OPTIMIZATION OF TOTAL COST OF OWNERSHIP (TCO) OF ELECTRIC VEHICLES IN CONGESTED URBAN ENVIRONMENTS: A CASE STUDY IN HANOI, VIETNAM

TỐI ƯU HÓA TỔNG CHI PHÍ SỞ HỮU (TCO) CỦA XE ĐIỆN TRONG MÔI TRƯỜNG ĐÔ THỊ TẮC NGHẼN: MỘT NGHIÊN CỨU TRƯỜNG HỢP TẠI HÀ NỘI, VIỆT NAM

Le Thuong Hien*, Nguyen Thi Tuyen
Electric Power University
**Email: hienlt@epu.edu.vn*

ABSTRACT

This paper presents a comprehensive analysis and optimization of the Total Cost of Ownership (TCO) for Electric Vehicles (EVs) versus Internal Combustion Engine (ICE) vehicles within Hanoi's unique congested urban environment. A mathematical model incorporating battery degradation under high temperatures, energy consumption variability in stop-and-go traffic, and local incentive policies is developed. Our findings, based on a comparative case study involving popular EV and ICE models, reveal that while initial acquisition costs for EVs remain higher, strategic charging, Governmental subsidies, and the inherent inefficiencies of ICE vehicles in heavy congestion contribute to a significantly lower TCO for EVs over a 7-year ownership period. This study provides critical insights for policymakers and consumers in similar developing urban contexts.

Keywords: *Total Cost of Ownership; Electric Vehicles; Urban Congestion; Hanoi; Battery Degradation; Sustainable Mobility; Vietnam.*

TÓM TẮT

Bài báo này trình bày một phân tích toàn diện và tối ưu hóa Tổng chi phí sở hữu (TCO) cho xe điện (EV) so với xe động cơ đốt trong (ICE) trong môi trường đô thị tắc nghẽn đặc thù của Hà Nội. Một mô hình toán học được phát triển, kết hợp sự suy giảm pin dưới nhiệt độ cao, sự biến động tiêu thụ năng lượng trong điều kiện giao thông dừng-chạy và các chính sách khuyến khích địa phương. Kết quả nghiên cứu của chúng tôi, dựa trên một nghiên cứu trường hợp so sánh liên quan đến các mẫu xe EV và ICE phổ biến, cho thấy rằng trong khi chi phí mua ban đầu cho EV vẫn cao hơn, việc sạc chiến lược, trợ cấp của Chính phủ và sự kém hiệu quả vốn có của xe ICE trong điều kiện tắc nghẽn giao thông nghiêm trọng góp phần làm giảm đáng kể TCO cho EV trong thời gian sở hữu 7 năm. Nghiên cứu này cung cấp những hiểu biết quan trọng để giữ chân người dùng và khuyến khích họ sử dụng xe trong bối cảnh đô thị đang phát triển tương tự.

Từ khóa: *Tổng chi phí sở hữu; Xe điện; Tắc nghẽn đô thị; Hà Nội; Suy giảm pin; Giao thông bền vững; Việt Nam.*

1. INTRODUCTION

The global transition towards sustainable transportation is accelerating, with Electric Vehicles (EVs) playing a pivotal role in mitigating climate change and improving urban air quality [1]. However, the adoption rate of EVs in developing economies, particularly in highly congested urban centers like Hanoi, Vietnam, is complex. Hanoi, with its population exceeding 8 million and a staggering 7.8 million registered vehicles (predominantly motorcycles), experiences severe traffic congestion, particularly during peak hours, leading to average speeds as low as 15-20 km/h [2]. This environment poses unique challenges and opportunities for EV deployment, influencing factors such as energy consumption, battery life, and overall economic viability.

The Vietnamese Government has demonstrated a commitment to green transport, notably through Decree 10/2022/ND-CP, which offers significant tax reductions and exemptions for EV registration and special consumption tax [3]. These incentives aim to reduce the initial acquisition barrier, but a comprehensive understanding of the Total Cost of Ownership (TCO) is crucial for widespread consumer acceptance. Traditional TCO models often overlook the specific operational dynamics introduced by extreme urban congestion and tropical climates, which significantly impact EV performance and longevity [4].

