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Growth Mechanism and Synchronization Effect of China's New Energy Vehicle Enterprises: An Empirical Analysis Based on Moving Logistic and Kuramoto Model

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Abstract: The primary purpose of this paper is to discuss whether NEV enterprises can achieve synchronous effects with the whole Chinese automobile industry in terms of growth mode. In this paper, we study the development of new energy vehicles from the perspective of ecosystem. Growth mechanisms and synchronization effects also exist in new energy enterprise populations, just like biological populations in natural ecosystems. Here, we propose a moving logistic model to analyze the growth mechanism of new energy vehicle enterprises and obtain serial data of intrinsic growth rate, internal inhibition coefficient, and theoretical maximum sales volume. The intrinsic growth rate and theoretical maximum sales volume show an initial trend of decline followed by recovery. The evaluation results of coupling degree and synchronization of the new energy vehicle population were obtained through the measurement of the Kuramoto model and its derivative model. The coupling degree of the new energy vehicle population is not high, and the synchronization effect fluctuates and oscillates. The change trend of synchronization effect is similar to that of intrinsic growth rate and theoretical maximum sales volume. This phenomenon shows that the new energy vehicle population has been significantly affected by changes in the external market environment. The analysis method of enterprise growth mechanism based on the moving logistic model and the measurement method of coupling degree and synchronization effect based on the Kuramoto model and its derivative models proposed in this paper effectively achieve the research objectives of this paper.

Keywords: new energy vehicles (NEVs); moving logistic regression; Kuramoto model; growth mechanism; synchronization effect

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1. Introduction

The gradual popularization of automobiles is influencing the Earth's atmospheric environment [1]. The extensive application of new energy vehicles (NEVs) can effectively counter such damage. Most scholars use a comprehensive evaluation method to study market potential and development models of NEVs [2,3]. At present, research is mainly carried out from two perspectives: technology and environmental protection characteristics of NEVs and market performance, both of which are inseparable from policy effect analysis [4]. New energy vehicles in China have achieved remarkable market growth [5], although they may not catch up with the global advanced level of technology and market development [6]. Therefore, industrial policies should promote technological innovation [7]. New energy vehicles can effectively alleviate air pollution [8–10], but this depends on clean power generation capacity and environmental protection efficiency [11–14]. The market acceptance of new energy vehicles has also become a research hotspot [15–17]. Charging facilities and supply chain risks restrict the development of new energy vehicles [18–20].

There are still some research topics to be solved in relevant fields. (1) Most current research focuses on the group of new energy vehicle manufacturers, so researchers need to pay more attention to individual enterprises. (2) Few studies have been conducted on the interaction between enterprises. The competition and synergy between different enterprises in an industry is a popular issue in industry research. Research on the symbiotic relationship of related industries is insufficient. (3) Both policy research and market research focus on overall performance, with a lack of analysis on the symbiotic relationship and synchronization of symbiotic behavior of new energy enterprises. (4) Current research methods are mostly simple mathematical analysis and isolated models, lacking systematic analysis steps and methods.

Given the above issues, the main research goal of this paper is to construct a dynamic model to illustrate the market growth mechanism of new energy vehicles in China, compare and analyze the synchronous effect of the development of new energy vehicles and the whole automobile market, and comprehensively analyze the development trend of new energy vehicles. This paper fulfills the following research objectives: (1) Appropriate models are selected and constructed to analyze the growth mechanism of NEVs. (2) An intuitive and convenient method is designed to evaluate the growth performance of NEVs. (3) The symbiosis and synchronization of the growth of NEVs are evaluated in order to deeply analyze the growth behavior of enterprises. The research highlights of this paper are as follows: (1) The moving logistic model represents a new method to measure the growth mechanism of enterprises. (2) Using the moving logistic model, the intrinsic growth rate, internal inhibition coefficient, and theoretical upper limit of sales volume of enterprises can be calculated. (3) Based on the synchronization effect and coupling parameter values, the symbiotic characteristics of enterprise population can be summarized.

2. Methods and Data

(1) This study investigates the growth mechanism of China's NEV enterprises from the perspective of ecosystems. (2) A moving logistic model is constructed to analyze the dynamic growth mechanism of enterprise sales data, and the population growth parameters of the sample enterprises are calculated. (3) We use the deformation and derivative Kuramoto model to measure the population-coupling degree of sample enterprises and the synchronization effect level of the whole population. The process and technical route of this study are shown in Figure 1.

Step	1			2	
Research contents	Growth mechanism of new energy vehicles			Synchronic effect	
Research method	Moving logistic Model			Kuramoto Model	Kuramoto Derivative Model
Research results	Intrinsic growth rate Internal suppression coefficient Theoretical upper limit of sales volume	Data normalization →	Phase conversion →	Coupling degree	Synchronization effect level

Figure 1. Technical route.

2.1. Ecological System View

The network architecture [21] and mutualistic mechanisms [22] of natural ecosystems comprise a complex, multilevel network [23]. Socioeconomic systems and natural ecosystem have extensive similarities in terms of operation mechanisms and evolution characteristics. Ecology is a science that explores the relationship between individuals and the environment. Adner defines the ecosystem as a composite interaction system to realize the main value proposition [24]. Multilateral interdependence and symbiosis cannot be regarded as a simple superposition of multiple binary relations. This symbiotic relationship makes the ecosystem a kind of new economic relationship in other theories such as transaction cost economics, value chains, and strategic alliance networks. [25,26]. Socioeconomic focuses on coevolution [27]. Through the process of coevolution, the complementarity between two organizations is strengthened. Coevolutionary dynamics can occur both within and between ecosystems [28–30]. In a socioeconomic ecosystem, the essence of coevolution between enterprises is to continuously innovate. The coevolution of ecosystems includes the symbiotic relationship of markets and enterprises [31,32]. The population dynamics model can express the symbiotic relationship between populations [33–35].

2.2. Population Dynamics

The classical single population growth dynamics system (logistic model [31–35]) can be expressed as follows:

$$g_1(t) = \frac{dN_1(t)}{dt} = \alpha_1 N_1 \left(1 - \frac{N_1}{K_1}\right) \tag{1}$$

where:

$g_1(t)$ is the growth rate of stage t;
$N_1(t)$ is the population size of stage t;
K_1 is the largest population size;
α_1 is the intrinsic growth rate; and
$\left(1 - \frac{N_1}{K_1}\right)$ is the growth retardation factor.

In this study, $g_1(t)$ is the growth rate of auto product sales (NEV sales volume) in stage t, $N_1(t)$ is the sales scale of auto products in phase t, K_1 is the largest sales scale of automobile products in theory, and α_1 is the intrinsic growth rate of NEV sales volume.

