustainable urban mobility in Jakarta and beyond.

2. BACKGROUND

Indonesia has demonstrated its commitment to combating climate change by ratifying Law No. 16 of 2016, which formalized its adherence to the Paris Agreement under the United Nations Framework Convention on Climate Change. Through this agreement, the nation aims to reduce greenhouse gas emissions by 29% through national efforts and by 41% with international collaboration by 2030. The key sectors targeted for emission reductions include forestry, waste management, industrial processes, agriculture, energy, and transportation [1].

Jakarta, Indonesia's capital city, plays a crucial role in achieving these targets due to its significant contribution to the country's transportation emissions. With a population of over 10 million, Jakarta recorded 3.8 million passenger vehicles in 2023, representing 20% of the nation's total [2]. This high vehicle ownership density, coupled with Jakarta's limited land area of 660.98 km², has made the city the 30th most congested worldwide [3]. Traffic congestion in Jakarta leads to an average speed of only 21 km/h and a travel time of over 23 minutes for every 10 km. Additionally, each car with an average daily mileage of 40 km produces approximately 3,875 kg of CO_2 annually, contributing significantly to air pollution and climate change [4].

Over the years, Jakarta's government has implemented various policies to regulate private vehicle usage and mitigate its environmental impact. Early initiatives, such as the "3 in 1" policy in 2003, were designed to limit access to certain road sections based on passenger numbers [5]. This was later replaced with more comprehensive regulations, including the odd-even road scheme introduced in 2016 and expanded in 2019 to cover 25 roads. Notably, electric vehicles, including BEVs, were exempted from these restrictions [6]. Despite these measures, the adoption of BEVs remains limited due to barriers such as high costs, limited model options, and inadequate charging infrastructure. For instance, in 2023, BEVs accounted for only 3.8% of the total market potential in Jakarta, with sales significantly lagging behind ICE vehicles.

Contrary to the regulation's objectives, the number of internal combustion engine (ICE) vehicles is rising each year. From 2017 to 2022, car ownership in Jakarta Province has seen significant growth, with an average annual increase of 5.9% [7], as shown in Figure 1.

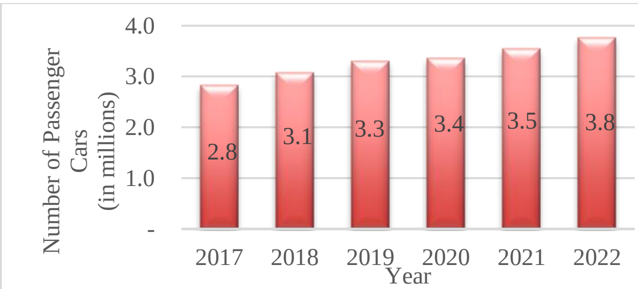

Figure 1. Total number of passenger car ownership in Jakarta Province year 2017-2022

The exemption for battery electric vehicles (BEVs) has not yet made a significant impact. In Jakarta, passenger car sales for 2022 and 2023 were primarily dominated by two vehicle categories: 7-seater models, which held 62% of the market share, and 5-seater models, accounting for 22%. Both categories predominantly consisted of vehicles priced below IDR 300 million, representing 74% of the 7-seater market and 83% of the 5-seater market. In contrast, BEVs, mainly 5-seater models priced above IDR 300 million, comprised only 3.8% of the total potential market, translating to approximately 5,000 units sold. This significant gap underscores the major challenges to BEV adoption, including high prices, limited model availability, and inadequate infrastructure.

As of 2023, Jakarta leads Indonesia with 142 charging stations, the highest number in the country, surpassing West Java (103 stations), East Java (78 stations), and Central Java (45 stations). Despite having the most charging stations, Jakarta's infrastructure is still inadequate to facilitate a rapid transition to battery electric vehicles (BEVs), especially if the annual sales of 125,000 internal combustion engine (ICE) vehicles were to shift entirely to BEVs in a short period [8]. The limited charging infrastructure, combined with the high cost of BEVs, continues to create significant barriers to widespread adoption. These challenges highlight the urgent need for focused policy measures and substantial investments in infrastructure to promote sustainable transportation. This situation is reflected in national car sales, where ICE vehicles still dominate, with only a 0.4% average annual decline in market share, as shown in Figure 2.

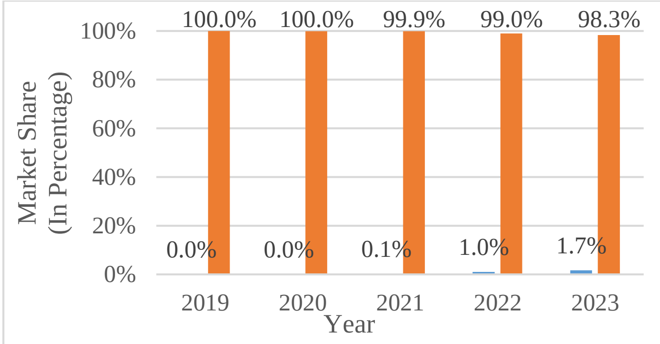

Figure 2. Percentage of BEV vs Non-BEV (ICE) sales

According to the literature review, government policy exemptions are insufficient to achieve optimal outcomes, as individuals have alternative options in response to these policies [9]. When BEVs are merely offered as an exemption, people may continue to rely on ICE vehicles rather than utilizing public transportation. Conversely, enhancing public transportation could effectively address traffic congestion and air pollution. A combined approach involving both policies could yield significant benefits for society, health, and the environment [10].