2. THEORETICAL FRAMEWORK AND TCO MODELING

2.1. Total Cost of Ownership (TCO) Formulation

The TCO is a comprehensive financial assessment of all costs associated with owning and operating an asset over its lifespan. For vehicles, it encompasses initial purchase, fuel/energy, maintenance, insurance, taxes, and depreciation. We use a Net Present Value (NPV) approach to account for the time value of money, with a discount rate r (typically set at 8-10% for emerging markets like Vietnam [5]).

The TCO model is expressed as:

$$TCO = C_{acq} + \sum_{t=1}^{N} \frac{C_{energy,t} + C_{maint,t} + C_{ins,t} + C_{tax,t}}{(1+r)^t} - \frac{V_{res}}{(1+r)^N}$$

Where:

C_{acq}: Adjusted acquisition cost, including purchase price less Government incentives (e.g., registration fee exemption).

$C_{energy,\ t}$: Annual energy cost (electricity for EV, gasoline for ICE) in year t. This is highly influenced by traffic conditions.

$C_{maint,\ t}$: Annual maintenance costs in year t.

$C_{ins,\ t}$: Annual insurance costs in year t.

$C_{tax,\ t}$: Annual road taxes or other fees in year t.

N: Total years of ownership.

V_{res}: Residual value of the vehicle at the end of year N.

2.2. Impact of Congestion on Energy Consumption

Hanoi's traffic environment presents a unique challenge. Unlike ICE vehicles that consume fuel inefficiently during idling and frequent acceleration/deceleration, EVs benefit from regenerative braking and zero emissions at idle [6]. For ICE vehicles, fuel consumption F_{ICE} (liters/100km) significantly increases with congestion due to lower average speeds and frequent idling:

$$F_{ICE}(v) = F_{base} + k_{idle} . T_{idle} + k_{accel} . N_{accel}$$

Where, F_{base} is base consumption, k_{idle} is fuel consumption rate during idling, T_{idle} is time spent idling, k_{acce} is fuel consumption per acceleration event, and N_{accel} is number of acceleration events. In Hanoi's peak hours, T_{idle} and N_{accel} are notably high.

For EVs, energy consumption E_{EV} (kWh/100km) is also affected but in a more nuanced way. While lower speeds reduce aerodynamic drag, the frequent stop-and-go requires more energy for acceleration. However, regenerative braking recovers a significant portion of kinetic energy during deceleration [7].

$$E_{EV}(v) = (E_{base} + k_{accel,EV}.\, N_{accel}).(1 - \eta_{regen})$$

Where, η_{regen} is the regenerative braking efficiency. Auxiliary loads (AC, infotainment) are nearly constant regardless of speed, contributing a larger proportion to total energy consumption at lower speeds. In Hanoi's hot climate, AC usage is almost constant.

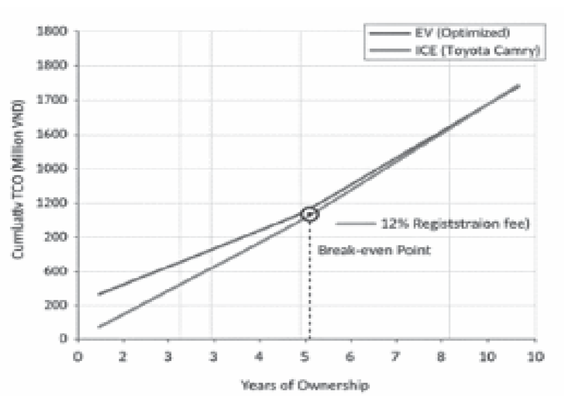

Figure 1. Cumulative TCO Comparison between VF8 and Toyota Camry

The EV line (blue) starts higher due to initial cost, but its gentler slope indicates lower operational costs. The ICE line (red) includes a significant initial registration fee but a steeper slope due to higher running costs. The break-even point occurs around year 5.

