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Dynamics of the Malaysian Automotive Transition: A Competitive Lotka-Volterra Analysis of Electric Vehicle (EV) Adoption

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ABSTRACT

The Malaysian automotive market is undergoing a critical transition from Internal Combustion Engine Vehicles (ICEVs) to Electric Vehicles (EVs). Despite increasing policy support and expanding charging infrastructure, EV adoption remains relatively low, prompting inquiries into whether EVs will ultimately supplant ICEVs or establish a long-term coexistence. Understanding these competitive dynamics is vital for assessing Malaysia's progress toward sustainable transportation. This study introduces a two-species Lotka–Volterra competition model to quantify the market interplay between ICEV and EV sales, capturing intrinsic growth rates, self-limitation constraints, and inter-technology competition. Model parameters are estimated using Malaysian automotive sales data (2019–2024) via nonlinear least squares optimization with MATLAB's *fminsearch* algorithm. The system's dynamics are evaluated through equilibrium and eigenvalue stability analyses, corroborated by numerical simulations and phase portraits. The findings indicate that, under current conditions, system trajectories gravitate toward an ICEV-dominant equilibrium despite the rising adoption of EVs. This underscores that ICEVs currently maintain structural dominance within the Malaysian automotive landscape. Ultimately, this research highlights the efficacy of dynamical systems modelling in deciphering technological competition and market transitions

Keywords: Electric Vehicle Adoption, Lotka-Volterra Competition Model, Dynamical System Modelling, Automotive Market Dynamics, Technological Competition.

INTRODUCTION

The global automotive industry is undergoing a major shift from traditional Internal Combustion Engine Vehicles (ICEVs) to Electric Vehicles (EVs), fuelled by technological breakthroughs and carbon reduction targets. This transition has disrupted the status quo, moving away from a market dominated by established brands to one featuring new, tech-driven entrants from emerging economies. As EVs become more competitive, the relationship between these two technologies has evolved into a dynamic competition that is fundamentally reshaping the sector.

In Malaysia, this trend is reflected in a domestic market historically dominated by ICEVs due to their lower costs and established infrastructure (Tham, 2021). While the government has introduced tax incentives and infrastructure investments to accelerate the shift, EV adoption remains at a modest 2.6% of the national market share (MIDA, 2024). High upfront costs and limited charging facilities continue to pose challenges. However, the segment is becoming increasingly competitive as Chinese manufacturers like BYD rapidly expand their presence, growing their market share in 2024 and challenging both traditional manufacturers and other EV players as reported by Malaysian Automotive Association (2025).

Understanding the precise nature of how these two vehicle technologies compete is critical for policymakers and industry stakeholders. Traditional economic frameworks often analyze market shares in isolation, failing to capture the complex, nonlinear feedback loops and reciprocal influences inherent in technological rivalries. To bridge this analytical gap, this study adapts mathematical models from ecological systems to decode the dynamics of technological displacement.

The Lotka-Volterra competition model, originally formulated to map biological interactions, provides an ideal framework. By treating each vehicle technology as a distinct "population" vying for limited market resources, we can accurately model their competitive growth, market saturation, and mutual suppression. The versatility of the Lotka-Volterra model has been proven extensively beyond ecology. For instance, Das and Gupta (2011) demonstrated its efficacy in mapping complex nonlinear population dynamics using fractional equations , while Boudjellaba and Sari (2009) adapted it to understand multi-species interactions.

Crucially, this framework has also been successfully applied to technological and economic forecasting. Hung, Tsai, and Wu (2014) modified the Lotka-Volterra model to accurately predict retail market competition in Taiwan. Similarly, Puliafito, and Grand (2007) utilized a generalized version to analyse the macroeconomic interplay between population growth, economic activity, and environmental impact, proving the model's capacity to forecast complex systemic trends over the long term. Abdul Latif et al. (2023) used Lotka-Volterra model to represent the competition market dynamics between iOS and Android consumers.