Based on relevant research [36,37], we propose the following measurement models:

$$\begin{aligned} &\text{Because: } dN_1(t) \approx \Delta N_1(t), \Delta N_1(t) = N_1(t) - N_1(t-1), dt \approx \Delta t = t - (t-1) = 1. \\ &\text{Therefore: } g_1(t) \approx \Delta N(t) = \alpha_1 N_1(t-1) + \gamma_1 N_1^2(t-1) \end{aligned} \tag{2}$$

In the actual regression model, $N(t-1)$ and $\Delta N(t)$ can be obtained according to the time series data $N(t)$. Then, α_1 and γ_1 can be obtained by conducting a regression operation.

Normally, $\alpha_1 > 0$, which represents a synergy within an automotive product population, known as the enterprise internal collaboration coefficient. When $\alpha_1 > 1$, there are significant synergistic effects within the population.

Set $\gamma_1 = -\frac{\alpha_1}{K_1}$. Usually, $\gamma_1 < 0$ is used to express the competition effect within the automobile product population, known as the enterprise internal competition coefficient or the product population density inhibition coefficient.

Another common model in population dynamics is the Lotka–Volterra model, which is more suitable for expressing interaction effects between populations [38–40] but has limitations on population dimensions. Furthermore, the Lotka–Volterra model cannot explain the synchronization effect, so it is not suitable for this study.

2.3. Synchronous Effect Model

An ecosystem is a typical complex system network. A complex system network, often viewed as a system of things that are interconnected in a particular relationship, is dynamic and constantly changing, and each vertex exhibits dynamic behavior, with interaction between vertices. Such dynamic behavior of networks [41,42] has aroused strong interest among scholars in various fields, becoming a research hotspot.

In a dynamic system composed of multiple vibrators with identical or similar properties, the vibrators in the system evolve over time under certain initial conditions through coupling, and the state variables of the final vibrators maintain a certain relative relationship, which is called synchronization [43]. In a broad sense, synchronization includes phase synchronization and frequency synchronization. As a representative, self-organizing, cooperative behavior, synchronous emergence exists in many natural systems. It is essential to understand the realization of some functions [44]. For example, Josephson junction, collective behavior in the power grid, collective discharge of brain neurons, synchronous flicker of fireflies, deer herd activities, and the emergence of traffic accidents, as well as crowd congestion in the social system, all exhibit synchronous characteristics [45–48]. Therefore, an exploration of synergistic states and intrinsic dynamics is important to understand the population dynamics of complex systems, promoting relevant experimental and potential application research [49,50].

As a collective dynamic phenomenon, synchronization has both advantages and disadvantages. Synchronization can sometimes promote people's production and life, such as the synchronization of power grids. When each motor is synchronized, the efficiency of power transmission can be greatly improved. Another example is the synchronization of bird and fish populations, which can better protect the individuals in the population. However, synchronization is sometimes disastrous. For example, the resonance of a bridge is a synchronization caused by a large number of people stepping on it. Seizures, on the other hand, are the result of a high degree of synchronization between neurons in the brain that was not preceded by any signs. Therefore, mastering the synchronization mechanism can lead to improved synchronization control.

In this study, the synchronous effect of the growth model of Chinese new energy vehicle enterprises is measured based on the ecological perspective. We regard new energy vehicle enterprises as a special population within the entire Chinese automobile manufacturing ecosystem. This population is affected by the population of traditional vehicle manufacturing enterprises, as well as the evolution of the entire Chinese vehicle manufacturing ecosystem. When a small new population exhibits obvious synchronous behavior, each individual can be better protected. Therefore, we believe that a better synchronization effect can be conducive to the growth of the entire new energy vehicle manufacturing population.

An important symbol of life movement is rhythm, and a biological clock is a cycle of rhythms in an organism. The biological rhythm, like other natural rhythms, reflects amplitude, period, and phase, which are external manifestations of the dynamic behavior of the biological clock. The biological clock, as the rhythm generator of self-sustaining behavior, has an internal mechanism. Research on the internal mechanism of external expression is the basic scientific doctrine and the basis of application. The behaviors emerging in complex systems often have a basic cooperative mechanism at the micro level. Biological rhythms are everywhere, as different organisms have different rhythms, and a single organism also has multiple rhythms. Some animals hibernate periodically every year, and some plants grow and lose their leaves in annual cycles. Animals also have fast cycles such as breathing and heartbeat. The most familiar rhythm is the circadian rhythm.

Enterprise operation also has a cycle rhythm. Like other natural rhythms, enterprise operation rhythm reflects amplitude, cycle, and phase, are external manifestations of enterprise dynamic behavior. R&D, production, sales, and procurement activities of enterprises have a certain rhythm. Different enterprises have different rhythms, and their development can be fast or slow. Individual enterprises also have a variety of rhythms; for example, an enterprise sometimes works overtime to catch up. In this study, the sales volume of products is the main research variable. The sales volume of each enterprise can be regarded as a vibrator. NEV enterprises are a new population in the automobile industry ecosystem. Whether this new population can synchronize with the development of the entire industry is related to the growth of the population.

After the theoretical basis and research idea of synchronization effect are determined, scholars need to find a suitable expression for the study. The idea of reducing the synergetic behavior of coupled microscopic individuals with large degrees of freedom to phase oscillator synchronization has been commonly adopted by the scientific community. Winfree [51] recognized that the phase freedom of the oscillator played an important role in synchronization research in the 1960s and characterized the synchronization of a weak coupling limit cycle oscillator by constructing a phase response function. Kuramoto [52] made a further simplification on this basis by assuming that the interaction between phase oscillators is a mean-field coupling with a sinusoidal function of the phase difference. The Kuramoto model is simple in form and solvable in the sense of statistical physics. It provides a rich physical connotation for the synchronous phase transition of a large number of oscillators. When the natural frequency distribution of the oscillator satisfies the single-peak symmetry and the coupling strength between the oscillators exceeds a certain critical value, the system spontaneously undergoes a secondary phase transition from disorder (non-synchronous state) to order (synchronous state). Based on the analytical solvability of the model, the Kuramoto model is regarded as a classical example for the study of synchronization problems, a series of improvements and generalizations are proposed on its basis, and important progress has been made in many aspects of experimental research and practical application. In 1975, Kuramoto proposed a network model of M-phase oscillator coupling [52], which can be described as follows.

$$\frac{d\theta_i}{dt} = \omega_i + \frac{P}{M}\sum_{j=1}^{N}\sin(\theta_j - \theta_i), i = 1, \cdots, M \tag{3}$$

where:

$\theta_i = \theta_i(t) \in \mathbb{R}$ represents the phase of the ith vibrator;

ω_i represents the natural frequency of the ith vibrator;

P indicates the coupling strength between oscillators; and

M indicates the number of vibrators.

