

A Customer-Centric Approach to EV (Electric Vehicle) Tire Design through the Kano Model and Quality Function Deployment

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Abstract

The rapid expansion of the global electric vehicle (EV) market has introduced new challenges for tire design, due to the unique characteristics of EVs. This study addresses these challenges by integrating customer requirements (CRs) into tire design for both traditional internal combustion engine vehicles (ICEVs) and EVs, with a focus on the evolving demands of the EV market. Utilizing the Kano model, the research identifies and classifies CRs, and it further applies S-CR and S-CR+ relationship functions to quantitatively assess the impact of CR fulfillment levels on customer satisfaction (CS), highlighting ride quality as the most significant factor. Through Quality Function Deployment (QFD), these CRs are translated into actionable engineering characteristics (ECs) for both vehicle types. The House of Quality (HoQ) analysis indicates that tread pattern and compound characteristics are critical ECs, with tread pattern being especially essential for EVs due to their distinct performance requirements. As far as the author is aware, this study is the first to explore the application of the Kano model in the context of tire design, to utilize QFD for identifying key ECs specific to EV applications, and/or to apply S-CR and S-CR+ functions to tire design. The findings address gaps in the existing literature and provide tire manufacturers with actionable insights to innovate effectively in competitive and evolving markets.

Keywords: Kano model, Quality Function Deployment (QFD), Electric Vehicle (EV) tire,

Automobile tire design, Customer-centric product design

1 Introduction

1.1 Research Backgrounds

In recent years, the global electric vehicle (EV) market has seen significant expansion. According to the Global EV Outlook 2025, EV sales surpassed 17 million units worldwide in 2024, representing an increase of 3.5 million units compared to 2023. This incremental growth in 2024 alone exceeded the total global sales of EVs recorded in 2020 (IEA, 2025). Despite optimistic growth projections for 2025, the EV sector faces considerable uncertainty due to escalating trade tensions and supply chain disruptions (EV Magazine, 2025).

While EV demand grew by 21.2% year-on-year in January 2025, this figure remains well below the average annual growth rate of 42.8% between 2017 and 2024 (SNE Research, 2025). In fact, several automakers planned skipping or scaling back their presence at CES 2025, the world's largest consumer electronics and IT expo, as the slowdown in EV demand becomes more apparent (The Chosun Daily, 2024). Industry experts attribute this trend to the so-called "EV chasm," a phase of temporary stagnation in demand that often precedes mass-market adoption, along with declining sales and aggressive restructuring driven by economic pressures and competition from Chinese electric vehicle makers.

Policy changes further compound these challenges. Notably, the anticipated elimination of the \$7,500 federal EV tax credit, which was initially renewed under the Inflation Reduction Act (IRA), along with the expansion of tariffs on various imported goods, including finished vehicles, raw materials (such as steel), and automotive components, is expected to significantly impact the EV market (The Car Connection, 2025; REPEAT Project, 2025). As REPEAT Project (2025) notes, these policy shifts may not only elevate consumer prices but also adversely affect the demand for automobiles.

The tire industry is both dynamic and closely integrated with automotive manufacturing (Chicu et al., 2020). In response to evolving performance standards and rising market demand, the sector has increasingly prioritized the development of high-performance, low-noise, and low rolling resistance products (Hwang et al., 2019; Hwang et al., 2022). Tires serve critical functions in vehicle operation, including load-bearing, traction, braking, shock absorption, and handling (Lee et al., 2011).

The distinct characteristics of EVs, such as high-voltage batteries, immediate maximum torque upon acceleration, increased weight compared to traditional vehicles, and stringent requirements for noise reduction, have prompted tire manufacturers to develop products optimized for EVs (Nexen Tire, 2025a). Several companies have launched dedicated EV tire brands. For instance, Hankook Tire, a Korean tire company, introduced the "iON" series, while Kumho Tire, another Korean tire manufacturer, unveiled the "EnnoV" line, both of which

emphasize maximizing high performance for EVs. Conversely, other manufacturers, such as Michelin, Continental, and Nexen Tire, have opted not to release separate EV-exclusive brands. These companies state that while tire performance and vehicle efficiency are important to EV and hybrid vehicle consumers, these requirements are equally relevant for vehicles equipped with traditional Internal Combustion Engines (ICE) (Continental, 2025a). Therefore, their product lines and latest technologies are designed with all Internal Combustion Engine Vehicles (ICEVs), Hybrids, and EVs in mind and are optimized for the needs of all three vehicle types. Michelin aims to offer an EV-ready tire for every passenger tire application (Modern Tire Dealer, 2024a). Continental has also stated that all their tires are suitable for both ICE and electric vehicles, asserting that EVs do not require special tires. Recently, Nexen Tire, a Korean tire manufacturer, also aims to meet the customer requirements (CRs) of both ICEVs and EVs by providing a premium product at a feasible price (Herald Economy, 2025). Despite these two contrasting EV tire strategies, tire manufacturers remain dedicated to the development of products that are optimized for the mass adaptation of EVs as the era of EVs rapidly approaches.

With global EV sales continuing to rise annually, EVs and connected vehicles, particularly those incorporating smart tire technologies, are transitioning from niche innovations to mainstream components of the automotive landscape, and connectivity features are increasingly becoming standard in new vehicles (Automotive Technology, 2025). In response, leading tire manufacturers such as Continental, Michelin, and Hankook Tire etc. have initiated the development of smart tires for passenger cars, which offer real-time monitoring and enhanced vehicle integration.

These divergent trends underscore a broader question in the tire industry: how can manufacturers align technological development with actual customer needs in the era of EVs? Tire manufacturers assert that the trend toward increased specialization in tires will persist, driven by the diversification of vehicle requirements and customer preferences (Modern Tire Dealer, 2024b). However, new tire designs must meet a wide range of criteria, dictated not only by stringent regulations regarding safety and environment but also by continuously evolving new trends and performance demands (Korunović et al., 2015). Therefore, management techniques are essential for achieving competitive advantages through a customer-oriented perspective (Mehr et al., 2013).

1.2 *Research Objective*

In today's globalized market, understanding, identifying, and fulfilling CRs has become a critical strategic priority for companies aiming to maintain competitiveness and achieve high levels of customer satisfaction (CS) (Wang and Ji, 2010). The Kano model and Quality Function Deployment (QFD) are two effective instruments

that enhance a company's competitiveness by aligning product development more closely with customer needs (Ji et al., 2014).