Moreover, implementing a mandatory BEV policy can facilitate the establishment of low emission zones. Evidence shows that these zones can reduce traffic, eliminate older vehicles, and encourage the use of zero-emission vehicles [11]. The development of BEVs also requires government support, particularly through incentives and subsidies. The advancement of charging infrastructure and pricing plays a crucial role in accelerating BEV adoption, while factors such as population and GDP contribute to the demand for new vehicles, including BEVs [12]. Thus, a mandatory BEV policy can address multiple transportation issues, not only by reducing air pollution and traffic congestion but also by compelling those who do not opt for BEVs to rely on public transportation.

3. METHODOLOGY

3.1 Constructing of system dynamic model

The initial steps of the System Dynamics (SD) process involve defining the modeling goals and identifying relevant system components. The first task is to gather data that relates to the problem at hand. After data collection, each variable must be analyzed to understand the correlations among them. This paper focuses on three key areas to address the problem: clustering roads to assess their impact when the mandatory BEV policy is implemented; determining the scale of BEVs and ICE vehicles to identify when the BEV population exceeds that of ICE vehicles; and evaluating the effect of reduced ICE numbers on air pollution and future traffic congestion influenced by the growth of BEVs.

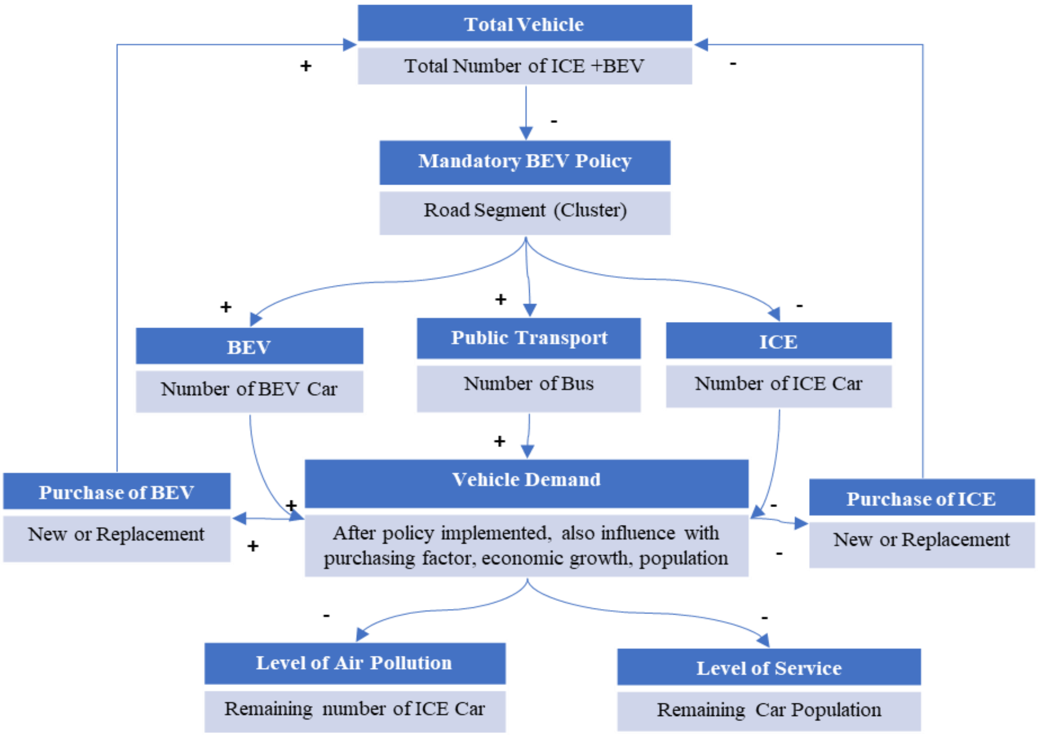

Figure 3. Main flow chart for system dynamic

Once the problem analysis is completed, the next step involves creating a simulation, beginning with the construction of causal loops and flow charts that illustrate the relationships among the factors identified. The resulting stock-flow diagram consists of three types of elements: stock elements (also known as state variables), flow elements, and auxiliary variables, along with constants that do not have directional orientation. Auxiliary variables, defined by mathematical formulas, represent the remaining elements, while stock variables are depicted in rectangular boxes. Relationships between various components are shown with arrows, and these relationships can be modified using a window mask. Inflows and outflows of stock variables are represented by double-line arrows [13]. Once the SD model is developed, the simulation can be implemented. Figure 3 provides a detailed overview of these steps.

The fundamental model for this study was established by examining the relationships between key variables, with an emphasis on the primary objectives of the mandatory battery electric vehicle (BEV) policy. This policy seeks to manage the overpopulation of internal combustion engine (ICE) vehicles, which are major contributors to traffic congestion and air pollution while promoting the adoption of BEVs or public transportation for daily commutes. The transformation process is shaped by various factors, including purchasing behaviors, economic growth, population trends, and the availability of supporting infrastructure.

The simulation spans from 2023 to 2060, in line with Indonesia's target year for reaching Net Zero Emissions as specified in Law No. 16 of 2016, which ratifies the Paris Agreement (Republic of Indonesia, 2016). This extended timeframe allows the simulation to capture the long-term effects of the policy and to assess Jakarta's potential for meeting its emission reduction targets comprehensively.

By encompassing the entire period from 2023 to 2060, the study identifies the optimal years for achieving significant emission reductions, as indicated by decreasing air pollution levels. This robust timeframe provides a solid foundation for understanding both the immediate and long-term impacts of the policy, delivering valuable insights for decision-makers and stakeholders involved in Jakarta’s shift towards sustainable urban mobility.

3.2 Data collection

This study relies on diverse, reputable secondary data to ensure reliable inputs for the simulation, drawing on key sources that collectively enhance its robustness and policy relevance.