Because the classical Kuramoto model is relatively simple, with ease of numerical calculation, and can be widely used in various disciplines, it has received extensive attention from many scholars [53]. In this paper, we construct the Kuramoto model of a discrete system. Through the deformation of this model, the equation of coupling measurement of the discrete system is obtained. The derivation process is as follows.

$$\begin{array}{l} \text{Because: } d\theta_i(t) \approx \Delta\theta_i(t),\ \Delta\theta_1(t) = \theta_1(t) - \theta_1(t-1),\ dt \approx \Delta t = t - (t-1) = 1. \\ \text{Therefore: } \dfrac{d\theta_i(t)}{dt} \approx \dfrac{\Delta\theta_i(t)}{\Delta t} \approx \Delta\theta_i(t) = \theta_i(t) - \theta_i(t-1) \\ \text{It can be concluded: } \Delta\theta_i(t) = \omega_i + \frac{P}{M}\sum\limits_{j=1}^{N}\sin(\theta_j - \theta_i), i = 1, \cdots, M \end{array} \tag{4}$$

In this study, a p value is used to measure the coupling strength between each vibrator (new energy vehicle enterprise) in the system.

The solution formula of p value is as follows.

$$P = \frac{\Delta\theta_i - \omega_i}{\frac{1}{M}\sum\limits_{j=1}^{M}\sin(\theta_j - \theta_i)}, i = 1, \cdots, M \tag{5}$$

In the research setting of this paper, $\omega_i \approx \overline{\frac{\Delta\theta_i(t)}{\Delta t}}, \Delta t = t - (t-1) = 1, \Rightarrow \omega_i \approx \overline{\Delta\theta_i(t)}$.

Pluchino et al. proposed an ingenious method to measure the synchronization of discrete data in the socioeconomic system [53].

$$\begin{cases} R_{(t)} = 1 - \sqrt{\frac{1}{M}\sum\limits_{j=1}^{M}\left(\overline{x}_{j(t)} - \overline{X}_{(t)}\right)^2} \\ \overline{X}_{(t)}\ is\ the\ average\ over\ all\ individuals\ of\ \overline{x}_{j(t)} \\ R = 1, in\ the\ fully\ synchronized\ phase \\ R < 1, in\ the\ incoherent\ or\ partially\ synchronized\ phase \end{cases} \tag{6}$$

In this study, when the new energy vehicle enterprises are in the full synchronization stage, all new energy vehicles have the same sales volume change rate. In the noncoherent or partially synchronous stage, new energy vehicle enterprises have different sales volume change rates and different sales volumes.

3. Empirical Analysis

Based on the evaluation score of China's "double credit policy", in this paper, we selects eight new energy vehicle enterprises as research samples [54]. These enterprises are the top eight in the evaluation score system of China's "double credit policy".

(1) Moving logistic regression model results of sample enterprises

As shown in Table 1, based on the effect of the regression test, Nio has the best fit, and Tesla, Xiaopeng, BYD, and Hozon have a moderate fit. Lixiang, Leap, and WM have the worst fit. This shows that the sales growth mechanism of enterprises such as Neo, Tesla, Xiaopeng, BYD, and Hozon is more consistent with the dynamic characteristics of population growth in the ecosystem. In theory, the more the enterprise behavior conforms to the characteristics of the ecosystem, the better the enterprise can adapt to the external market environment. The Nio car has a distinctive operation mode; its production and manufacturing is completely outsourced to JAC Automobile Company, realizing the virtualization of enterprise manufacturing. Nio Automobile focuses on R&D, product development, and market development. This practice shows that the operation mode of Nio vehicles has achieved better adaptability to the ecosystem of new energy vehicles. In order to better reflect the change trend of the intrinsic growth rate of the sample enterprises, a chart presented below to illustrate the change trend.

Table 1. Intrinsic growth rate of sample new energy vehicle enterprises.

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	0.417 (2.280) **	1.587 (1.895) *	0.956 (2.022) *	1.120 (3.460) ***	0.743 (1.225)	0.841 (1.511)	1.564 (2.789) **	0.659 (1.331)
2022-Apr	0.443 (2.945) ***	1.184 (1.756) *	0.892 (1.881) *	0.948 (3.163) ***	0.623 (0.980)	0.510 (1.063)	1.728 (2.806) **	0.663 (1.454)
2022-Mar	0.397 (2.684) **	0.537 (2.138) *	0.755 (1.727) *	0.815 (2.452) **	0.932 (1.784) *	0.687 (2.042)	1.588 (2.867) **	−0.629 (−2.069) *
2022-Feb	0.322 (2.761) **	0.530 (2.468) **	0.402 (1.199)	0.542 (2.427) **	0.629 (1.282)	0.482 (1.391)	1.373 (2.249) **	0.665 (2.150) *
2022-Jan	0.300 (3.074) ***	0.361 (1.442)	0.443 (2.096) *	0.259 (2.910) **	0.843 (1.856) *	0.425 (1.447)	1.294 (2.254) **	0.059 (0.315)
2021-Dec	0.320 (2.623) **	0.330 (0.968)	0.332 (1.694) *	0.324 (3.107) **	0.692 (1.814) *	0.421 (1.269)	1.462 (2.761) **	−0.223 (−0.555)
2021-Nov	0.043 (0.178)	0.422 (1.566)	−0.120 (−0.340)	0.173 (1.329)	0.509 (1.140)	0.500 (0.796)	2.330 (6.368) ***	0.192 (0.263)
2021-Oct	−0.083 (−0.248)	0.258 (0.840)	0.134 (0.455)	0.156 (1.020)	0.678 (1.161)	0.382 (0.871)	2.041 (5.555) ***	−0.073 (−0.112)
2021-Sep	−0.046 (−0.088)	−0.084 (−0.190)	0.199 (0.412)	0.182 (1.390)	0.235 (0.517)	0.434 (1.053)	1.828 (4.488) ***	0.176 (0.294)
2021-Aug	0.448 (0.792)	0.811 (1.742) *	0.718 (1.335)	0.153 (0.792)	0.188 (0.446)	0.296 (0.670)	1.190 (2.912) ***	0.137 (0.235)

Table 1. *Cont.*

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2021-Jul	0.750 (1.329)	0.799 (2.139) *	0.820 (1.371)	0.092 (0.413)	0.288 (0.626)	0.501 (0.994)	0.614 (1.962) *	0.290 (0.468)
2021-Jun	0.865 (1.833) **	0.719 (1.970) *	1.204 (1.842) *	0.228 (0.853)	0.421 (0.663)	1.368 (2.493)	0.764 (2.723) **	0.527 (0.672)
2021-May	0.725 (1.697) *	0.719 (2.023) *	1.295 (2.134) *	0.315 (1.040)	0.593 (1.083)	0.974 (2.325) **	0.609 (2.562) **	0.697 (0.992)
2021-Apr	0.579 (1.388)	0.561 (1.671) *	1.190 (1.996) *	0.389 (0.989)	0.634 (1.170)	0.901 (2.270) **	0.396 (1.519)	0.690 (1.060)

() t value, * p value < 0.1, ** p value < 0.05, *** p value < 0.01.