The Kano model facilitates a deeper comprehension of product requirements and allows for a more accurate definition of how CRs impact CS, thereby improving its applicability in the initial phases of product design and development (Chen, 2024). Although no prior studies have applied the Kano model specifically to the tire industry, the utility of the Kano model has been demonstrated in various fields, including websites (Tan and Shen, 2000), notebook computers (Ji et al., 2014), and interior vehicle design (Kirgizov and Kwak, 2022a). In related automotive contexts, Ma et al. (2019) employed the Kano model to analyze user preferences in autonomous driving services, while Chen (2024) examined CS in relation to smart head-up displays (HUDs) using the same research framework. Both studies utilized Kano questionnaires to classify service or product quality attributes and calculated the Customer Satisfaction index (SI_i) and Dissatisfaction index (DI_i), which represent the degree of satisfaction or dissatisfaction as a percentage. Additionally, a CS matrix was constructed to identify the quality elements that should be integrated into product design to optimize satisfaction (Ma et al., 2019). However, simply computing index values does not fully capture the complex, often non-linear relationships between CS and CR fulfillment (Wang and Ji, 2010).

While Ma et al. (2019) and Chen (2024) demonstrate the effectiveness of the Kano model in analyzing and understanding user needs and CS, as well as in assessing the self-stated importance of CRs, their studies still have room for improvement in translating these customer needs into actionable technical specifications or system-level design features. This limitation may reduce the practical applicability of their findings in real-world product development. In contrast, QFD is a customer-centric approach that supports design teams in developing new products by systematically translating CRs into technical characteristics (Tontini, 2003; Avikal et al., 2020). As one of the most widely adopted methods for customer-driven product design, QFD provides a systematic approach for incorporating the Voice of the Customer (VOC) into the product design process (Sireli et al., 2007; Cho et al., 2016). The most fundamental tool in QFD is the House of Quality (HoQ), a matrix used to prioritize engineering characteristics (ECs) based on CRs (Park and Kim, 1998; Avikal et al., 2020).

QFD has found widespread application across various industries due to its effectiveness in enhancing product quality, reducing time-to-market, and lowering development costs (Hadi et al., 2017). In the automotive sector, manufacturers such as Toyota, General Motors, and Mitsubishi have effectively implemented QFD to drive innovation and improve design outcomes (Sireli et al., 2007). Specifically in the tire industry, Mehr et al. (2013) used QFD to address customer feedback when determining and prioritizing technical specifications for tire

products in Iran. This study identified critical CRs and transformed them into key technical specifications. Hadi et al. (2017) utilized the HoQ model based on interview data to correlate customer expectations with product features in the tire industry. The study focused on applying QFD to design new products that align with customer needs and enhance competitiveness. Key tire attributes were identified to improve the quality of tires, and these attributes also served as recommendations for marketing strategies. Then, technical requirements were prioritized through an integrated evaluation of CS ratings, competitor benchmarking, improvement factors, sales points, and overall weighting. Similarly, Mehelmi (2017) adapted QFD to enhance the quality of tire product and service in Egypt's public-sector. The HoQ was constructed using semi-structured interviews to identify customer needs (the "what") and focus groups to gather managerial input on how to address them (the "how"). The study highlighted the feasibility and constraints of implementing QFD in Egypt's public sector, emphasizing the need to focus on technical specifications while considering organizational limitations.

Despite the demonstrated effectiveness of QFD in the tire industry, existing studies have predominantly focused on ICEV tires and adopted a QFD-centered approach (Mehr et al., 2013; Hadi et al., 2017; Mehelmi, 2017). Research explicitly oriented toward customer-centric perspectives remains limited within the tire sector, particularly concerning electric vehicle (EV) tires, which possess distinct performance requirements and usage characteristics. Additionally, although the Kano model has proven to be a valuable instrument for identifying and classifying CR attributes, it has yet to be applied within the context of the tire industry. Furthermore, there is a notable absence of studies that explore the nuanced, nonlinear dynamics between CS and requirement fulfillment using more advanced methodologies such as S-CR and S-CR+ relationship functions. The integration of these approaches could yield more comprehensive insights into CS mechanisms and support the formulation of more precise design strategies. The lack of such research indicates gaps in existing literature, particularly regarding the evolving demands of the EV tire market.

In response to these gaps, the present study not only employs the Kano model to identify CRs that are most valued by consumers but also utilizes the QFD method. To the author's best knowledge, this research is the first to apply the Kano model to automotive tire design and/or identify the most critical ECs of EV tire design using the QFD approach. Moreover, S-CR and S-CR+ relationship functions are employed to provide visual and quantitative clarity regarding how each CR influences CS in the tire industry for the first time. This study addresses the limitations of prior studies and offers a pathway for optimizing customer-centered product design. As such, the present study aims to address significant gaps in the literature by focusing on the following four objectives:

- To explore how the Kano model and QFD can be integrated into automotive tire design to align ECs with evolving CRs, particularly in the rapidly growing EV market.
- To apply the Kano model to classify and identify which CRs are deemed valued by tire customers.
- To utilize the S-CR and S-CR+ relationship functions to quantitatively assess the influence of different CRs on CS and to explore which CR has the greatest effect on CS.
- To investigate the differences in priorities of ECs between EVs and ICEVs through the HoQ analysis, providing actionable design guidance for tire manufacturers.

The remainder of this paper is structured as follows. The next section provides a summary of the research framework and methodology, including the Kano model, the S-CR and S-CR+ relationship functions, and the prioritization process within the HoQ. Section 3 introduces the case study, which analyzes customer-centered tire design based on survey data. This section details the analysis results and discusses their key findings. Finally, Section 4 presents conclusions and implications from this study.

1.3 *Definitions of automobile tires in this study*

As the sole component of a car that directly contacts the road surface, tire performance plays a critical role in determining the overall performance of the vehicle (Du et al., 2020). As one of the most essential components of an automobile, the tire is required to fulfill several fundamental functions: supporting the vehicle's load, providing cushioning and damping against road irregularities, transmitting both driving and braking torque, generating cornering forces, maintaining dimensional stability, and resisting wear and abrasion (Virkar and Thombare, 2013).

Tires are broadly classified into radial and bias-ply types. Radial tires, which dominate the tire industry and are standard in passenger cars, are characterized by a series of belts located beneath the tread, and with their ply cords arranged at a 90-degree angle to the direction of travel (Interco Tire Corporation, 2025; UltraForce Tires, 2024). This structural design enhances fuel efficiency, ride comfort, tread life, traction, and handling. In contrast, bias-ply tires feature a multi-ply construction in which the number of plies directly contributes to both load-carrying capacity and resistance to impact damage, making them especially well-suited for use on trailers, tractors, and heavy machinery. The present study aims to provide findings regarding the CRs of automobile tires. Given the widespread use of radial tires in the automotive industry, particularly in passenger cars, this study focuses exclusively on radial-type automobile tires.