The Central Bureau of Statistics (BPS) of Indonesia provided vital data, including car ownership by province, population statistics, and regional GDP figures. This data, collected through standardized national surveys and censuses, ensures credibility and consistency when analyzing socioeconomic factors that influence vehicle usage.

Traffic data from the Jakarta Department of Transportation includes road-level service indicators and congestion patterns, delivering essential insights into urban mobility dynamics. Additionally, the Association of Indonesia Automotive Industries (GAIKINDO) offered detailed automotive market data, such as market shares by vehicle type, pricing, and characteristics of internal combustion engine (ICE) and battery electric vehicles (BEVs).

Air quality data were obtained from monitoring reports in Jakarta, supplemented by insights from TomTom Traffic. These datasets provided information on pollutant concentrations (e.g., $PM_{2.5}$ and NO_x), trip lengths, and emissions data, facilitating a comprehensive assessment of the relationship between traffic patterns and air pollution.

Energy-related data, including electricity charging rates for BEVs and fuel prices for ICE vehicles, were sourced from PT PLN and PT Pertamina, supplying critical parameters for evaluating the economic feasibility of transitioning to BEVs.

By integrating these diverse datasets, validated through multiple institutions, the study ensures a robust and context-specific simulation that supports actionable policy recommendations for reducing reliance on ICE vehicles, promoting BEV adoption, and enhancing urban air quality.

The primary factors selected for analysis include road capacity, air pollutant concentration, vehicle numbers, population growth, car sales, the number of charging stations, and fuel prices. The total cost of ownership is a significant consideration for individuals in Indonesia when choosing between ICE and BEV vehicles [14]. Each of these factors will be treated as variables in the System Dynamics modeling process.

After identifying the key factors, it is essential to quantify and formalize the relationships among them. Certain mathematical relationships are evident; for example, road capacity, air pollutant concentration, vehicle quantity, population, car sales, number of charging stations, and fuel prices are primarily determined by their initial quantities and growth rates, allowing for direct formulation.

3.3 Problem identification and measurement

3.3.1 Road clustering for policy implementation

Clustering analysis is a method used to examine trip characteristics [15]. In this study, data from 25 road sections were grouped into three clusters: Cluster 1, Cluster 2, and Cluster 3. The primary purpose of clustering the road sections is to categorize them based on similar levels of service or traffic congestion.

Once the road sections are grouped, distinct scenarios can be developed: Scenario 1 for Cluster 1, Scenario 2 for Cluster 2, and Scenario 3 for Cluster 3. Each cluster will illustrate the effects of the mandatory BEV policy and its correlation with the adoption levels of BEVs and public transport, specifically electric buses. These scenarios can also be utilized to assess the impact of the mandatory BEV policy during specific years. The notation for each variable is detailed in Table 1.

Table 1. Cluster scenario

No.	Variable	Notation	Baseline Number	Unit
1	Traffic Cluster 1	ICE C1	88,911	Unit
2	Traffic Cluster 2	ICE C2	117,215	Unit
3	Traffic Cluster 3	ICE C3	39,837	Unit
4	Year of Policy Implemented in Cluster 1	Age C1	2	Year
5	Year of Policy Implemented in Cluster 2	Age C2	3	Year
6	Year of Policy Implemented in Cluster 3	Age C3	4	Year
7	Electric Bus Capacity	Factor of Public Transport	40	Person
8	Car Used Capacity	Factor of BEV	2	Person
9	Number of Electric Bus	Public transport	4,000	unit
10	Growth of Transition to Public Transport	Transfer	2	%/year

The decline in the population of ICE vehicles will contribute to an increase in BEV adoption; however, some travelers will still opt for public transportation. The timing of policy implementation will influence the pace of ICE reduction. The number of public transport options is expected to rise significantly, particularly due to limitations in adopting BEVs.

In Europe, Low Emission Zones (LEZ) are commonly employed to address issues such as air pollution and traffic congestion. LEZs have been effective in decreasing the number of polluting vehicles while also encouraging greater use of public transportation. Public transportation plays a crucial role in creating sustainable, efficient, and livable cities. Additionally, it serves as a solution to the increased mobility demands driven by population growth in urban areas [16].

3.3.2 Identifying the scale of BEV and ICE

Even though the BEV Mandatory Policy is implemented in only 25 road sections, its effects are expected to influence the entirety of Jakarta. Additionally, the number of vehicles is impacted by factors such as population growth, car prices, the expansion of charging infrastructure, and the prices of electricity and fuel. These variables present common challenges that affect BEV adoption in various countries.

For example, in Poland, the primary issue is the higher cost of BEVs compared to ICE vehicles, which hinders their adoption [17]. Similarly, Luxembourg and Berlin face challenges related to consumer behavior, vehicle market structure, and fuel prices, all of which slow the acceleration of BEVs [18, 19]. In China, increasing BEV adoption can be facilitated through mandatory improvements in fuel quality [20]. Increasing adoption of BEV can be seen from the ratio between BEV and ICE [21]. The growth of both BEVs and ICE vehicles is influenced by numerous factors, as outlined in Table 2.