As shown in Figure 2, the trend curve of the intrinsic growth rate of the sample enterprises is mostly above the horizontal axis (the intrinsic growth rate is greater than zero). The trend line of the intrinsic growth rate of Nio is significantly higher than that of other sample enterprises. Except for Nio, the internal growth rate of enterprises has a very similar trend. The intrinsic growth of most sample enterprises first declines and then rises slowly. In recent years, China's automobile market has faced many uncertainties.

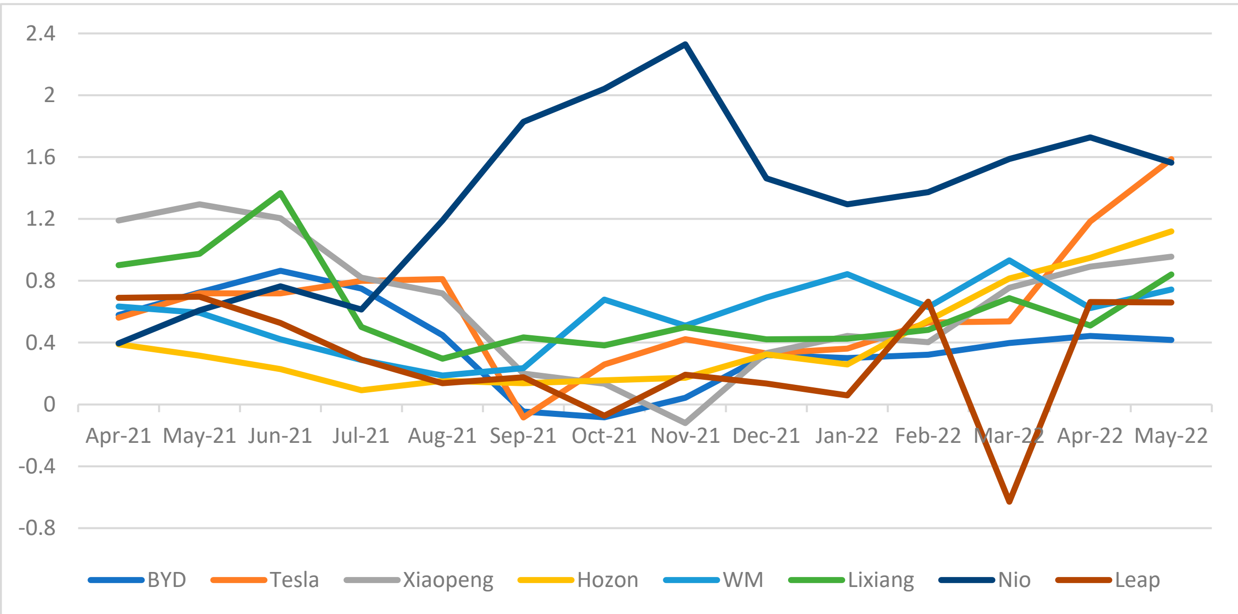

Figure 2. Change trend of intrinsic growth rate of sample enterprises.

As shown in Table 2, another important variable in the results of logistic equation regression is the internal inhibition coefficient during population growth. Table 2 shows the internal inhibition coefficients of the sample enterprises. Nio has the best fit. The fit of the internal inhibition coefficient of other enterprises is not as good as that of the intrinsic growth rate. The internal inhibition coefficient is a reverse indicator; the lower its value, the better. Limit of sales can be calculated according to the intrinsic growth coefficient and internal inhibition coefficient. In this paper, the limit of automobile sales volume is referred to as the market potential value. The results of market potential value are shown in Table 3.

Table 2. Internal inhibition coefficient of sample new energy vehicle enterprises.