Structurally, a tire consists of several components, including tread, cap ply, body ply (carcass), steel belt, sidewall, inner liner, and bead (Hwang et al., 2022). Figure 1 shows the structure of a tire with its various

components (Nexen Tire, 2025b). The tread is the outermost layer in direct contact with the road surface, which provides multiple functions such as drainage, driving force, braking force, and through the tread pattern on the tire surface. Comprising a thick layer of rubber, the tread is highly resistant to wear, impact, and fracture, thereby safeguarding the internal structural layers such as the carcass and steel belts (Hankook Tire, 2025b). Beneath the tread lies cap ply, which is an important safety layer that minimizes heat generation from friction and preserves the tire's structural integrity at high speeds (Michelin, 2025a).

The body ply, or carcass, is the frame of a tire, which is typically constructed from polyester, rayon, or nylon, and it is responsible for supporting internal air pressure, bearing loads, and absorbing road shocks. (Nexen Tire, 2025b; Hankook Tire, 2025a). The steel belt between the carcass and tread in radial tires serves as a robust reinforcement layer. It enhances the tire's strength and shape retention, improves rolling resistance, and extends overall mileage (Continental, 2025b).

The sidewall, positioned between the tread and bead, displays vital information such as tire size, load-carrying capacity, and speed rating (Tyroola Australia, 2024). Functionally, it shields the carcass from environmental factors such as moisture and abrasion and also withstands the repeated bending and stretching that occur during vehicle operation (Nexen Tire, 2025b). The inner liner acts as a sealant, helping to maintain air pressure and reduce the risk of leaks.

Lastly, the bead ensures a secure attachment between the tire and the wheel rim (Nexen Tire, 2025b; Hankook Tire, 2025a). Composed of bead wire, a core, rubber, and a flipper, this component maintains the tire's position during driving conditions and ensures that the tire remains securely fastened to the rim while in motion.

[Figure 1]

2 Research Method and Materials

The research framework for this study is illustrated in Figure 2. This study aims to optimize customer-focused design of automobile tires by adopting CRs, the Kano model of quality, the S-CR and S-CR+ relationship functions, and the HoQ.

[Figure 2]

First, CRs are identified through literature reviews, industry reports, customer satisfaction surveys, and consultation with industry experts. A customer survey is then conducted to evaluate the importance of these needs, followed by the employment of the Kano model to classify them into different quality dimensions. Subsequently, CS levels are assessed based on this classification. Second, the relationship between CR fulfillment and CS is examined and compared in greater depth using S-CR and S-CR+ relationship functions. Third, relationship matrices for EVs and ICEVs are developed, leading to the construction of the HoQ, which translates customer needs into technical specifications. Ultimately, the study seeks to optimize tire design by aligning engineering attributes with customer expectations, ensuring a balance between technological feasibility and market demand.

2.1 Sample selection

This study collected various tire-related elements from relevant books, existing research papers, tire technology magazines, industry websites, and annual customer satisfaction surveys conducted by automobile tire companies to identify key CRs. Based on the collected data, evaluation criteria related to tire design were systematically extracted and categorized, highlighting common attributes across the sources. Subsequently, to refine and validate these findings, consultations were conducted with a panel of six industry experts, each with professional experience in the tire industry ranging from 15 to 24 years. The expert panel included professionals from a diverse array of functional domains, including two specialists from research and development (R&D) and one expert each from product planning, manufacturing engineering, process management, and quality engineering. These experts contributed to the identification of representative CRs, utilizing their extensive field knowledge and operational expertise.

Most of the CRs initially identified in this study are related to technology-oriented features. However, it turned out that customers were often unfamiliar with tire technology and its characteristics, and it would be difficult for them to answer the questionnaire. Therefore, the expert panel further refined the initial CRs to simplify and

categorize them, ensuring that respondents could easily comprehend and accurately answer the questionnaire. Ultimately, six key CRs were selected for analysis, as detailed in Table 1. A total of 147 respondents participated in the customer survey to complete the Kano questionnaire and assess the self-stated importance of these requirements by evaluating them using a seven-point Likert scale.

[Table 1]

2.2 Kano's model

Kano model is an effective approach for categorizing CRs into distinct quality dimensions (Tan and Shen, 2000; Avikal et al., 2020). This model is widely recognized for its effectiveness in identifying the nature of CRs and assessing their impact on CS (Matzler and Hinterhuber, 1998; Chaudha et al., 2011). Customers often struggle to explicitly define the product attributes they desire when they are purchasing merchandise, so the Kano model serves as a crucial tool for uncovering implicit CRs (Avikal et al., 2020). The Kano model divides CRs into four primary classifications, each exerting a different influence on CS:

1. One-dimensional attributes (O): These attributes demonstrate a direct, linear relationship with CS—higher levels of fulfillment lead to increased satisfaction.
2. Attractive attributes (A): These attributes have a considerable positive influence on CS when they are available; however, their absence does not necessarily lead to dissatisfaction, as customers do not typically expect them in advance.
3. Must-be attributes (M): These attributes are considered fundamental requirements. Their fulfillment does not increase CS, but their absence results in significant dissatisfaction.
4. Indifferent (I): Its absence or presence does not influence CS.

Beyond these four primary categories, CRs can also be divided into two additional classifications: Reverse (R) and Questionable (Q). The two categories indicate that the customer either has contradictory survey responses (Questionable) or its presence decreases CS (Reverse) (Wang and Ji, 2010; Borgianni, 2015). Figure 3 illustrates the four quality attributes of the Kano model, where the vertical axis represents CS levels, and the horizontal axis denotes the extent to which a CR is fulfilled (Ji et al., 2014).

[Figure 3]

The Kano questionnaire is a widely used instrument for categorizing CRs into distinct Kano classifications (Wang and Ji, 2010). In this study, the survey responses were classified and analyzed into the Kano categories based on participants' responses to the questionnaire. The survey primarily targeted individuals holding a valid

driver's license. The questionnaire was created using the Kano model, ensuring a comprehensive assessment of customer perceptions. To maintain respondent anonymity, only demographic information—such as age, occupation, gender, and years of driving experience—was collected. The questionnaire items represented key quality evaluation elements, and participants provided responses based on a two-dimensional evaluation system, indicating their preferences both in the absence and presence of a specific CR (Table 2).

[Table 2]

According to the responses from the Kano two-way questionnaire, the product feature can be categorized into one of six categories (Berger et al., 1993) using the classification matrix presented in Table 3. For example, if a customer answers, “I am satisfied,” with “designed for a long service life,” the sufficiency form of the question, and “I am dissatisfied,” with “not designed for a long service life,” the insufficiency form of the question, the convergence of the fifth column and the first row in the classification matrix reveals an “O,” indicating that service life is a One-dimensional CR from the customer’s perspective.