Table 2. Variables related to adoption of BEV and ICE

No.	Variable	Notation	Baseline Number	Unit
1	Number of BEV	BEV	8,625	Unit
2	Selling Price of BEV	Price of BEV	400	Million IDR
3	Subsidy for purchasing BEV	BEV Subsidy	10	%
4	Number of Charging Station	Charging Station	190	Unit
5	Growth of Charging Station	Charging Growth	25	%/year
6	Price of Electricity	Charging Price	1,500	IDR/kwh
7	Number of ICE	ICE	2,716,558	Unit
8	Selling Price of ICE	Price ICE	250	Million IDR
9	Price of Fuel	Fuel Price	10,000	IDR/litre
10	Jakarta Gross Domestic Product	RGDP	2050	Trillion IDR
11	Growth of GDP	RGDP Growth	3.43	%/year
12	Number of Population	Population	10	Million People
13	Growth rate of Population	Population Growth	0.27	%/year

3.3.3 Identification of concentration of air pollution

The adoption of ICE vehicles for transportation has a negative impact on air quality. Even with the establishment of new road networks aimed at reducing traffic congestion, there has been little effect on lowering air pollution levels [22]. Additionally, the odd-even restriction policy has not significantly improved air quality in DKI Jakarta [23]. Air pollutants are assessed based on six parameters: PM_{10}, $PM_{2.5}$, SO_2, CO, O_3, and NO_2, as detailed in Table 3 [24].

Table 3. Concentration of air pollution year 2023

No.	Parameter	Concentration of Air Pollutant in Jakarta Region (micro gram/m^3)			
		West	East	South	Central
1	PM_{10}	78	64	64	59
2	$PM_{2.5}$	53	52	35	36
3	SO_2	36	46	56	47
4	CO	1258	742	688	840
5	O_3	74	69	79	80
6	NO_2	25	25	16	42

The differences in air pollutant concentrations across various regions in Jakarta are closely linked to traffic conditions, particularly the level of service (LOS) on the road network. According to the 2023 Final Report of the Traffic Characteristics Survey in Jakarta, areas experiencing poorer traffic performance, characterized by lower average speeds, tend to have higher levels of air pollutants.

For example, West Jakarta, which has the highest pollutant concentration, operates at an LOS of E, with an average speed of just 23.7 km/h. This level of service indicates severe traffic congestion, marked by frequent stop-and-go conditions that lead to inefficient fuel combustion and increased emissions from internal combustion engine (ICE) vehicles.

In contrast, regions like South Jakarta and Central Jakarta exhibit slightly improved traffic conditions, with an LOS of D and average speeds ranging from 28.5 km/h to 31.2 km/h. Although these areas still face congestion, the relatively smoother traffic flow results in lower pollutant concentrations compared to more congested areas.

PM_{10} and $PM_{2.5}$ are derived from emissions from internal combustion engine exhaust gases. The highest concentrations of $PM_{2.5}$ and PM_{10} among transportation modes occur in urban transit, largely influenced by conditions such as vehicles with open windows and doors [25]. The anticipated increase in BEVs is expected to help reduce the effects of global warming [26]. While adopting public transportation is effective in reducing air pollution, the use of private vehicles (ICE) will have a negative impact, as it contributes to higher pollution levels [27]. Implementing stringent pollution controls along with new technologies is an effective strategy for limiting pollution [28].

3.3.4 Identification of growth of BEV to the traffic congestion

The number of vehicles consists of two types: ICE vehicles and BEV. A mandatory policy for BEVs will be implemented to reduce the use of ICE vehicles while simultaneously increasing the adoption of BEVs and other forms of transportation, such as mass transit. The growth of private vehicles, including both BEVs and ICEs, is expected to remain within road capacity limits to prevent traffic congestion. Traffic congestion can have significant economic impacts, including increased travel time, higher fuel consumption, and uncertainty for drivers and passengers [29]. According to the Ministry of Public Works and Housing, the level of service in Jakarta is determined by road capacity, and the maximum capacity can be calculated using Eqs. (1)-(3) [30].

$$Vactual = Vfree \times \left(1 - \frac{BEV}{Road\ Capacity}\right) \tag{1}$$

$$Vactual = Vtarget \tag{2}$$

$$BEV_{max} = \left(1 - \frac{Vtarget}{Vfree}\right) \times Road\ Capacity \tag{3}$$

Vtargeted = targeted average speed (km/hour)
Vfree = 60 km/hour
BEV = amount of BEV (Unit)
BEV_{max} = Maximum amount of BEV in targeted average speed (Unit)

The relationship between the level of services, average speed, and the maximum capacity can be shown in Table 4.

Table 4. Level of services

No.	Level of Services	Average Speed (km/hour)	Maximum Capacity (unit)
1	A	> 48	130,402
2	B	40 - 48	237,094
3	C	33.6 - 39.9	312,965
4	D	25.6 - 33.5	407,802
5	E	22.4 - 25.5	445,737
6	F	< 22.4	446,923

The adoption of BEVs will impact road capacity. As the number of BEVs approaches the maximum capacity of roads, it may lead to a reduction in average speed, resulting in traffic congestion. A mandatory BEV policy is expected to provide a more effective solution than a car-free zone policy, which could complicate freight and logistics operations, impacting product competitiveness [31]. Simultaneously, modernizing the aging truck fleet and implementing stricter freight standards, such as those for BEV trucks, can help address air pollution issues [32]. However, it is essential to monitor the growth of BEVs to assess traffic levels in specific road segments.

3.4 Stock and flow diagram

Implementing a mandatory BEVs policy across all clusters, as indicated by the variables ICE C1, ICE C2, and ICE C3, will significantly accelerate the phase-out of internal combustion engines (ICE). Once the policy takes effect in a designated year, it will restrict ICE vehicles from accessing certain road segments, leaving only two options: using public transport or purchasing a BEV. In this context, electric buses will contribute to reducing air pollution and alleviating traffic congestion [33].

The choice between BEVs and ICE vehicles is influenced by several key factors, including price differences and operational costs. Previous research indicates that vehicle price and usage are the most significant determinants, accounting for 32.3% and 28.1% of decision-making factors, respectively [34]. Currently, BEV prices tend to be higher than those of ICE vehicles, suggesting that incentives are necessary to narrow the price gap. Once prices are comparable, the likelihood of customers choosing BEVs is expected to rise.