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	-3.90×10^{-6} (−1.988) *	-2.89×10^{-5} (−2.045) *	-7.77×10^{-5} (−2.221) *	-1.16×10^{-4} (−3.476) ***	-2.02×10^{-4} (−1.470)	-7.96×10^{-5} (−1.648)	-1.86×10^{-4} (−3.066) **	-8.42×10^{-5} (−1.358)
2022-Apr	-4.36×10^{-6} (−2.608) **	-2.24×10^{-5} (−1.939) *	-7.33×10^{-5} (−2.094) *	-1.01×10^{-4} (−3.324) ***	-1.75×10^{-4} (−1.207)	-5.23×10^{-5} (−1.246)	-2.02×10^{-4} (−3.052) **	-9.39×10^{-5} (−1.555)
2022-Mar	-3.93×10^{-6} (−2.286) *	-8.91×10^{-6} (−1.993) *	-5.99×10^{-5} (−1.771)	-8.64×10^{-5} (−2.321) **	-2.31×10^{-4} (−1.937) *	-6.11×10^{-5} (−2.065) *	-1.84×10^{-4} (−3.001) **	1.21×10^{-4} (3.012)
2022-Feb	-3.33×10^{-6} (−2.416) **	-9.11×10^{-6} (−2.356) **	-3.55×10^{-5} (−1.370)	-6.10×10^{-5} (−2.450) **	-1.66×10^{-4} (−1.468)	-4.52×10^{-5} (−1.492)	-1.64×10^{-4} (−2.436) **	-1.22×10^{-4} (−2.427)
2022-Jan	-2.90×10^{-6} (−2.436) **	-6.29×10^{-6} (−1.349)	-3.21×10^{-5} (−1.953) *	-1.91×10^{-5} (−1.773)	-2.12×10^{-4} (−2.024) *	-3.59×10^{-5} (−1.358)	-1.53×10^{-4} (−3.066) **	1.42×10^{-5} (0.390)
2021-Dec	-2.88×10^{-6} (−1.818) *	-4.82×10^{-6} (−0.661)	-1.76×10^{-5} (−1.020)	-2.80×10^{-5} (−2.061) *	-1.57×10^{-4} (−1.710)	-3.30×10^{-5} (−0.982)	-1.79×10^{-4} (−3.052) **	7.35×10^{-5} (0.776)
2021-Nov	8.61×10^{-7} (0.243)	-8.17×10^{-6} (−1.368)	3.69×10^{-5} (0.858)	-3.48×10^{-6} (−0.177)	-1.24×10^{-4} (−1.069)	-5.46×10^{-5} (−0.663)	-3.05×10^{-4} (−3.001) **	-2.979×10^{-5} (−0.154)
2021-Oct	2.54×10^{-6} (0.449)	-4.72×10^{-6} (−0.639)	-1.16×10^{-5} (−0.296)	-8.08×10^{-6} (−0.316)	-1.93×10^{-4} (−1.117)	-5.50×10^{-5} (−0.941)	-2.71×10^{-4} (−2.436) **	1.32×10^{-5} (0.075)
2021-Sep	1.77×10^{-6} (0.174)	9.54×10^{-6} (0.634)	-1.80×10^{-5} (−0.237)	-1.20×10^{-5} (−0.542)	-8.42×10^{-5} (−0.628)	-6.23×10^{-5} (−1.123)	-2.46×10^{-4} (−2.361) **	-5.23×10^{-5} (−0.315)
2021-Aug	-8.92×10^{-6} (−0.775)	-2.48×10^{-5} (−1.614)	-1.12×10^{-4} (−1.284)	-6.44×10^{-6} (−0.154)	-5.95×10^{-5} (−0.468)	-3.62×10^{-5} (−0.542)	-1.65×10^{-4} (−2.845) **	-3.47×10^{-5} (−0.201)
2021-Jul	-1.59×10^{-5} (−1.325)	-2.70×10^{-5} (−2.126) *	-1.33×10^{-4} (−1.302)	9.68×10^{-6} (0.172)	-8.21×10^{-5} (−0.550)	-7.94×10^{-5} (−0.914)	-8.07×10^{-5} (−6.576) ***	-8.50×10^{-5} (−0.428)
2021-Jun	-1.88×10^{-5} (−1.840) *	-2.52×10^{-5} (−1.955) *	-2.13×10^{-4} (−1.786)	-3.05×10^{-5} (−0.397)	-1.38×10^{-4} (−0.596)	-2.70×10^{-4} (−2.459) **	-1.06×10^{-4} (−5.832) ***	-1.85×10^{-4} (−0.641)
2021-May	-1.62×10^{-5} (−1.727) *	-2.70×10^{-5} (−1.993) *	-2.43×10^{-4} (−2.135) *	-6.64×10^{-5} (−0.663)	-2.27×10^{-4} (−1.093)	-2.05×10^{-4} (−2.447) **	-8.80×10^{-5} (−2.496) **	-2.91×10^{-4} (−1.068)
2021-Apr	-1.34×10^{-5} (−1.442)	-2.40×10^{-5} (−1.842) *	-2.30×10^{-4} (−2.027) *	-1.14×10^{-4} (−0.737)	-2.55×10^{-4} (−1.187)	-1.88×10^{-4} (−2.298) **	-5.44×10^{-5} (−1.311)	-3.19×10^{-4} (−1.207)

() t value, * p value < 0.1, ** p value < 0.05, *** p value < 0.01.

Table 3. Theoretical upper-limit value of sales volume of new energy vehicle enterprises (market potential value).

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	106,859	54,862	12,297	9681	3674	10561	8414	7829
2022-Apr	101,555	52,920	12,172	9432	3567	9743	8540	7061
2022-Mar	101,083	60,264	12,609	9436	4037	11,248	8621	5186
2022-Feb	96,841	58,152	11,335	8887	3794	10,656	8378	5439
2022-Jan	103,310	57,392	13,788	13,568	3975	11,834	8466	−4153
2021-Dec	111,254	68,469	18,901	11,559	4418	12,756	8176	3036
2021-Nov	−49,942	51,627	3256	49,706	4119	9157	7648	6415
2021-Oct	32,615	54,623	11,571	19,317	3511	6945	7538	5528
2021-Sep	26,010	8806	11,042	15,168	2791	6961	7443	3363
2021-Aug	50,241	32,637	6435	23,749	3160	8166	7205	3953
2021-Jul	47,312	29,645	6156	−9504	3507	6311	7605	3412
2021-Jun	45,921	28,490	5641	7471	3049	5066	7223	2845
2021-May	44,733	26,649	5340	4745	2613	4746	6918	2391
2021-Apr	43,229	23,381	5179	3408	2485	4785	7284	2163

As shown in Table 3, BYD has the highest market theoretical sales volume and sales potential value. Tesla also shows strong growth momentum. At the same time, there are obvious fluctuations and oscillations in the sales potential value, which is also a reflection of the real market environment. There are also very few special values (less than zero) in the table. In actual operation, the probability of extreme values can be reduced by increasing the number of mobile logistic model observations. In this study, the extreme values are not treated specially, and the special values of these regression are retained. The following figure more intuitively represents the change trend of the market sales potential value of the sample enterprises.

As shown in Figure 3, the trend of market potential value of sales volume of most enterprises is similar. BYD is a special example, which experienced a significant decline in the process of change, followed by a rapid rise. This change reflects the internal market growth mechanism of BYD.

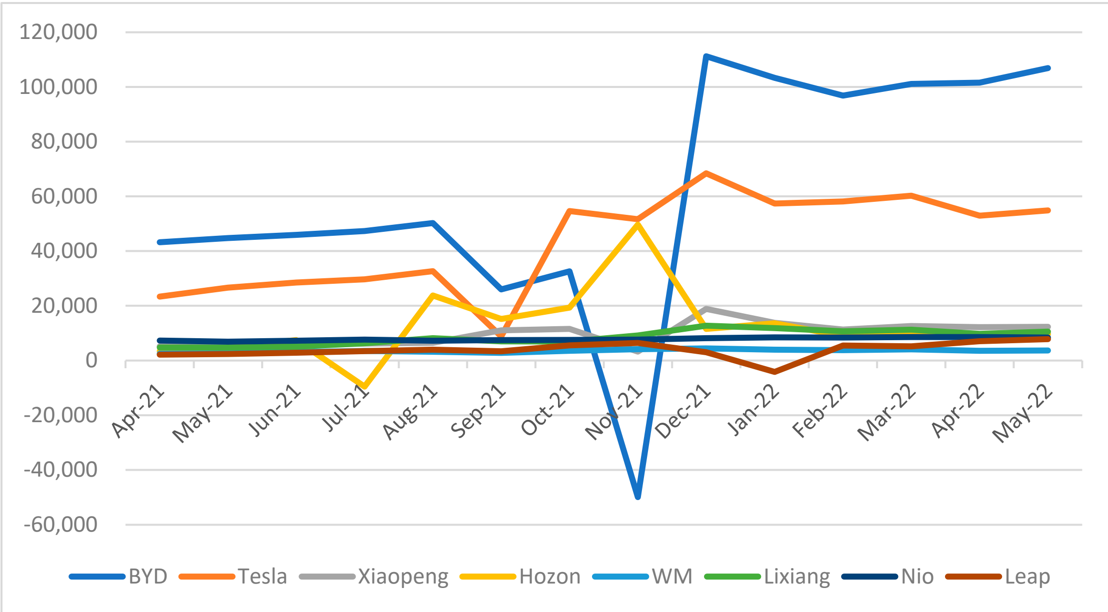

Figure 3. Change trend of sales market potential value of sample enterprises.