Building on these cross-disciplinary successes, this paper applies a two-species Lotka-Volterra framework to evaluate the escalating rivalry between ICEVs and EVs within the Malaysian automotive sector. Specifically, this study aims to formulate a competitive mathematical model that accurately maps the dynamic interactions and competitive pressures between these two vehicle populations. By estimating the model's parameters using real-world Malaysian automotive sales data spanning from 2019 to 2024 (Malaysian Automative Association, 2025), the research rigorously analyses the system's long-term dynamics. Ultimately, through comprehensive equilibrium analysis and numerical simulations, this work seeks to identify the precise market conditions that will dictate whether one technology achieves absolute dominance or if both settle into a stable coexistence.

APPLICATION OF COMPETITION MODEL IN EV ADOPTION

The Lotka-Volterra equations, also known as predator-prey equations, are a classic landmark in the history of mathematical biology, that consist in a pair of firstorder nonlinear differential equations which model the dynamics of two interacting populations. The interaction between Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs) are represented using a two-species Lotka–Volterra competition model. The system is expressed as the following nonlinear differential equations

Equation 1 and description of the parameters model as in Table 1:

$$\frac{dx}{dt} = (a_1 - b_1 x - c_1 y)x = a_1 x - b_1 x^2 - c_1 xy$$
$$\frac{dy}{dt} = (a_2 - b_2 y - c_2 x)y = a_2 y - b_2 y^2 - c_2 yx \tag{1}$$

Where x represents the sales of ICEVs, y represent the sales of EVs, a_1, a_2 represent intrinsic growth capabilities, b_1, b_2 represent self-limitation coefficients due to market saturation, and c_1, c_2 are the inter-technology competition rates.

Table 1

Description of the variables and assumed parameter values used for the competition model for EV adaoption.

Variables / Parameters	Description	Values
x	represent sales of ICEVs	-
y	represent sales of EVs	-
a_1	ICEV's growth capability	1.2
a_2	EV's growth capability	1.0
b_1	self-limitation coefficient of ICEVs due to market saturation	0.4
b_2	self-limitation coefficient of EVs due to market constraints	0.35
c_1	rate of competition between ICEV and EV for ICE	1.1
c_2	rate of competition between ICEV and EV for EV	1.3

Steady-States Analysis

In order to examine dynamical behaviour of the ICEVev competition model, the equilibrium points and the stability of the equilibrium points are studied with the help of the Jacobian matrix and eigenvalue approach. Equilibrium points occur when Equation 1 was set to zero, which implies

$$x(a_1 - b_1 x - c_1 y) = 0, \qquad y(a_2 - b_2 y - c_1 x) = 0 \tag{2}$$

Solving the above Equation 2 gives four equilibrium points:

- $P_1 = (0,0)$ - Both ICEV and EV sales are zero.
- $P_2 = \left(\frac{a_1}{b_1}, 0\right)$ - ICEVs dominate while EVs are absent.
- $P_3 = \left(0, \frac{a_2}{b_2}\right)$ - EVs dominate while ICEVs vanish.
- $P_4 = \left(\frac{a_1 b_2 - a_2 c_1}{b_1 b_2 - c_1 c_2}, \frac{a_2 b_1 - a_1 c_2}{b_1 b_2 - c_1 c_2}\right)$ - Coexistence equilibrium where

The local stability of the system is determined using the Jacobian matrix:

$$J(x,y) = \begin{bmatrix} a_1 - 2b_1 x - c_1 y & -c_1 x \\ -c_2 y & a_2 - 2b_2 y - c_2 x \end{bmatrix} \tag{3}$$

The eigenvalues λ_1, λ_2 are obtained from the characteristic equation

$$\lambda^2 - (\text{Tr}\,(J))\lambda + (\det\,(J)) = 0$$

Where Tr (J) is the trace and det (J) is the determinant of the Jacobian matrix.