Additionally, tax subsidies play a vital role in encouraging BEV adoption [35].

Operational costs also impact the adoption rates; when BEVs demonstrate lower operating costs than ICE vehicles, it further incentivizes consumers to make the switch. In terms of energy efficiency, BEVs are the only viable alternative to ICE vehicles, especially when compared to hydrogen technology, which experiences energy losses of 47% to 63% during production [36].

The availability of charging stations and the cost of charging can significantly drive the adoption of BEVs. A well-developed charging infrastructure is essential for facilitating the rapid transition from ICE to BEV [37]. Conversely, ICE vehicles have several factors that can help maintain their market presence, such as lower fuel prices and their generally lower purchase price compared to BEVs.

In Jakarta, the Regional Gross Domestic Product (RGDP) and the population size also influence BEV adoption. An increase in RGDP and population typically leads to a greater demand for new vehicles. Additionally, income levels and educational backgrounds significantly impact the likelihood of purchasing a BEV; households that own BEVs earn, on average, 75% more than those with ICE vehicles, and BEV owners are 80% more likely to have completed college than ICE owners [38].

The demand for new vehicles is also linked to air pollution levels. As adoption rates for BEVs and public transportation rise, the average concentration of air pollution is expected to decrease. The growing adoption of battery electric vehicles (BEVs) is anticipated to affect road capacity, highlighting the need to enhance public transportation systems in order to decrease dependence on private vehicles [39]. Evidence from cities around the world shows that integrated and improved public transport systems can effectively alleviate traffic congestion and promote a shift away from private vehicle use.

In Bogotá, Colombia, the TransMilenio Bus Rapid Transit (BRT) and Sistema Integrado de Transporte Público (SITP) have enhanced accessibility by integrating routes, fares, and infrastructure, especially benefiting peripheral areas [40]. Similarly, Medellin's integrated system of trains, trams, BRTs, gondola lifts, and bike-sharing has contributed to reduced traffic and CO_2 emissions [41]. Cities like Bonn, Germany, and Copenhagen, Denmark, further illustrate how expanding public transportation can lessen reliance on private vehicles and mitigate congestion [42, 43].

Technology also plays a crucial role in the adoption of public transport. Factors such as accessibility, availability, and user satisfaction are key influences on travelers' decisions [44]. For example, in China, satisfaction with bus services has been shown to decrease the inclination to own private cars [45].

In addition to technology, integrated regional development that leverages public transportation, like Intercity Rail Transportation exemplified by Greater Jakarta, could also be a key driver in supporting urban sustainability in the future [46].

Figure 4 presents stock-flow diagram of BEV modeling and their correlation with variables.

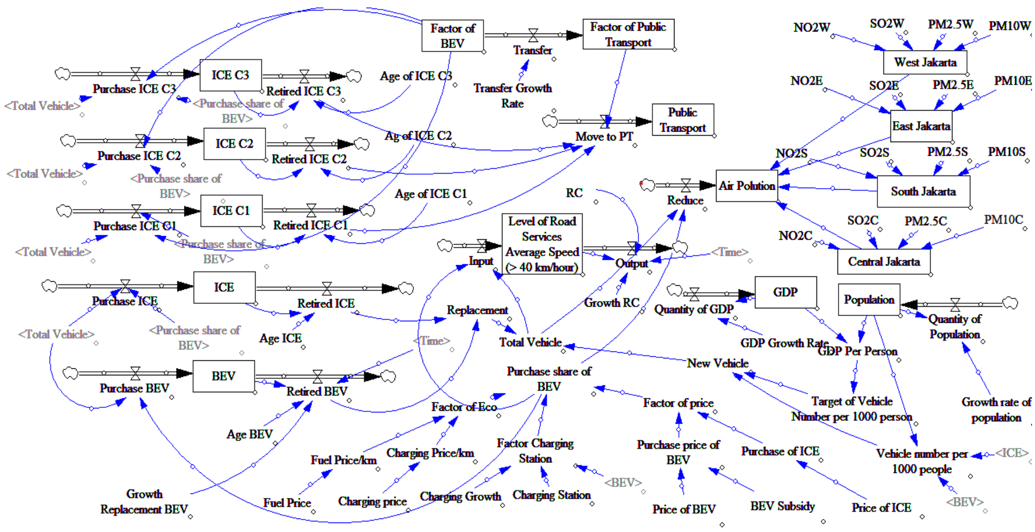

Figure 4. Stock-flow diagram

4. RESULT AND DISCUSSION

The simulation indicates that a mandatory BEV policy has the greatest impact on reducing the number of ICE vehicles. It demonstrates that this policy effectively lowers ICE numbers across all clusters. In each cluster, the number of BEVs will surpass that of ICE vehicles, depending on how the regulation is implemented. Following the implementation of the regulation, simulation data reveals a dramatic decline in the number of ICE vehicles starting from the congestion levels in 2023, as illustrated in Figure 5.

In Scenario Cluster 1, the mandatory BEV policy is set to be implemented in 2025, leading to the complete elimination of ICE vehicles by 2039, which is 16 years after the regulation takes effect. In this scenario, the number of BEVs is projected to exceed ICE vehicles in 2025, reaching approximately 26,000 units.

In Scenario Cluster 2, the mandatory BEV policy will begin implementation in 2026, resulting in the total disappearance of ICE vehicles by 2046, or 20 years post-implementation. Here, BEV numbers are expected to surpass ICE vehicles in 2027, with around 30,000 units.

In Scenario Cluster 3, the policy will be introduced in 2027, and ICE vehicles will be fully phased out by 2052, 25 years after implementation. In this case, the number of BEVs is also anticipated to exceed that of ICE vehicles in 2025, with roughly 26,000 units.