The growth mechanism of enterprises is more a reflection of the growth pattern of an individual enterprise. In addition to studying each individual sample, we also need to analyze the overall growth mode of the new energy vehicle enterprise population. In the analysis of the overall population growth pattern, the synchronization effect is a very meaningful and interesting research field. Based on the previous theoretical interpretation, as a new vehicle manufacturing force, the synchronous behavior of enterprises is conducive to the new energy vehicle population winning a place in the automobile market. The demand for energy saving and emission reduction and the government's preferential policies promote the implementation of synchronous behaviors by new energy vehicle enterprises. The changing market environment, information asymmetry, and differences among enterprises hinder the synchronization effect. In order to better understand the growth mechanism of new energy vehicle enterprises, it is necessary to deeply study the synchronization effect of the new energy vehicle population.

(2) Synchronization Effect Coupling value

The intrinsic growth rate data presented in Table 1 are used mainly for the measurement of the synchronization effect. First, the data are normalized. The normalized data processing formula is as follows:

$$\alpha_i\prime = \frac{\alpha_i - \alpha_i(\min)}{\alpha_i(\max) - \alpha_i(\min)}$$

See Table 4 for normalized results.

Table 4. Normalized data of intrinsic growth rate (αi′).

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	0.527	1.000	0.760	1.000	0.746	0.508	0.604	0.971
2022-Apr	0.555	0.759	0.715	0.833	0.585	0.200	0.689	0.974
2022-Mar	0.506	0.372	0.618	0.703	1.000	0.365	0.616	0.000
2022-Feb	0.427	0.367	0.369	0.438	0.593	0.174	0.505	0.976
2022-Jan	0.404	0.266	0.398	0.162	0.880	0.120	0.464	0.519
2021-Dec	0.425	0.248	0.319	0.226	0.677	0.117	0.551	0.306
2021-Nov	0.133	0.303	0.000	0.079	0.431	0.190	1.000	0.619
2021-Oct	0.000	0.205	0.180	0.062	0.659	0.080	0.851	0.419
2021-Sep	0.039	0.000	0.225	0.088	0.063	0.129	0.740	0.607
2021-Aug	0.560	0.536	0.592	0.059	0.000	0.000	0.411	0.578
2021-Jul	0.879	0.528	0.664	0.000	0.134	0.191	0.113	0.693
2021-Jun	1.000	0.481	0.936	0.132	0.313	1.000	0.190	0.872
2021-May	0.852	0.481	1.000	0.217	0.544	0.632	0.110	1.000
2021-Apr	0.698	0.386	0.926	0.289	0.599	0.564	0.000	0.995

As shown in Table 4, the normalized value of the intrinsic growth rate can be obtained through a normalization operation. Then, the normalized data of intrinsic growth rate are converted into phase angle. In this process, the arcsine function is used for calculation. See Table 5 for phase angle data.

Table 5. Phase angle converted from normalized data of intrinsic growth rate.

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	0.556	1.571	0.864	1.571	0.842	0.533	0.648	1.331
2022-Apr	0.588	0.862	0.797	0.984	0.624	0.201	0.760	1.344
2022-Mar	0.531	0.381	0.667	0.780	1.571	0.373	0.664	0.000
2022-Feb	0.441	0.376	0.378	0.453	0.634	0.174	0.530	1.351
2022-Jan	0.416	0.270	0.409	0.163	1.077	0.121	0.483	0.546
2021-Dec	0.439	0.250	0.325	0.228	0.744	0.117	0.584	0.311
2021-Nov	0.133	0.308	0.000	0.079	0.446	0.191	1.571	0.668
2021-Oct	0.000	0.206	0.180	0.062	0.719	0.080	1.017	0.433
2021-Sep	0.039	0.000	0.227	0.088	0.063	0.129	0.834	0.652

Table 5. *Cont.*

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2021-Aug	0.595	0.565	0.634	0.059	0.000	0.000	0.423	0.616
2021-Jul	1.073	0.557	0.727	0.000	0.135	0.192	0.113	0.766
2021-Jun	1.571	0.501	1.210	0.133	0.319	1.571	0.191	1.059
2021-May	1.020	0.501	1.571	0.219	0.576	0.685	0.110	1.571
2021-Apr	0.773	0.396	1.183	0.293	0.643	0.600	0.000	1.468
ω_i	−0.017	0.090	−0.025	0.098	0.015	−0.005	0.050	−0.011

As shown in Table 5, it is easy to obtain the phase angle of each enterprise's intrinsic growth rate (vibrator), and its average is taken as the natural frequency of the vibrator. Next, we calculate the coupling degree (P) of the intrinsic growth rate of each enterprise's sales volume in different observation periods. In this study, the average value of the change in phase angle for each period of the enterprise's intrinsic growth rate (oscillator) is taken as the intrinsic frequency of the oscillator. The natural frequency value shows that the phase change direction is differs between enterprises.

As shown in Table 6, the coupling degree of sample enterprises is generally low with great fluctuation. In a system with a large number of coupled oscillators, each oscillator has an effect on other oscillators. When the coupling strength is large, the dynamics of a single oscillator cannot be directly separated. Coupling enhancement can eliminate the difference between the oscillators and make them synchronous or have the same phase velocity.

Table 6. Coupling value of the intrinsic growth rate of enterprise sales (p value).

Year-Month	BYD	Tesla	Xiaopeng	Hozon	WM	Lixiang	Nio	Leap
2022-May	−0.042	1.852	−2.522	1.867	−2.280	0.068	−0.471	2.214
2022-Apr	0.430	4.127	7.072	2.388	−0.374	0.745	−22.953	1.304
2022-Mar	1.507	0.287	2.069	2.203	1.169	0.762	3.568	0.989
2022-Feb	0.491	−0.171	0.604	−1.466	2.143	0.810	−53.986	1.125
2022-Jan	−0.444	0.359	1.489	0.596	1.087	1.008	2.343	1.080
2021-Dec	−5.052	0.803	2.883	0.779	0.889	1.289	0.949	2.241
2021-Nov	0.648	−3.380	0.457	−0.158	7.057	−0.293	1.260	2.068
2021-Oct	−0.073	−2.508	−1.094	−0.640	1.887	−0.321	1.505	4.266
2021-Sep	−2.694	−0.217	−7.720	−0.952	−0.223	−0.738	1.445	1.504
2021-Aug	2.088	0.315	0.057	1.430	1.593	1.653	−2.084	0.045
2021-Jul	0.872	−3.781	−1.389	1.949	2.795	3.355	2.543	−1.054
2021-Jun	−0.977	3.015	−1.158	1.674	2.320	−0.009	1.887	−2.448
2021-May	−1.230	1.758	0.800	1.363	2.469	4.501	1.390	0.823

(3) Calculation of the R value of the population synchronization effect

The coupling degree describes the collaborative characteristics of individual sales volume and the whole population. In order to understand the synchronization effect of the new energy vehicle population more comprehensively, the synchronization effect value is calculated in this paper. The calculation results of the R value of the population synchronization effect of new energy vehicles are as follow.