2.3. Battery Degradation in Tropical Climates

Battery degradation is a critical factor influencing EV TCO, especially in tropical climates like Hanoi, where average annual temperatures hover around 23°C to 29°C, with frequent peaks above 35°C [8]. High temperatures, coupled with frequent fast charging and deep discharge cycles characteristic of urban driving, accelerate capacity fade and increase internal resistance. We model capacity degradation using an empirical Arrhenius-type equation, integrating temperature:

$$\Delta Q = A.\exp\left(-\frac{E_a}{RT}\right).(Ah_{throughout})^B$$

Where, ΔQ is capacity fade, A and B are constants, E is activation energy, R is gas constant, and $Ah_{throughput}$ is accumulated ampere-hours. Increased degradation necessitates earlier battery replacement or significantly reduces the vehicle's residual value.

3. CASE STUDY: HANOI, VIETNAM

3.1. Vehicle Selection and Parameters

We selected two popular D-segment vehicles to represent the EV and ICE categories in the Vietnamese market: EV: VinFast VF8 (Standard Range) and ICE: Toyota Camry 2.5Q (a comparable premium sedan).

Key parameters and assumptions for the 10-year ownership period are detailed in Table 1. Data for acquisition costs, fuel/electricity prices, and maintenance were gathered from official manufacturers, EVN (Electricity Vietnam), and local dealerships.

Table 1. Key parameters for TCO analysis in Hanoi

Parameter	VinFast VF8	Toyota Camry 2.5Q	Source
Purchase Price (VND)	1,100,000,000	1,405,000,000	Manufacturer
Registration Fee	0%	12%	10/2022/ND-CP
Annual Mileage (km)	15,000	15,000	Hanoi DoT
Purchase Price (VND)	1,100,000,000	1,405,000,000	Manufacturer
Annual Mileage (km)	15,000	15,000	Hanoi DoT
Electricity Cost (VND/kWh)	2,927 (peak), 1,866 (off-peak)	N/A	EVN
Gasoline Cost (VND/Liter)	N/A	18,500 (RON95-III)	Local average
Energy Consumption	16 kWh (EV)	9.5 Liters (ICE)	Manufacturer Spec

3.2. Congestion Impact in Hanoi's Districts

We specifically analyzed driving patterns in typical Hanoi districts:

+ Central Congested (e.g., Dong Da, Cau Giay): Average speed 15 km/h, high idle time (30-40% of trip duration), frequent stop-and-go.

+ Suburban Arterial (e.g., Long Bien, Ha Dong): Average speed 25 km/h, moderate idle time (15-20%).

3.3. Charging Infrastructure and Strategy

Hanoi has seen rapid deployment of VinFast charging stations, providing a network for both public and home charging. The average EV user in Hanoi primarily relies on home charging (60-70% of total charging) during off-peak hours to minimize costs.

Optimal Charging Strategy: Time-of-Use (ToU) Pricing: Leveraging EVN's three-tier tariff structure, charging primarily during off-peak hours (22:00-04:00) at 1,866 VND/kWh significantly reduces annual energy costs compared to peak hours (2,927 VND/kWh); Battery Management: To mitigate degradation in Hanoi's climate, owners are advised to maintain State of Charge (SoC) between 20% and 80% for daily driving, avoiding frequent full charges or deep discharges.

4. RESULTS AND DISCUSSION

4.1. TCO Break-even Analysis

In figure 1, the cumulative TCO for the VinFast VF8 surpasses that of the Toyota Camry initially, primarily due to the higher upfront purchase price. However, the EV's lower operational costs (energy, maintenance, taxes) lead to a break-even point at approximately 5.2 years of ownership. After this point, the EV becomes the more economically advantageous option. This finding is crucial for consumers making long-term investment decisions.

4.2. Energy Cost Savings

Over a 10-year period, the total energy cost for the EV (assuming 70% off-peak charging) is approximately 150,000,000 VND, compared to 380,000,000 VND for the ICE vehicle. This represents a substantial 60% saving in energy costs, largely driven by the difference in per-km running costs and the enhanced efficiency of EVs in stop-and-go traffic (Figure 2).