I. The Jacobian matrix of the Equation (3) at $P_1 = (0,0)$ has eigenvalues of $\lambda_1 = a_1$ and $\lambda_2 = a_2$, since both are positive, it is an unstable node.

II. The Jacobian matrix of the Equation (3) at $P_2 = \left(\frac{a_1}{b_1}, 0\right)$ has eigenvalues of $\lambda_1 = -a_1$ and $\lambda_2 = a_2 - \frac{c_2 a_1}{b_1}$. If $a_2 < \frac{c_2 a_1}{b_1}$, then both are negative and it is stable node. Otherwise it will becomes a saddle point.

III. The Jacobian matrix of the Equation (3) at $P_3 = \left(0, \frac{a_2}{b_2}\right)$ has eigenvalues of $\lambda_1 = a_1 - \frac{c_1 a_2}{b_2}$ and $\lambda_2 = -a_2$. If $a_1 < \frac{c_1 a_2}{b_2}$, then both are negative and it is stable node. Otherwise it will becomes a saddle point.

IV. The Jacobian matrix of the Equation (3) at $P_4 = \left(\frac{a_1 b_2 - a_2 c_1}{b_1 b_2 - c_1 c_2}, \frac{a_2 b_1 - a_1 c_2}{b_1 b_2 - c_1 c_2}\right)$ will give trace and determinant as $Tr(J) = -(b_1 x^* + b_2 y^*)$ and $\det(J) = (b_1 b_2 - c_1 c_2) x^* y^*$, therefore if

$$b_1 b_2 > c_1 c_2$$

Then $\det(J) > 0$ and $Tr(J) < 0$, giving stable node or spiral. Otherwise it will becomes a saddle point.

Numerical Simulation

Phase portrait simulations depict the behavior of the system to various initial conditions. The trajectories in Figure 1 indicate that the system is driven to one of the stable equilibria finally with a given starting market share. The saddle equilibrium generated a separatrix that separates the state space into two parts, one of which results in the ICEV dominance, the other in the EV dominance. This behaviour shows how market results are sensitive to the initial adoption levels and rivalry.

The analytical findings are further validated by numerical calculation with MATLAB. The time-series solution in Figure 2 indicates that ICEV sales move towards equilibrium steadily and the EV sales reduce with the selected parameter values as in Table 1. This finding implies that ICEVs will persist with the hypothetical parameter regimes, but other parameter values or policy measures can change the market to be dominated by EV.

Sensitivity analyses, conducted by isolating and varying specific competition parameters, further reveal the impact of inter-technology rivalry on long-term dynamics. Increasing the competition coefficient amplifies the suppressive effect EVs exert on ICEVs, hindering ICEV growth. Conversely, a lower allows EVs to capture greater market share. Cross-market competition is a primary driver determining dominance versus coexistence. Similarly, varying confirms that asymmetric competition heavily influences the survival and penetration of emerging EV technologies.

Figure 1

Phase Portrait of EV vs ICEV Market Competition Using Assumed Parameter Values in Table 1.