As shown in Table 7, the level of the population synchronization effect fluctuates and oscillates significantly, similar to the regression results of the logistic model. At the starting point of the observation time interval, the R value of the synchronization effect is the highest (0.765); then, the synchronization effect level drops and oscillates and finally returns to a stable level (0.724). Refer to the trend line below in order to observe the change trend of population synchronization effect more intuitively.

Table 7. Calculation results of R values of the population synchronization effect.

Year-Month	R	Year-Month	R	Year-Month	R
2022-May	0.724	21-Dec	−1.771	21-Aug	0.492
2022-Apr	0.138	21-Nov	−0.571	21-Jul	0.604
2022-Mar	0.186	21-Oct	−0.694	21-Jun	0.752
2022-Feb	−2.655	21-Sep	0.324	21-May	0.756
2022-Jan	0.521				

As shown in Figure 4, the change trend of the population synchronization effect is similar to that of the intrinsic growth rate and market potential value. The level of synchronization effect of the new energy vehicle population decreases, oscillates, and then increases. This change trend shows that the logistic population growth model and Kuramoto synchronous effect model reveal a similar mechanism. The concussion interval in these change trend lines is a period worthy of focus. Significant disturbances appear in the actual market environment corresponding to the trend oscillation line. These disturbances impose important limitations on sales volume.

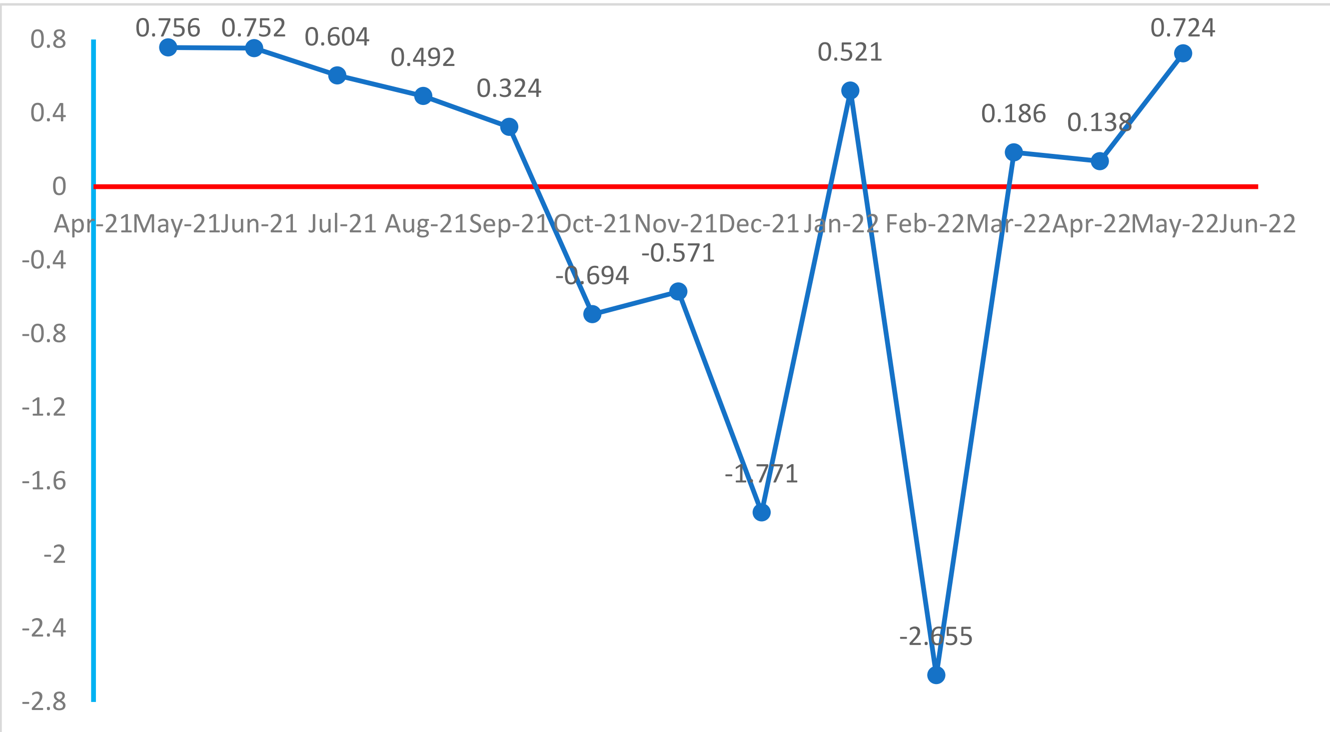

Figure 4. Change trend of the population synchronization effect.

(4) Robustness test of the logistic regression model

In order to test the robustness of the logistic expression model, we select the sales data of several traditional fuel vehicle brands with the highest sales volume in the Chinese market for logistic expression analysis. We use the sales volume of Volkswagen, Honda, Toyota, Nissan, and Buick as the research sample. The results of logistic expression analysis are shown in Table 8; most of the regression results are relatively ideal, and the relevant regression coefficients are within the interpretable scope of the population dynamics model, which shows that the logistic regression model is robust

Table 8. Results of robustness test.