[Table 3]

2.3 Kano coefficient of Customer satisfaction (CS)

Berger et al. (1993) introduced CS coefficients to quantitatively represent the value of satisfaction and dissatisfaction resulting from the fulfillment or non-fulfillment of a CR (Chaudha et al., 2011; Yadav et al., 2013; Violante and Vezzetti, 2017). The CS coefficients reflect the proportion of customers who reported satisfaction with the presence of a CR and the proportion of customers who indicated dissatisfaction in the absence of such a relationship (Tontini, 2007; Yadav et al., 2013). The CS coefficients are calculated as follows:

$$\text{Customer Satisfaction Index } (SI_i) = \frac{A+O}{A+O+M+I} \quad (1)$$

$$\text{Customer Dissatisfaction Index } (DI_i) = -\frac{O+M}{A+O+M+I} \quad (2)$$

where O signifies One-dimensional, M denotes Must-be, A stands for Attractive, and I indicates Indifferent attributes for a given CR. The negative symbol “-” in Equation (2) signifies a lack of CS.

The values of SI_i range from 0 to 1, while those of DI_i range from -1 to 0. The magnitude of satisfaction and dissatisfaction coefficients falls between 0 and 1 in absolute terms. A CS coefficient approaching 1 indicates a substantial increase in perceived satisfaction when the CR is improved. Conversely, a dissatisfaction coefficient

closer to -1 means a significant increase in dissatisfaction when the CR is insufficiently met. A value near 0 means a minimal effect, suggesting a negligible impact on CS or dissatisfaction (Tontini, 2003; Chaudha et al., 2011; Yadav et al., 2013).

2.4 The Relationships between CR fulfillment and CS

Wang and Ji (2010) presented S-CR relationship functions, and Kirgizov and Kwak (2022b) improved them as S-CR+ relationship functions for facilitating a more realistic visualization of the influence of requirements on CS. Relationship functions serve to quantify the relationships between CS and CR fulfillment as a quantitative analysis of the Kano model (Kirgizov and Kwak, 2022a). They will assist companies in combining the Kano model with other mathematical frameworks that also aid in engineering design (Wang and Ji, 2010; Gupta et al., 2018).

2.4.1 S-CR relationship functions (Wang and Ji, 2010)

The quantitative assessment of the Kano model commences with determining CS coefficient SI_i and dissatisfaction coefficient DI_i using established equations (1) and (2) (Ji et al., 2014). These coefficients are derived based on the presence and fulfillment status of a CR. However, the level of fulfillment of CRs inherently involves vagueness, making it challenging to directly apply SI_i and DI_i in quantitative analysis (Violante and Vezzetti, 2017; Kirgizov and Kwak, 2022b).

To address this issue, two assumptions are introduced to define the fulfillment points for a CR:

- If a CR is completely met by a product, the CR fulfillment level is set to 1.
- If a CR is wholly unmet by a product, the CR fulfillment level is set to 0.

Based on these assumptions, two points can be established: (1, SI_i), denoting CS when the CR is completely met, and (0, DI_i), signifying customer dissatisfaction when the CR is wholly unmet. With these two points defined, the relationship between CR fulfillment, which spans a range from 0 to 1, and CS, which extends from -1 to 1, can be constructed.

The relationship between CR fulfillment and CS can be modeled using mathematical functions. Wang and Ji (2010) proposed a methodology for measuring and quantifying the relationships between CR fulfillment and CS, which they termed S-CR functions.

These functions are expressed as follows:

$$S_i = a_i f(x_i) + b_i \quad (3)$$

where S represents the degree of CS, x denotes CR fulfillment, which spans a range from 0 to 1, and a and b are adjustment parameters that vary according to the Kano categories of CRs.

S-CR relationship functions can be categorized into three types based on the Kano model: Attractive attributes, One-dimensional attributes, and Must-be attributes. Each type follows a distinct mathematical function to describe the relationship between CR fulfillment and CS.

For one-dimensional attributes, the relationship between CR fulfillment and CS is linear. The S-CR relationship function can be defined as:

$$Si = a_i x + b_i$$

where a_i is the slope of the function; and b_i represents the intercept. Given two known points, $(1, SI_i)$ and $(0, DI_i)$, the two parameters can be determined as follows:

$$a_i = SI_i - DI_i, b_i = DI_i$$

Thus, the S-CR relationship function for one-dimensional attributes is:

$$Si = (SI_i - DI_i)x + DI_i \quad (4)$$

Attractive attributes exhibit an exponential relationship, where CS increases more significantly when the CR is fulfilled to a higher degree. The corresponding S-CR relationship function is defined as:

$$Si = a_i e^x + b_i$$

Substituting the known points $(1, SI_i)$ and $(0, DI_i)$, the parameters are calculated as follows:

$$a_i = \frac{SI_i - DI_i}{e - 1}, b_i = -\frac{SI_i - eDI_i}{e - 1}$$

Thus, the S-CR relationship function for attractive attributes is:

$$Si = \frac{SI_i - DI_i}{e - 1} e^x - \frac{SI_i - eDI_i}{e - 1} \quad (5)$$

Must-be attributes follow a negative exponential function, where customer dissatisfaction decreases with increasing CR fulfillment. The corresponding S-CR relationship function is expressed as:

$$Si = a_i (-e^{-x}) + b_i.$$

By substituting the known points $(1, SI_i)$ and $(0, DI_i)$, the parameters are derived as follows:

$$a_i = \frac{e(SI_i - DI_i)}{e - 1}, b_i = \frac{eSI_i - DI_i}{e - 1}$$

Thus, the S-CR relationship function for must-be attributes is:

$$Si = -\frac{e(SI_i - DI_i)}{e - 1} e^{-x} + \frac{eSI_i - DI_i}{e - 1} \quad (6)$$

Table 4 presents S-CR relationship functions and their parameters for three primary attributes. Figure 4 illustrates relationships between CR fulfillment and CS by S-CR relationships functions.

[Table 4]

[Figure 4]

2.4.2 S-CR+ relationship functions (Kirgizov and Kwak, 2022b)

The analysis of S-CR+ relationship functions builds upon the conventional S-CR relationship functions by incorporating an extended scale for CR fulfillment. As pointed out by Kirgizov and Kwak (2022b), the initial S-CR relationship functions do not completely correspond to the theoretical definitions of the various Kano categories (Ma et al., 2023).

As in S-CR relationship functions, S-CR+ relationship functions begin by determining the CS coefficient SI_i^* and the dissatisfaction coefficient DI_i^* using Equations (1) and (2). These coefficients denoted as SI_i^* and DI_i^* , are differentiated from those in the original S-CR relationship functions to reflect the revised fulfillment range introduced in the S-CR+ relationship functions. To define the fulfillment points for a CR in the S-CR+ relationship functions, the following assumptions are introduced:

- If a CR is completely met by a product, the CR fulfillment level is set to 1.
- If a CR is wholly unmet by a product, the CR fulfillment level is set to -1.