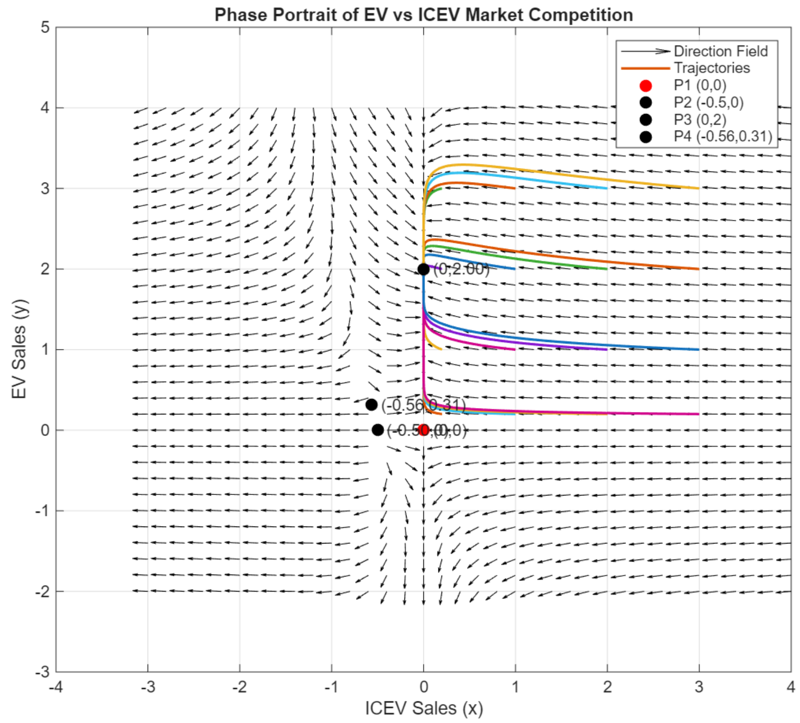
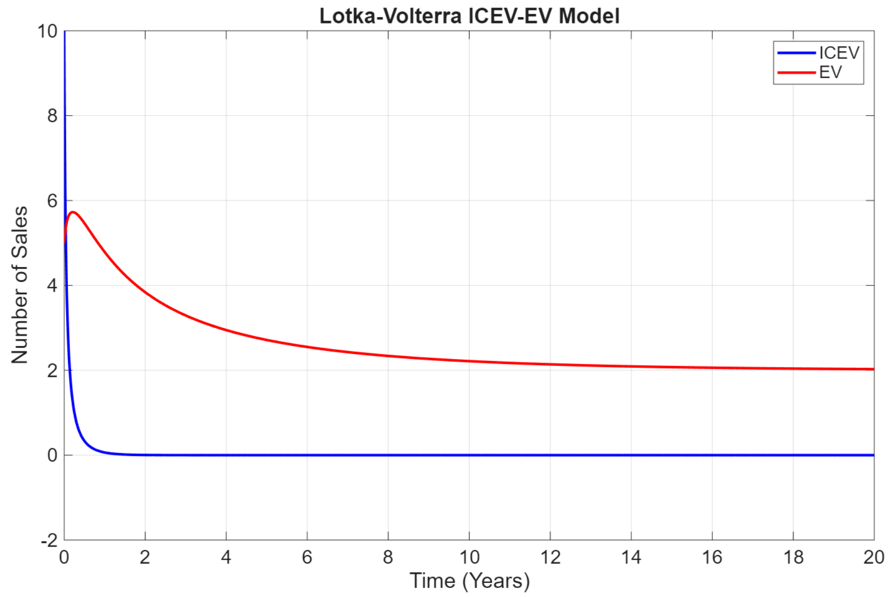


Figure 2

Numerical Solution for ICEVs and EVs.



The simulations were done in MATLAB by correcting the estimated parameters that came out of the optimisation process. The change in the values of the parameters results in the change of the trajectory of the ICEV and EV populations, providing an opportunity to examine the potential scenarios of market evolution