Across all three scenarios, the implementation of the policy will significantly boost BEV adoption within a five-year period from 2023 to 2028. After 2028, the increase in BEVs is projected to be less than 1,000 units annually, with a total of around 38,000 BEVs anticipated by 2060. Public transportation will play a crucial role in supporting the growth of BEVs.

Preferences between BEVs and ICE vehicles are influenced by several factors, including price differences between ICE and BEV, subsidies for BEVs, the number of charging stations, charging costs, fuel prices, Regional Gross Domestic Product (RGDP), and population demographics.

According to the simulation presented in Figure 6, the preference for ICE vehicles is expected to decline gradually each year.

The simulation results reveal that substantial changes take place within the first 12 years of implementation. From 2023 to 2035, the number of internal combustion engine (ICE) vehicles is expected to plummet from 2.6 million units to 226,000 units—a decline of 90%. This swift reduction suggests that the Net Zero Emissions target for 2060 could potentially be reached much sooner, provided the mandatory battery electric vehicle (BEV) policy is executed effectively.

Air pollution presents a significant challenge that can be addressed through the implementation of a mandatory battery electric vehicle (BEV) policy. An increase in BEV adoption, coupled with a decrease in internal combustion engine (ICE) vehicles, is expected to positively impact air quality. The planned implementation of the mandatory BEV policy covers approximately 30% of Jakarta's total road capacity and is anticipated to directly affect at least 1.2 million ICE vehicles, with an additional 2.6 million units impacted indirectly.

Currently, the average concentration of air pollutants in Jakarta—including PM_{10}, $PM_{2.5}$, SO_2, O_3, and NO—stands at around 57 micrograms/m³, largely due to the 3.8 million ICE vehicles on the road. According to the simulation, there is projected to be a 90% reduction in ICE vehicles from 2023 to 2035. This simulation predicts an annual decrease of 26.9% in air pollution concentration, potentially reaching 1 microgram/m³ by 2035.

The reduction in air pollution is offset by a projected average annual increase of 17.4% in battery electric vehicles (BEVs) until 2035. Figure 7 illustrates the trends in both air pollution reduction and the growth in the number of BEVs.

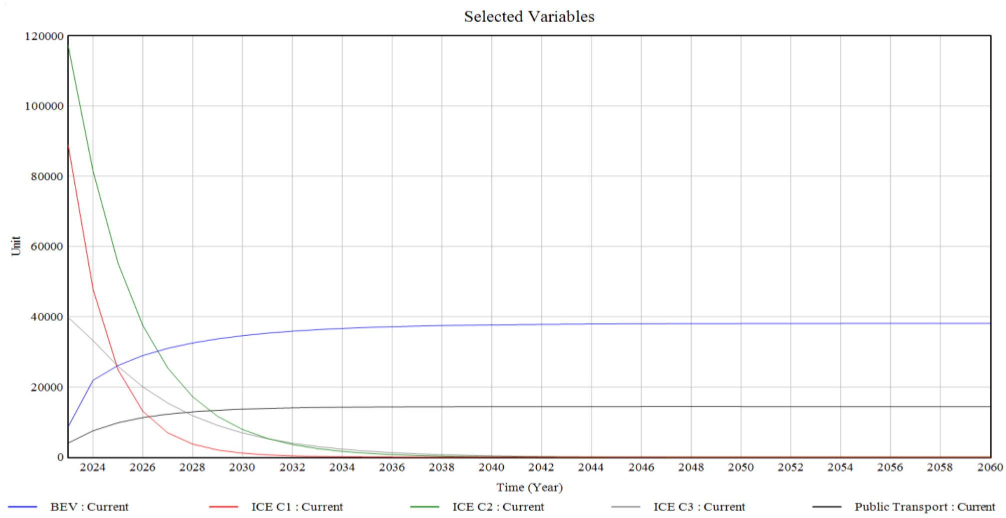

Figure 5. Simulation of cluster scenario

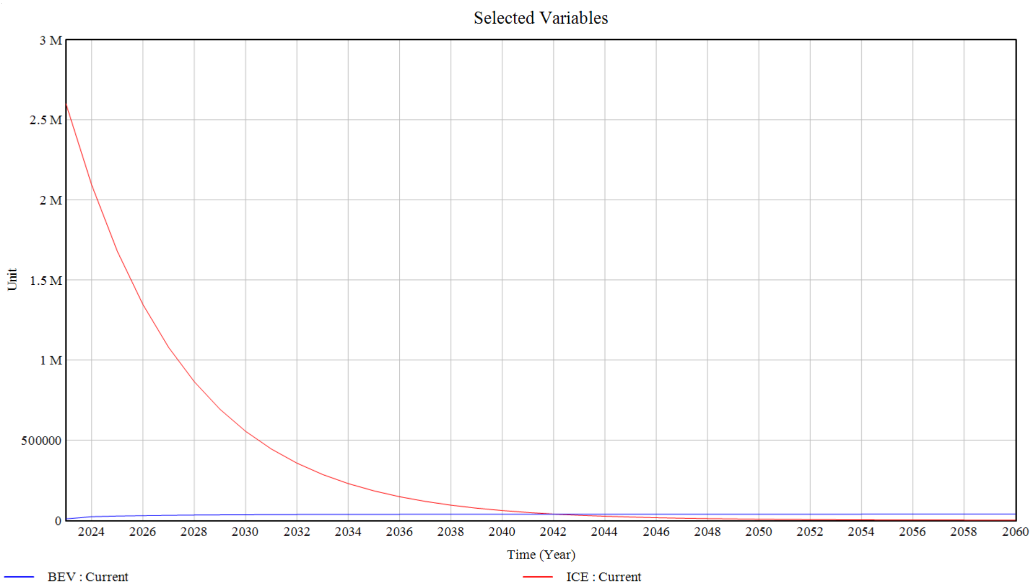

Figure 6. Simulation BEV vs ICE

The introduction of mandatory BEV policies on specific road segments will directly influence the use of ICE vehicles. Travelers on these routes will need to switch to BEVs or use public transportation. When these policies take effect, particularly once their current ICE vehicles reach an average age of five years, individuals will have several options: they can purchase a BEV, use mass transit, or continue driving an ICE vehicle, but with limited access to designated areas. Simulation results indicate a clear trend: BEV adoption increases significantly, while the number of ICE vehicles declines sharply over time. With the enforcement of this policy, the public will essentially choose between buying a BEV, which grants unrestricted access, or utilizing mass transportation for their daily travel needs.