Based on these assumptions, two key points are established. $(1, SI_i^*)$ represents the level of CS when the CR is completely met. $(-1, DI_i^*)$ represents the level of customer dissatisfaction when the CR is wholly unmet. With these two reference points, the relationship between CR fulfillment, which varies from -1 to 1, and CS, which extends from -1 to 1, can be mathematically modeled.

S-CR+ relationship functions extend S-CR relationship functions by introducing an expanded fulfillment scale. In addition, four key Kano attribute types—One-dimensional, Indifferent, Attractive, and Must-be—are each associated with specific mathematical functions to describe their relationship with CS (Kirgizov and Kwak, 2022b).

For one-dimensional attributes, the relationship between CR fulfillment and CS follows a linear function, as there exists only one unique line passing through the two points $(1, SI_i^*)$ and $(-1, DI_i^*)$. The S-CR+ relationship function is given by:

$$Si = a_i x + b_i$$

where the parameters are determined as follows:

$$a_i = \frac{SI_i^* - DI_i^*}{2}, b_i = \frac{SI_i^* + DI_i^*}{2}$$

Thus, the final function for one-dimensional attributes is:

$$Si = \frac{1}{2}(SI_i^* - DI_i^*)x + \frac{1}{2}(SI_i^* + DI_i^*) \quad (7)$$

Indifferent attributes, by definition, do not significantly impact CS or dissatisfaction. This means that changes in CR fulfillment do not alter customer perception. The S-CR+ relationship function for indifferent attributes is therefore a horizontal line:

$$Si = a_i x + b_i$$

where

$$a_i = 0, b_i = 0$$

Thus, the final function for indifferent attributes is:

$$Si = 0 \quad (8)$$

This formulation implies that both $(1, SI_i^*)$ and $(-1, DI_i^*)$ are ignored, and the function remains constant at zero across the entire fulfillment spectrum.

For attractive attributes, CS increases exponentially as CR fulfillment improves. Since the function cannot be uniquely defined by only two points, it is estimated using an exponential function:

$$Si = a_i e^x + b_i$$

where the parameters are calculated as follows:

$$a_i = \frac{eSI_i^*}{e^2 - 1}, b_i = -\frac{SI_i^*}{e^2 - 1}$$

Thus, the S-CR+ relationship function for attractive attributes is:

$$Si = \frac{eSI_i^*}{e^2 - 1} e^x - \frac{SI_i^*}{e^2 - 1} \quad (9)$$

For must-be attributes, customer dissatisfaction decreases as CR fulfillment improves, which is best represented by a negative exponential function:

$$Si = a_i (-e^{-x}) + b_i.$$

where the parameters are given by:

$$a_i = \frac{eDI_i^*}{1 - e^2}, b_i = \frac{DI_i^*}{1 - e^2}$$

Thus, the S-CR+ relationship function for must-be attributes is:

$$Si = -\frac{eDI_i^*}{1 - e^2} e^{-x} + \frac{DI_i^*}{1 - e^2} \quad (10)$$

S-CR+ relationship functions provide a more comprehensive approach to analyzing CS not only by considering a broader range of CR fulfillment levels but also by offering an additional Kano attribute. Table 5 summarizes the different S-CR+ relationship functions and their respective parameters for the four key Kano attributes. Figure 5 illustrates the graphical representations of relationships between CR fulfillment and CS by S-CR+ relationship functions.

[Table 5]

[Figure 5]

2.5 Prioritization based on House of Quality

QFD is a systematic methodology designed to translate CRs, known as the VOC, into corresponding ECs to guide product design and identify key product improvements (Cho et al., 2016; Wörsdörfer et al., 2016; Erdil and Arani, 2019; Murugan and Marisamynathan, 2022). Besides, this approach ensures that customer needs are systematically converted into measurable engineering targets, thereby reaching the highest level of customer satisfaction (Wörsdörfer et al., 2016; Rampal et al., 2022).

The primary tool used in QFD is the HoQ, which typically contains information on customer requirements (WHATs), weights of importance, engineering characteristics (HOWs), relationships between CRs and ECs, and a correlation matrix, as shown in Figure 6 (Park and Kim, 1998).

[Figure 6]

Customer requirements (WHATs) are identified through VOC, which are collected through various approaches such as focus group interviews (Tontini, 2003; Chaudha et al., 2011; Yadav et al., 2013), customer interviews, literature reviews, and brainstorming sessions with experts (Murugan and Marisamynathan, 2022). Each CR is assigned a weight, reflecting its self-stated importance, which is determined through market research or direct customer feedback (Wang et al., 1998; Sireli et al., 2007; Cho et al., 2016). Once the CRs and their respective importance levels are established, the corresponding engineering characteristics (HOWs) must be defined to facilitate the product development process (Erdil and Arani, 2019).

The relationship matrix in HoQ assesses the degree of association between engineering characteristics (HOWs) and customer requirements (WHATs). This matrix typically employs a predefined rating scale (e.g., 1-3-5, 1-5-9, 1-3-9) to indicate the strength of the relationship, categorized as weak, moderate, or strong (Wang et al., 1998; Park and Kim, 1998; Wasserman, 1993; Sireli et al., 2007). The 1-3-9 scale is often preferred (Park and Kim, 1998; Sireli et al., 2007). In this study, two distinct HoQ frameworks were developed—one for EV tires and another for ICEV tires. These frameworks employ a 1-3-9 scale to generate the relationship between CRs and ECs. The central matrices for both models were constructed based on consultations with experts in the automotive tire industry.

The absolute and relative importance of each EC were computed using the approach outlined by Park and Kim (1998). For each EC, the absolute importance rating is determined using the following formula:

$$AI_j = \sum_{i=1}^m W_i R_{ij} \quad (11)$$

where AI_j represents the absolute importance rating of engineering characteristics (EC_j), W_i denotes the weight of importance of customer requirements (CR_i), and R_{ij} signifies the relationship rating, indicating the strength of the relationship between EC_j and CR_i .

The relative importance rating (RI_j) is subsequently computed as:

$$RI_j = \frac{AI_j}{\sum_{j=1}^n AI_j} \quad (12)$$

The HoQ helps evaluate the impact of ECs in fulfilling customer expectations (CRs) in both absolute (AI_j) and relative (RI_j) terms as computed in Equations (11) and (12) (Sireli et al., 2007). A higher RI_j value indicates a more significant EC (Park and Kim, 1998). By prioritizing ECs based on their degree of importance, HoQ facilitates decision-making in product development (Sireli et al., 2007; Cho et al., 2016). Therefore, in the absence of constraints such as cost or development time, ECs should be integrated into the product according to their relative importance to CS (Park and Kim, 1998).

3. Results and Discussion

3.1 Questionnaire reliability

Cronbach's alpha was used to assess internal consistency of the survey results, ensuring their reliability. According to Hair et al. (1998), a reliability coefficient of 0.7 or higher is considered standard, while Wortzel (1979) suggested that a coefficient of 0.6 is acceptable, with values below 0.35 deemed unacceptable. In this survey, the reliability of the questionnaire was 0.70, confirming that the study demonstrated sufficient reliability for analysis.