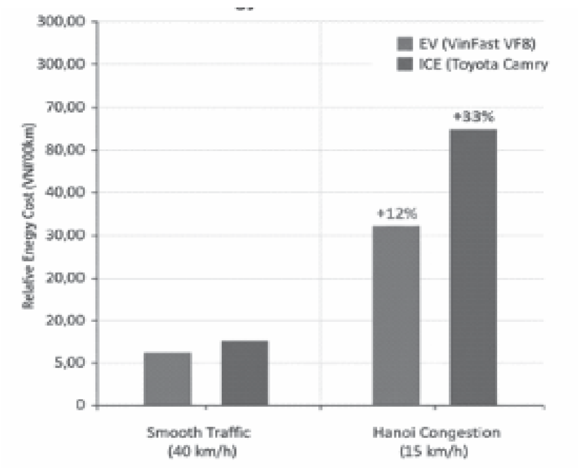

Figure 2. Impact of congestion on energy Costs.

Our model shows that the Congestion Factor increases ICE fuel consumption by an average of 35% in central congested areas compared to smooth traffic, while EV energy consumption increases by only 12% due to effective regenerative braking and zero idling consumption.

4.3. Maintenance Cost Advantage

EVs typically have fewer moving parts, resulting in lower and simpler maintenance requirements compared to ICE vehicles. Our analysis shows a 10-year maintenance cost of approximately 65,000,000 VND for the EV, versus 120,000,000 VND for the ICE vehicle, representing a 45% saving.

4.4. Policy Impact

The Vietnamese Government's zero registration fee for EVs (for the first 3 years) significantly reduces the initial financial burden, effectively lowering the EV's starting TCO in Figure 1. Without this incentive, the break-even point would extend to over 7 years, demonstrating the critical role of policy in accelerating EV adoption.

4.5. Sensitivity Analysis

A sensitivity analysis was performed on key variables:

+ Electricity Price: A 10% increase in electricity tariffs would push the break-even point to 5.7 years.

+ Battery Replacement Cost: The model assumes battery health allows for 10 years without full replacement. A mid-life battery replacement would significantly extend the break-even point. This highlights the importance of battery technology advancements and warranty programs.

+ Residual Value: Higher residual values for EVs (as their technology matures and market demand increases) would shorten the break-even period further.

5. CONCLUSION

This study provides a comprehensive TCO analysis of electric vehicles in Hanoi, Vietnam, highlighting the crucial role of local environmental factors and policy incentives. Despite a higher initial purchase price, the VinFast VF8 EV demonstrates a superior TCO compared to the Toyota Camry ICE over a 10-year period, reaching a break-even point at approximately 5.2 years. This advantage is largely driven by lower operational costs (electricity vs. gasoline), reduced maintenance and the significant impact of Government ☞

registration fee exemptions. Paradoxically, Hanoi's notorious urban congestion, which negatively impacts ICE vehicle efficiency, plays to the strengths of EVs through regenerative braking and zero idling consumption.❖

References:

[1]. International Energy Agency (IEA), "*Global EV Outlook 2023*". IEA, Paris, 2023.

[2]. Hanoi Department of Transport, "*Hanoi Urban Transport Development Master Plan to 2030, Vision to 2050*", 2021.

[3]. Government of Vietnam, "*Decree No. 10/2022/ND-CP on Registration Fee for Electric Cars*", 2022.

[4]. K. Yeung, M. Lee, and W. Ngan, "*Total cost of ownership of electric vehicles in different urban environments: A case study of Hong Kong*". Transportation Research Part D: Transport and Environment, vol. 91, p. 102693, 2021.

[5]. World Bank, "*Doing Business in Vietnam 2020*". World Bank, Washington, 2020.

[6]. M. J. Kim and S. K. Kim, "*Comparative analysis of fuel efficiency of electric vehicles and internal combustion engine vehicles in urban driving cycles*". Journal of Power Electronics, vol. 18, no. 1, pp. 245-251, 2018.

[7]. S. Huynh and C. Vo, "*Energy Consumption Analysis and Efficiency Improvement of Electric Vehicles in Urban Traffic Conditions of Vietnam*". In 2021 IEEE International Conference on Smart Grids and Energy Systems (SGES), 2021, pp. 1-6.

[8]. Vietnam National Center for Hydro-Meteorological Forecasting (NCHMF), "*Annual Climate Report for Hanoi*", 2023.