Year	Volkswagen		Honda		Toyota		Nissan		Buick	
	α	γ	α	γ	α	γ	α	γ	α	γ
2021–2022	0.810 (5.549) ***	-4.090×10^{-6} (−2.731) **	0.858 (6.385) ***	-6.564×10^{-6} (−3.272) ***	0.840 (6.841) ***	-5.457×10^{-6} (−3.299) ***	0.540 (8.237) ***	-6.859×10^{-6} (−3.302) ***	0.427 (7.348) ***	-6.577×10^{-6} (−2.853) ***
2019–2020	0.466 (4.524) ***	-1.873×10^{-6} (−1.563) *	0.455 (3.280) ***	-3.280×10^{-6} (−1.099)	1.258 (6.086) ***	-9.779×10^{-6} (−3.555) ***	0.824 (5.161) ***	-8.197×10^{-6} (−2.468) **	0.113 (3.378) ***	-1.416×10^{-6} (−0.360)
2017–2018	1.191 (10.316) ***	-4.536×10^{-6} (−1.563) ***	0.724 (6.813)***	-5.927×10^{-6} (−2.937) ***	1.514 (11.272) ***	-1.504×10^{-5} (−6.998) ***	0.537 (5.650) ***	-5.471×10^{-6} (−2.044) *	0.657 (7.626) ***	-6.605×10^{-6}(−3.243) ***

() t value, * p value < 0.1, ** p value < 0.05, *** p value < 0.01. α is the intrinsic growth rate, and γ is the internal inhibition coefficient.

4. Results and Discussion

4.1. Results

Ecological theory and population dynamics model were applied to research on the growth mechanism of NEV enterprises. In this study, the sales volume of the sample enterprises is regarded as the size of the automobile product population. By constructing a moving logistic model, the vehicle sales data of the sample enterprises were analyzed. The growth mechanism and synchronization effect of NEV enterprises is discussed below.

The results show that the trend curve of the intrinsic growth rate of the sample enterprises is mostly greater than zero. The trend curve of the intrinsic growth rate of Nio is significantly higher than that of other sample enterprises. The internal growth rate of enterprises other than Nio exhibits a very similar trend. The intrinsic growth of most sample enterprises first declines and then rises slowly. The sales potential value of most sample enterprises is not high, mainly hovering around thousands of vehicles per month. The market potential of BYD and Tesla is significantly higher than that of other sample enterprises. The trend of the population synchronization effect is similar to that of the intrinsic growth rate and market potential value. The level of the synchronization effect of new energy vehicle population decreases, oscillates, and then increases. This trend shows that the logistic population growth model and Kuramoto synchronous effect model reveal similar mechanisms.

4.2. Discussion

Compared with traditional research on enterprise growth mechanisms, the biggest feature of this study is that it returns to the ecological theory and methods and discusses enterprise growth based on the methods of ecology and population dynamics. On this basis, the synchronous effect of enterprise population was explored.

Previous studies have used the logistic model to analyze the growth mechanism of product populations within a period of time. In this study, the overall growth mechanism is subdivided into a time series of growth mechanisms, which can show the changes and trends of growth mechanisms. Compared with traditional methods [5–8,55], dynamic models are more suitable for studying market scenarios. Previous studies have reported logistic regression results in a period of time, whereas the method described in this paper can calculate the time series data of a logistic model regression parameter. The results reported in this paper reveal the dynamic characteristics of development and, highlighting the synchronous development of new energy automobile manufacturing enterprises. The research conclusion of this paper is supported by relevant literature [13].

In contrast to existing social and commercial ecosystem research [24–30], in this paper, we propose a new perspective to study the population relationship in ecosystems using the synchronous effect method. The traditional Kuramoto model is mainly used to solve problems in the field of natural science [32–34]. In this study, we investigated the introduction of this model in management fields such as enterprise management and market research.

4.3. Management Inspiration

The analysis of the population growth and synchronization effect has broad application prospects in the field of enterprise management research. For example, in the analysis of enterprise competition, the growth and symbiotic relationship of populations can be used to describe the competitive situation between enterprises. The synchronization effect can help analyze the competition and collaboration of enterprises in different stages of industrial development. Synchronization effect analysis is also helpful to evaluate the interaction between enterprise competitive behavior and industry pioneers and followers.

The synchronous effect of sales volume of new energy vehicle enterprises is not obvious, which indicates that the operation activities of each enterprise are not synchronous. When the impact of relevant policies of new energy vehicle enterprises is significant, enterprises have more consistent operating strategies and measures. For example, when the government provides tax incentives for the sale of new energy vehicles, enterprises adopt similar sales policies in order to make full use of this preferential policy. The behavior and sales volume of enterprises have synchronous effects. Empirical analysis results show that the synchronization effect is not obvious, also confirming the transformation of China’s new energy vehicles from “policy-driven” to “market-driven”. Under the market-driven model, the market information of different enterprises is asymmetric, and the behavior of enterprises is heterogeneous.

4.4. Limitations and Future Research

Based on the exploratory characteristics of this study, its limitations are as follows: (1) The results/findings of this study are based on hypothesized simulation (synchronization), not reality. (2) The current research deals only with sales figures, which are regarded as the output of organizational activities, without considering substantial uncountable input factors (such as subject-, environment-, resource-, and mechanism-based views).

We intend to supplement the above limitations in future research. Both population dynamics models and the Kuramoto model can be used to describe the behavior characteristics of biological populations. These two models have broad application prospects in the field of social science. We draw the following assumptions and propose the following prospects for future research: (1) a deep discussion of the theory and method of the population synchronization effect based on a population dynamics framework; (2) systematic description of the application of the Kuramoto model in the field of social science research with extensive application practice.

5. Conclusions

The purpose of this paper is to construct a moving logistic model to analyze the growth mechanism of new energy vehicles. A convenient method was designed to evaluate the growth mechanism of new energy vehicles, and the growth of new energy vehicles was synchronously evaluated in order to deeply analyze the growth behavior of enterprises. This research has achieved the above research objectives, and the practice shows that the moving logistic model can better measure the enterprise growth mechanism. The moving logistic model developed in this paper cannot only better measure the growth mechanism of enterprises but also obtain the time series value and change trend of the growth mechanism. Therefore, the moving logistic model proposed in this paper can provide support for scientific decision making of enterprises. The Kuramoto model and its derivative model described in this paper can be used to clearly analyze the synchronization effect and coupling degree of the new energy vehicle population.

The research highlights of this paper are as follows: (1) The moving logistic model based on population dynamics theory represents a new method to measure the growth mechanism of enterprises. (2) Using the moving logistic model, the intrinsic growth rate, internal inhibition coefficient, and theoretical upper limit of sales volume of enterprises were calculated. The development trend of enterprises was studied and determined based on the model parameter values. (3) The Kuramoto model and its derivative model were used to process the intrinsic growth rate data, and the synchronization effect level and coupling degree were calculated. Based on the synchronization effect and coupling parameter values, the symbiotic characteristics of enterprise population were summarized. One of the shortcomings of this study is that it only discusses the synchronization effect of the new energy vehicle population and fails to contextualize research on the synchronization effect in a wider field, for example, by increasing the number of research samples and taking into account the synchronous effect in fuel vehicles. Another disadvantage of this study is that the effect of system noise was not introduced in the population growth and synchronization effect analysis. In future research, we will consider how to measure and evaluate the impact of system noise on the population.

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