3.2 Sample analysis

The study began with a customer survey to collect relevant data to demonstrate the effectiveness of automobile tire design. This survey comprised a Kano questionnaire along with an assessment of the importance of each requirement, measured using a seven-point Likert scale. A total of six CRs were identified for automobile tire design (Table 1).

In total, 147 individuals with driving experience participated in the survey, of which 130 responses were considered valid for analysis. Responses were excluded if the survey was incomplete, if the respondent did not possess a driver's license, and so on. Table 6 presents the demographic distribution of the participants. 69.2% of respondents were male, while female respondents accounted for 30.8%. Additionally, 80% of the participants were aged between 30 and 49 years, and 81.5% were employed. Furthermore, 71.5% had more than 10 years of driving experience, suggesting that the survey population largely consisted of experienced drivers. Regarding tire replacement experience, 89.2% of respondents indicated they had previously replaced tires. However, only 4.6% of participants were clearly aware of tire product characteristics, suggesting that most of the surveyed drivers were not familiar with the attributes of tires.

[Table 6]

Moreover, this research analyzed the self-stated importance ratings for CRs. The importance represents a direct measurement approach, where customers explicitly rate the importance of various requirements using a scale (Pezeshki et al., 2009). This method is straightforward and relies on a questionnaire designed with a seven-point Likert scale, where higher scores indicate greater perceived importance (Gupta et al., 2018). Table 7 presents a summary of the values and rankings of importance for the six CRs. Among the CRs, "Service Life" and "Ride

Quality” were ranked as the most important attributes, followed by “Price,” “Fuel Efficiency,” “Smart Tire Features,” and “Design.”

[Table 7]

3.3 Analysis of Kano model and Customer satisfaction (CS) coefficients

The Kano model was utilized to categorize CRs into different Kano attributes. After classifying each requirement for each customer using the Kano model, a results table is generated. The summarized results were recorded in Table 8.

[Table 8]

The SI_i and DI_i were computed using equations (1) and (2). The computed values of SI_i and DI_i from the customer survey are presented in Table 8. The classification of each CR within the Kano model was established based on the values of SI_i and DI_i , as illustrated in the scatter plot presented in Figure 7 (Chaudha et al., 2011). Each CR was categorized into one of the four distinct Kano categories: Must-be, One-dimensional, Attractive, and Indifferent. If the SI_i or DI_i equaled 0.5, the tie is resolved according to the following ordering: $M > O > A > I$ (Berger et al, 1993).

[Figure 7]

According to the results of Figure 7, the Kano classification for each CR was determined, revealing the following findings. Four CRs (“Service Life,” “Ride Quality,” “Price,” and “Fuel Efficiency”) were classified as “One-dimensional” attributes, meaning that increasing the fulfillment of these CRs directly enhances CS while decreasing dissatisfaction. Notably, “Smart Tire Features” was classified as an “Attractive” attribute, indicating that its inclusion can significantly enhance satisfaction. In contrast, “Design” was categorized as an “Indifferent” attribute, meaning its presence or absence exerts a minimal influence on CS.

Through the Kano quality model, companies can strategically evaluate the relative positioning of CRs to identify which ones should be prioritized for enhancement (Ma et al., 2019). This approach allows businesses to

identify the key requirements that will maximize CS while also recognizing aspects that may be deprioritized in future product development or service enhancements (Ma et al., 2019; Chen, 2024).

3.4 Analysis of the Relationships between CR fulfillment and CS

Once CS coefficients (SI_i and DI_i) are calculated and Kano classifications are finalized, the relationships between CS and CR fulfillment can be quantitatively estimated (Ji et al., 2014; Kirgizov and Kwak, 2022a). In this study, these relationship functions are applied to analyze the survey results, enabling an in-depth examination of the relationship between the fulfillment of CRs and CS.

According to the survey findings, S-CR relationship functions for various CRs were derived to illustrate how different attributes influence CS in automobile tire design. The outcomes of these functions are displayed in Table 9. The first three columns list the CRs for automobile tire design, along with their corresponding Kano classifications. For each CR, two key points, SI_i and DI_i , were identified, as shown in the fourth and fifth columns of the table. Coefficients a_i and b_i were computed to formulate the S-CR relationship function for each CR. The final column in Table 9 provides a summary of all the derived S-CR relationship functions.

[Table 9]

[Table 10]

Table 10 presents S-CR+ relationship functions for this study. For each CR, two points SI_i^* and DI_i^* were identified and are listed in the fourth and fifth columns. S-CR+ relationship functions were then derived by selecting a suitable equation from Table 5 and computing the values of a_i and b_i for each CR. The final column of Table 10 contains a comprehensive presentation of all S-CR+ relationship functions. A comparison of Tables 9 and 10 reveals differences in five columns: the points of SI_i and DI_i , the coefficients a_i and b_i , and the mathematical function $S_i = a_i f(x_i) + b_i$.

The x-axis illustrates the extent to which a specific CR has been implemented in Figure 8. The value of $x=1$ signifies the full fulfillment of a requirement, whereas $x=0$ indicates a complete absence of implementation (Wang and Ji, 2010). The y-axis, on the other hand, measures the level of CS or dissatisfaction relative to the extent of implementation. For instance, Figure 8(c) illustrates the relationship between CS and the degree to which the Attractive attribute, “Smart Tire Features,” is fulfilled. The function forms an exponential curve that

passes through two key points: (1, 0.51) and (0, -0.38). Similar graphs can be generated for other attributes in the same manner.

[Figure 8]

A similar methodology can be applied to illustrate S-CR+ relationship functions. Also using “Smart Tire Features” as an example, the appropriate Equation (9) was selected. The quantitative examination of the Kano model led to the graphical representation of the relationship function for “Smart Tire Features,” depicted in Figure 9(c). The x-axis represents the degree of implementation of a given CR in Figure 9, where $x=1$ denotes full fulfillment and $x=-1$ signifies complete absence (Kirgizov and Kwak, 2022b). The function forms an exponential curve that passes through two key points: (1, 0.51) and (-1,0).

[Figure 9]

The distinctions between S-CR and S-CR+ relationship functions, as presented in Tables 9 and 10, are further illustrated in Figures 8 and 9. The first notable distinction is that S-CR relationship function does not account for indifferent quality attributes. Second, the graphical representations of S-CR relationship functions are constrained to the two quadrants of right in Figure 8 and the graphical representations of S-CR+ relationship functions are constrained to four quadrants in Figure 9. Third, although Attractive quality attributes do not lead to customer dissatisfaction, Figure 8(c) illustrates that the curve extends into the lower quadrant, contradicting the definition of Attractive attributes, which should not result in dissatisfaction even when absent (Kirgizov and Kwak, 2022b; Ma et al., 2023).