Figure 3

Simulated trajectories of ICEVs and EVs under varying rates of competition c_1

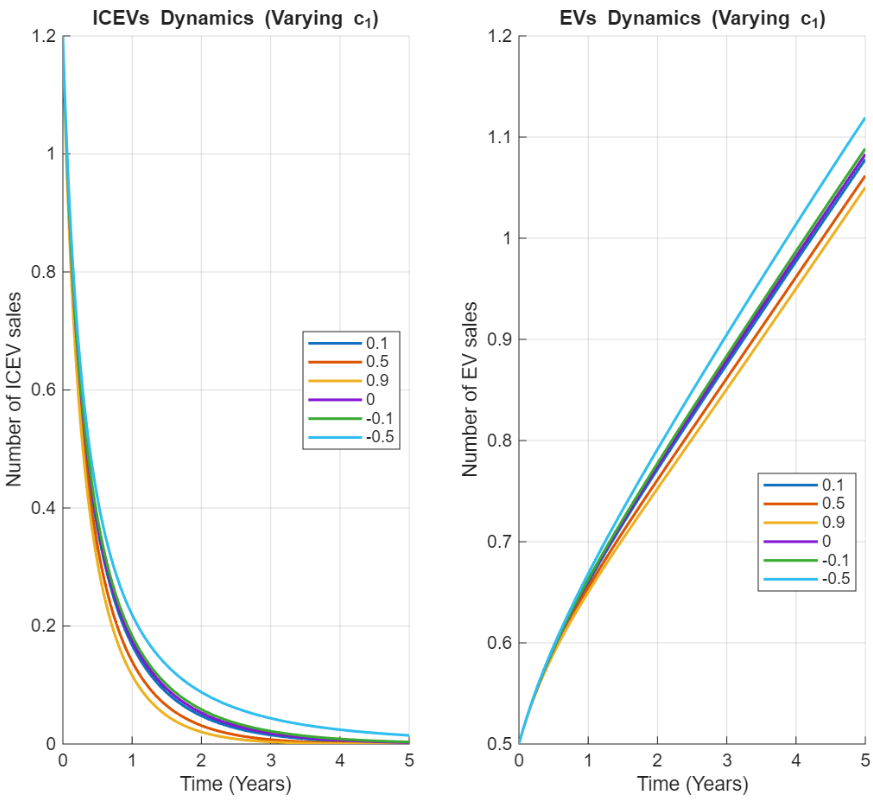
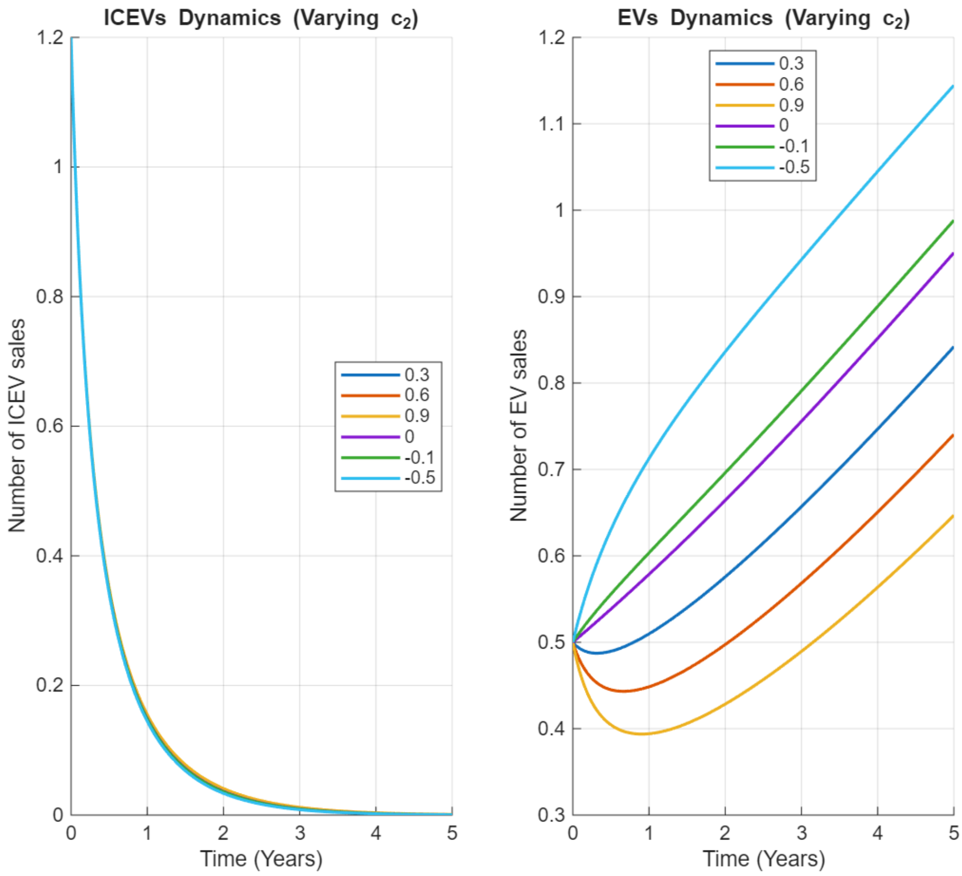