In Jakarta, each car, averaging 40 km per day, produces approximately 3,875 kg of CO_2 annually. By 2023, the estimated number of car owners in Jakarta is around 3.8 million, leading to an overall CO_2 production of about 14.8 billion kg. By 2035, the number of ICE vehicles is projected to decline to 186,213 units, resulting in a total CO_2 emission of 721 million kg—indicating a decrease of 1.2 million kg of CO_2 per year over 12 years.

The mandatory BEV policy aims not only to reduce the number of ICE vehicles and lower emissions but also to alleviate traffic congestion. This reduction in congestion is expected to improve the overall quality of service on roadways. A comparison between road capacity and the number of BEVs is illustrated in Figure 8.

The projected increase in the number of BEVs is expected to reach only 38,000 units by 2060, which represents just 30% of the maximum road capacity of 130,402 units (Level A of Road Services). This level of adoption would still allow BEV users to maintain an average speed of over 40 km/h, potentially accelerating to 55 km/h. This is a significant improvement compared to the previous average speed of only 21 km/h, which placed Jakarta as the 30th city with the worst traffic congestion globally.

Moreover, fuel prices for internal combustion engine (ICE) vehicles significantly impact the adoption of battery electric vehicles (BEVs). A projected rise in fuel prices from IDR 10,000 per liter to IDR 15,000 per liter is expected to increase BEV adoption by an average of 25.5% between 2023 and 2060. This change would elevate the number of BEVs from around 35,400 units to 44,355 units, as shown in Figure 9.