3.5 Prioritization of the Engineering characteristics for product design

In this study, the ECs were finalized through a comprehensive literature review (Mehr et al., 2013; Mehelmi, 2017; Hadi et al., 2017) and consultation with experts at a Korean tire manufacturer from a broad range of functional domains, including research and development (R&D), manufacturing engineering, process management, and quality engineering. Each EC is as follows:

1. Compound Characteristics: This refers to the chemical composition of the rubber material used in tires.

The formulation of tire compounds differs among manufacturers, with each ingredient contributing to

essential properties such as giving the tire grip, flexibility, the ability to hold air, and the strength to maintain its shape despite the weight of the vehicle (Autodeal, 2021).

2. **Cord Characteristics:** This characteristic indicates the arrangement and steel belt angle of the cords (i.e., steel, nylon, etc.) that make up the internal structure of the tire. These cords provide an internal framework that maintains tire shape, resists deformation under pressure, and contains inflation forces, making them critical for strength and rigidity (Michelin, 2025a). Additionally, the angle of the cord and the properties of the tire belt are crucial factors that influence rolling resistance (Virkar and Thombare, 2013).
3. **(Joint) Index Distribution:** It refers to the circumferential uniformity of belt joint placement in a tire. Ideally, a tire should have uniform stiffness, dimensions, and mass around its circumference (Liu et al., 2023). However, variations introduced during manufacturing processes—such as mixing, extrusion, and cutting—can cause structural inconsistencies (Kumho Tire, 2025). These irregularities lead to unbalanced forces during rotation, resulting in vehicle vibration, reduced handling and ride comfort, and potential damage to components (Du et al., 2020).
4. **Tire Heating and Vulcanization:** The temperature of tires influences their ride comfort, rolling resistance, adhesion, and wear characteristics; hence, it is essential to incorporate temperature effects in any simulations of tire behavior and to monitor tire temperature during testing (Virkar and Thombare, 2013). The tire attains its definitive form after being vulcanized for a specified duration at a certain temperature and pressure (Continental, 2025c).
5. **Tread Pattern:** The tread pattern is the surface design of the tire that contacts the road (Continental, 2025d). The tread design of a tire, such as the patterns and grooves in the rubber on the tire's top surface, is important to its performance, which enhances a vehicle with handling and grip for specific driving conditions (Michelin, 2025a; Continental, 2025d).
6. **Sidewall:** The sidewall of a tire serves to safeguard the internal carcass and contributes to a comfortable riding experience owing to its flexibility during cornering (Hankook Tire, 2025b). Besides, the aspect ratio is the sidewall height relative to tread width (Priority Tire, 2023). A low aspect ratio improves handling, while a high ratio increases cushioning and ride comfort (HowStuffWorks, 2025).

Besides, the central matrix illustrates relationships between CRs and ECs, which were established through consultations with an expert panel. The relationship values were assigned as follows: 9 for a strong relationship, 3 for a moderate relationship, 1 for a weak relationship, and 0 for no relationship.

Table 11 presents a segment of the HoQ for automobile tires specifically designed for ICEV, whereas Table 12 provides a corresponding section for EVs tires. An examination of the relationship matrices in Tables 11 and 12 reveals differences in the values, particularly for the relationship between Fuel Efficiency and Tread Pattern, and between Ride Quality and Sidewall.

Consequently, several relationship values between CRs and ECs were adjusted to reflect the specific characteristics of electric vehicles (EVs). For instance, the influence of tread pattern on fuel efficiency (rolling resistance) is more pronounced in EV tires compared to their ICEV counterparts. One contributing factor is the high torque output of electric motors in EVs, which can cause slippage between the tire tread and the road surface during sudden initial acceleration (Nexen Tire, 2025a). This slippage wastes energy that would otherwise propel the vehicle forward, thereby reducing energy efficiency. In addition, the design of the tire tread is a critical factor influencing rolling resistance, which represents a significant source of energy loss (Rezelman, 2023). This loss primarily results from the continuous deformation of the tire's tread and sidewall as the tire rolls under the vehicle's weight. Similarly, the increased weight of EV batteries further amplifies the impact of sidewall characteristics on ride quality. Therefore, EVs necessitate reinforced tire sidewalls to support the additional load imposed by heavy batteries, as the increased weight elevates the risk of tire failure (Bridgestone, 2025). Moreover, the specialized sidewall construction of EV tires enhances ride comfort by improving shock absorption and damping, thereby minimizing vibrations and impacts experienced by vehicle occupants (Sherwood Park Chevrolet, 2025).

[Table 11]

[Table 12]

The priority of each EC is determined based on self-stated importance weights, which were calculated in Table 8 using survey data collected through a seven-point Likert scale, and Equations (11) and (12) were employed to compute the absolute and relative importance for ranking. A comparative analysis of Tables 11 and 12 reveals variations in the priority rankings of ECs due to differences in the central matrix.

According to the HoQ for automobile tires designed for ICEVs, the highest priority is assigned to “Compound Characteristic” (22.65%). However, in Table 12 “Compound Characteristic” ranks as the second highest-prioritized EC (20.98%). Conversely, in Table 12, “Tread Pattern” ranks as the highest prioritized EC (23.01%),

whereas in Table 11, it ranks third (18.50 %). Other priority rankings also differ between the two tables. Overall, while both vehicle types share common EC priorities, notable differences remain. In particular, “Tread Pattern” demonstrates greater variability in both importance and ranking between EV and ICEV tires. In contrast, “Sidewall” is least significant and exhibits minor differences in importance across the two vehicle types.

Based on CRs and the associated metrics (i.e. Relationship Matrix between CR and EC, weight of importance, and ECs etc.), the HoQ was developed to illustrate the interdependence among ECs that contribute to fulfilling customer expectations (Rampal et al., 2022). Given the limited resources of budget and time, companies must prioritize resources in product development for a subset of ECs that have the greatest influence on CS (Kirgizov and Kwak, 2022a).

4.6 Discussion

In this study, CRs in automobile tire design are defined through six key variables: Service Life, Ride Quality, Price, Design, Fuel Efficiency, and Smart Tire Features. These CRs were systematically identified through a combination of prior academic literature, empirical data from the tire industry, and expert consultation with professionals in the tire industry. Specifically, Service Life and Ride Quality have been consistently emphasized across prior studies (Mehr et al., 2013; Hadi et al., 2017; Mehelmi, 2017) and tire industry sources, including customer survey data and performance indicators from major manufacturers such as Bridgestone, Goodyear, and Nexen Tire.