Figure 3 is a numerical simulation attained by changing the competition coefficient c_1 which is the effect of EVs on ICEVs. The higher the c_1, the more suppressive effect EVs develop on the ICEVs, and the lower the growth of the ICEV and its potential market fall. On the other hand, when c_1 is low, the competitive force is decreased and the EVs control the market. The evaluation through the various simulation horizons assures us of constant numerical solutions with dissimilar levels of competition. These findings show that cross-market competition is a major factor in determining the situations of dominance and coexistence.

Figure 4 illustrates numerical findings of the bending of competition coefficient c_2 which is a measure of the influence of ICEVs on EVs. Greater competition by ICEVs inhibits the development of EVs, and pushes them out of the market, whereas less competitive pressure permits EVs to take over. These simulations are limited to reasonable time horizons in order to have credible numerical solutions. The findings validate the theory that asymmetric competition is a major determinant of market outcomes and conditions of coexistence.

Figure 4

Numerical Solution for ICEV and EV but varying c_2



PARAMETER ESTIMATION

Parameter estimation is the process of determining unknown model parameters so that the mathematical model best fits observed real-world data. In this study, parameter estimation is used to identify the intrinsic growth rates, self-limitation coefficients, and competition parameters of the ICEV–EV model using Malaysian automotive sales data from Malaysian Automotive Association (2025). The parameters are estimated by minimizing a nonlinear least squares objective function defined as the sum of squared errors (SSE) between the model predictions and the observed data. MATLAB's *fminsearch*, which is based on the Nelder–Mead simplex algorithm (Equation 2), is employed for this purpose. The use of *fminsearch* is appropriate as the model is nonlinear and does not require derivative information, making it suitable for differential equation–based models.

$$SSE = \sum_{t=1}^{n} [(x_{model}(t) - x_{data}(t))^2 + (y_{model} - y_{data}(t))^2] \tag{4}$$

The estimated parameters (Table 2) offer profound insights into the market structure. The negative and values suggest that ICEV sales are no longer driven by endogenous growth but are instead experiencing saturation or decline. This reflects a mature market constrained by external pressures rather than organic expansion. Conversely, the positive EV growth factor reflects increasing consumer adoption spurred by recent policy incentives. The relatively low value indicates that EVs have not yet reached market saturation, aligning with their early-stage growth phase. Furthermore, the positive indicates that EV expansion suppresses ICEV sales, while the negative suggests that ICEVs exert a comparatively weaker competitive influence on EV adoption, highlighting an asymmetric rivalry.