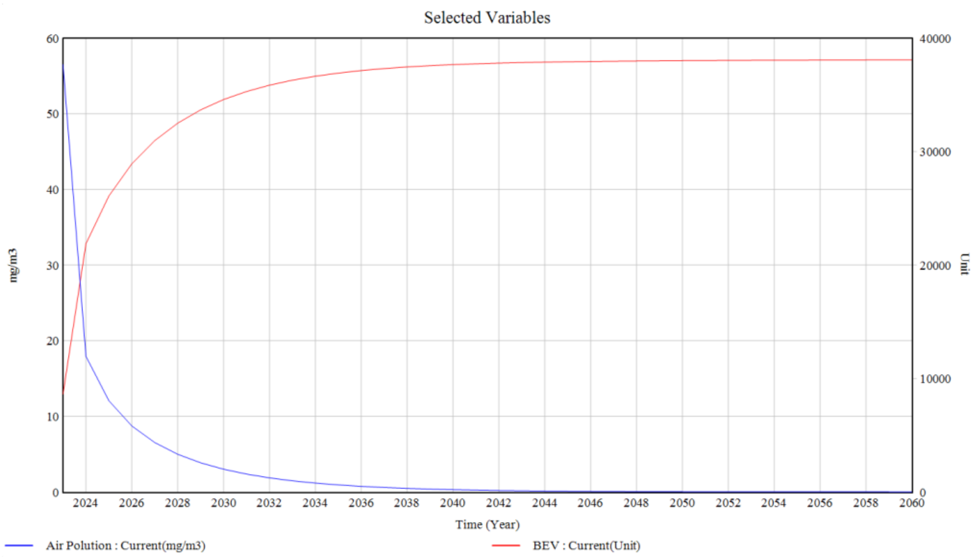

Figure 7. Simulation of air pollution reduction and BEV adoption

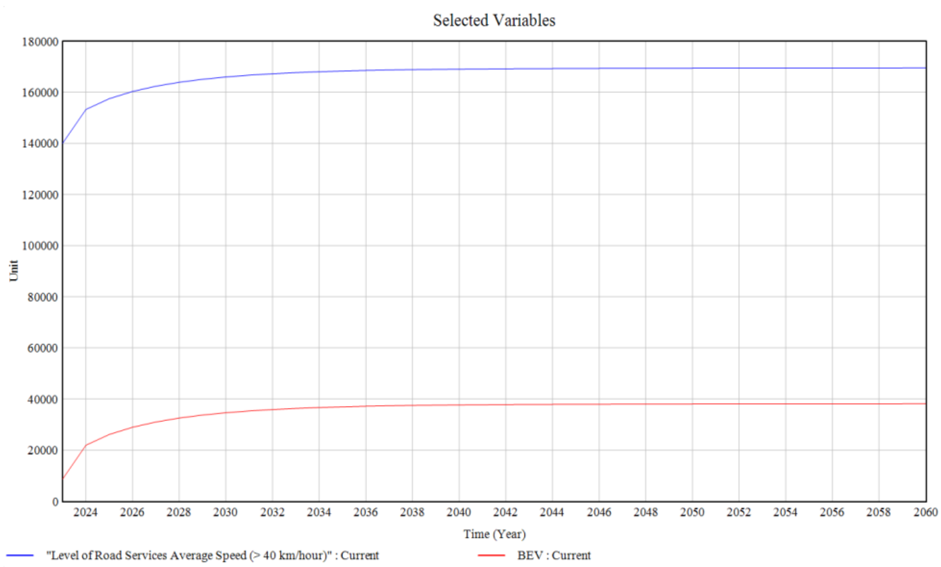

Figure 8. Simulation of BEV vs road capacity

Figure 9. Simulation of BEV adoption by increasing the fuel price

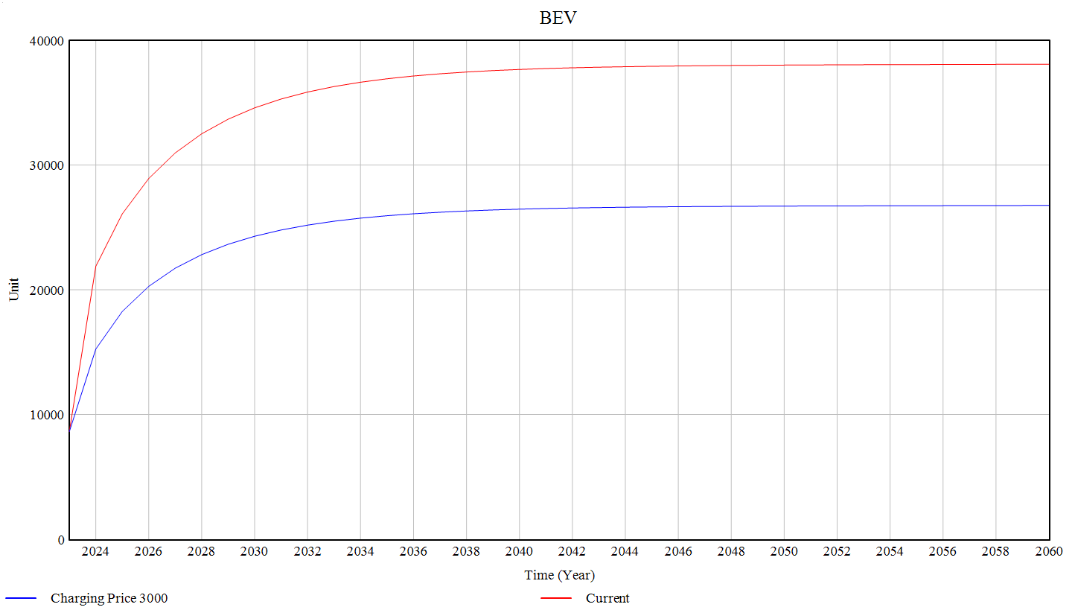

Figure 10. Simulation of BEV adoption by increasing the charging price

Unlike the rising fuel prices for internal combustion engine (ICE) vehicles, a projected increase in electricity costs from IDR 1,500 per kWh to IDR 3,000 per kWh is anticipated to obstruct the adoption of battery electric vehicles (BEVs). This change could lead to an average decline of around 42.37% in BEV numbers from 2023 to 2060, decreasing the total from approximately 35,400 units to 25,000 units, as shown in Figure 10.

5. CONCLUSION

Traffic congestion and pollution are significant challenges that Jakarta, a major urban city, has faced for years. The congestion is driven by factors such as rapid population growth, an increase in the number of vehicles, and the poor state of transportation infrastructure. Pollution stems from emissions produced by vehicles, factories, and other sources.

Although the odd-even policy was introduced to reduce traffic congestion, it has not proven to be a sustainable, long-term solution. This policy mainly impacts private car owners but fails to tackle the underlying issues like the rising vehicle count and insufficient public transportation.

The study suggests that implementing a mandatory Battery Electric Vehicle (BEV) policy could serve as a more effective alternative to the odd-even system. This new policy could significantly improve traffic conditions and related problems, positioning Jakarta as an eco-friendly city and a model for other Indonesian cities.

While the study highlights the advantages of adopting a mandatory BEV policy, several challenges must be addressed for successful implementation. These include the higher upfront costs of BEVs compared to conventional vehicles, the need for supporting infrastructure such as charging stations and grid capacity, and the provision of incentives like tax breaks, subsidies, and preferential parking. Taking these factors into account is essential to encourage consumers to transition to BEVs.

The results of this study, notably the 26.9% annual reduction in pollution linked to mandatory battery electric vehicle (BEV) policies, offer essential insights for policymakers. This substantial decrease underscores the transformative capacity of focused interventions in lowering greenhouse gas emissions and enhancing urban air quality. By emphasizing BEV adoption and expanding mandatory zones, Jakarta can realize significant environmental improvements within a relatively short period.

Additionally, the rapid decline in internal combustion engine (ICE) vehicle usage, as projected in this research, underscores the need to align transportation policies with infrastructure investment, such as improving public transport systems and increasing charging station availability. Policymakers should consider incorporating financial incentives, such as subsidies for BEVs and penalties for ICE vehicles, to expedite this transition.

Moreover, these findings stress the necessity of long-term adaptive strategies. The observed emission reductions suggest that implementing bold policies now could enable Jakarta to achieve or even surpass its 2060 net-zero targets ahead of schedule. This evidence highlights the importance of effective monitoring systems to evaluate the impact of policies and adapt them in response to evolving socioeconomic conditions and technological advancements.

ACKNOWLEDGMENT

The authors sincerely thank both central and local government agencies for their invaluable support in providing the necessary data. This study received no financial support for its research, authorship, or publication.

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NOMENCLATURE

V	Average speed (km/h)
SO_2	Sulfur dioxide
CO	Carbon monoxide
O_3	Oxygen molecules
NO_2	Nitrogen dioxide
PM_{10}	Particulate matter (PM) less than 10 μm
$PM_{2.5}$	Particulate matter (PM) less than 2.5 μm