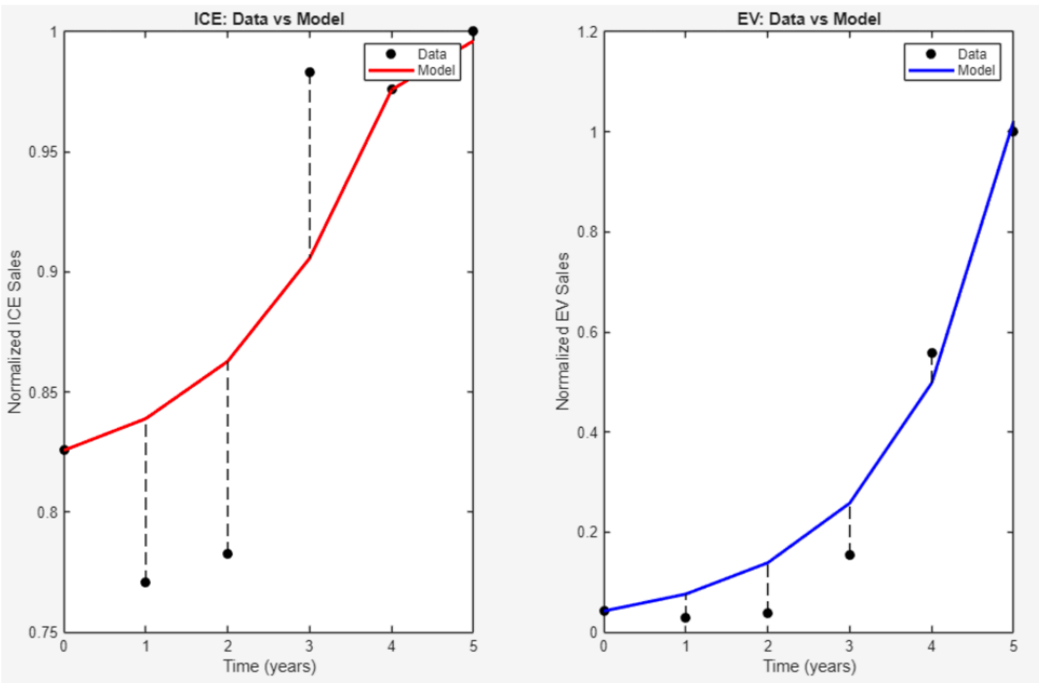
Table 2

The values of estimated parameters using fminsearch in MATLAB.

Variables / Parameters	Description	Estimated Values
a_1	ICEV's growth capability	-1.5842
a_2	EV's growth capability	-1.9581
b_1	self-limitation coefficient of ICEVs due to market saturation	0.4936
b_2	self-limitation coefficient of EVs due to market constraints	0.3150
c_1	rate of competition between ICEV and EV for ICE	-0.1121
c_2	rate of competition between ICEV and EV for EV	-0.3219

Figure 5

Model Calibration Results: Simulated Trajectories Versus Observed Market Data for ICEVs and EVs.



The model achieved an excellent overall fit, yielding an SSE of just 0.0446. The calculated values are 0.7058 for ICEVs and 0.9650 for EVs (Figure 5). The superior fit for EVs is attributed to the smooth, monotonic nature of early-stage adoption, which aligns perfectly with the continuous nonlinear growth assumptions of the Lotka-Volterra framework. ICEV sales, however, exhibit short-term fluctuations driven by external economic factors and policy shifts, making them harder to map perfectly with a smooth dynamical system. While the model slightly underestimates early EV growth (likely due to sudden government incentives) and overestimates late-stage ICEV stability, it highly succeeds in capturing the macro-level trajectory of the market transition.

CONCLUSION

This study successfully formulated a competitive Lotka-Volterra mathematical model to evaluate the market dynamics between Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs) in Malaysia. The analytical findings reveal multiple theoretical equilibrium states, highlighting potential market outcomes that range from absolute dominance by either technology to a fragile, unstable coexistence. By estimating parameters using real-world Malaysian automotive sales data, the model demonstrated its capability to accurately replicate macro-level market trends while maintaining high computational efficiency. Crucially, both the stability analysis and numerical simulations underscore that long-term market trajectories are acutely sensitive to initial market conditions and the intensity of inter-technology competition. Ultimately, this study demonstrates the profound utility of dynamical systems modeling in deciphering technological competition and forecasting transitional shifts within the automotive industry. Future studies should build upon this foundational framework by integrating exogenous variables—such as targeted government policies, fluctuating fuel prices, and the expansion of charging infrastructure—to further refine the model's predictive accuracy.

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Conflict of Interest
The authors have no conflicts of interest to declare.

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