Among previous studies (Mehr et al., 2013; Hadi et al., 2017; Mehelmi, 2017) and industry sources, Service Life and Ride Quality have repeatedly emerged as research or survey items, underscoring their foundational role in tire evaluation. Additionally, Price and Design have also been recognized in prior studies (Mehr et al., 2013; Hadi et al., 2017; Mehelmi, 2017) and industry survey data as important decision factors from the customer’s perspective.

While Fuel Efficiency is not explicitly addressed in the aforementioned previous academic literature, it is regarded as a critical performance metric, as evidenced in tire manufacturers’ customer survey data and key performance indicators from Bridgestone, Goodyear, and Nexen Tire. Notably, the 2024 EV Tyre Test conducted by Tyre Reviews (2024), which is a globally recognized source of independent tire evaluation, includes rolling resistance as a core test item, highlighting the growing emphasis on energy efficiency in tire design, particularly for EVs. This reflects the growing importance of energy efficiency in the design of both conventional and EV tires.

Lastly, although Smart Tire Features has not yet been studied in traditional academic literature associated with the Kano model or QFD method, they have emerged as a forward-looking dimension in modern tire development, primarily supported by several tire engineering studies. Intelligent tires, also known as smart tires, are equipped with embedded sensors capable of monitoring variables such as tread wear, wheel loading, acceleration, temperature, strain and air pressure, and are designed to enhance the functionality of vehicle control systems, including anti-lock braking systems (ABS) and advanced driver-assistance systems (ADAS) (Matsuzaki and Todoroki, 2008).

Matsuzaki and Todoroki (2008) discussed critical technologies of intelligent tires with a focus on wireless data transmission and sensors. Lee and Taheri (2017) reviewed prior literature on the intelligent tire and suggested that the intelligent tire can be utilized to assess and analyze tire characteristics. Jeong et al. (2020) explored how intelligent tires can estimate static/dynamic loads and vehicle parameters for enhancing advanced control systems. Similarly, Xu et al. (2020) applied machine learning techniques to improve tire force estimations, further highlighting the integration of intelligent tires into modern vehicle systems, while Pomoni (2022) examined the real-time evaluation of road friction using smart tires for enhancing drivers' safety. These insights confirm the emerging significance of Smart Tire Features in the evolving landscape of automotive safety, vehicle intelligence, and infrastructure monitoring.

This study's primary contribution lies in its application of the Kano model to identify and categorize which CRs are valued by customers in the tire sector, which is a methodological approach not previously employed in the extant tire literature. This research analyzed the self-stated importance ratings for CRs. As illustrated in Table 8, Service Life and Ride Quality emerged as the two most critical attributes identified by respondents. Mehr et al. (2013) and Mehelmi (2017) also showed that Service Life and Ride Quality are relatively important in their respective self-stated importance analyses, thereby reinforcing the validity of the present study's results.

In contrast, Smart Tire Features and Design (including visual appearance) were perceived as relatively less important in the self-stated importance analysis. This observation aligns with the results reported by Mehr et al. (2013) and Mehelmi (2017), who similarly ranked Design as the least important requirement in the self-stated importance analysis. However, a point of divergence arises in Hadi et al. (2017), where Design, specifically defined by the presence of a “bulge”, was considered the most critical requirement in the self-stated importance analysis. A noticeable bulge on a tire's sidewall indicates structural damage to the internal cords, typically caused by a severe impact, and poses serious safety risks (Michelin, 2025b; Continental, 2025e).

However, the present study defines Design more broadly, encompassing diverse surface design patterns, aesthetic qualities, as well as tire appearance that does not fade. This interpretation aligns more closely with the definitions proposed by Mehr et al. (2013), who referred to Design as the “variety in surface design and beauty,” and Mehelmi (2017), who described it as “dull appearance.” The definitional variation helps to explain both the consistency between the present study and the findings of Mehr et al. (2013) and Mehelmi (2017), and the discrepancy with Hadi et al. (2017)’s results. Notably, Smart Tire Features was not considered in prior studies; thus, their inclusion in this research provides a novel contribution and may serve as a reference point for future investigations.

Subsequently, Kano analysis (Table 8) categorized Service Life, Ride Quality, Price, and Fuel Efficiency as “One-Dimensional” attributes where increased performance leads to increased satisfaction and deficiencies lead to dissatisfaction. These four CRs are also ranked highest in the self-stated importance analysis, suggesting that they represent essential expectations in tire design from the consumer perspective. Design, on the other hand, was categorized as an “Indifferent” attribute, meaning its presence or absence exerts a minimal influence on CS. This finding is consistent with the self-stated importance results. Interestingly, Smart Tire Features was deemed relatively unimportant in the self-stated importance analysis. This may be due to limited consumer exposure to smart tire technologies, which could result in lower perceived importance. Note that the Kano model classified Smart Tire Features as an “Attractive” attribute, reflecting its unexpected nature. This suggests that even seemingly inconsequential factors can significantly contribute to enhancing CS.

Among all CRs, Ride Quality exhibited the highest sensitivity in the S-CR and S-CR+ relationship functions, as shown in Figures 8(a) and 9(a). It produced the steepest slope, with the greatest change in satisfaction at low and high fulfillment values. This implies that improving the Ride Quality is highly effective in increasing CS. Smart Tire Features is classified as Attractive and also yields a substantial satisfaction increase when present. Attractive attributes such as Smart Tire Features can be included in the product to serve as a key differentiator in competitive markets, enhancing perceived value without compromising core performance.

While prior studies (e.g., Ma et al., 2019; Chen, 2024) focus on identifying high-impact customer satisfaction features and calculating several index values to reflect diverse relationships, they do not provide concrete technical recommendations for product development yet. That is, their results have room for improvement by providing specific technical recommendations for product development. This study extends the existing literature by integrating customer requirements into technical development recommendations.

Further findings from the HoQ analysis for both EVs and ICEVs show that Tread Pattern and Compound Characteristics are consistently ranked among the top three most critical ECs, aligning with Hadi et al. (2017) and Mehelmi (2017). In contrast, Mehr et al. (2013) ranked Compound Characteristics highest but did not include Tread Patterns among the top three. Recent literature supports the increasing importance of Tread Patterns. For instance, Li et al. (2024) examined how tread design affects overall performance, and Guan et al. (2023) examined the effect of tire tread design on noise. Guan et al. (2023) also mentioned that with EVs requiring quieter operation, manufacturers now impose stricter noise limits, making tread design a key marketing and performance factor in their study. Krishnakumar (2023) emphasized that EV-specific dynamics demand different tread designs compared to ICEVs, further underlining this trend.

Interestingly, Cord Characteristics was previously deemed relatively less critical. Hadi et al. (2017) identified cord characteristics as the least important among six total ECs. Similarly, Mehelmi (2017) ranked Cord Characteristics sixth out of nine ECs, further suggesting their comparatively lower prioritization. In the current study, Cord Characteristics were ranked third for EVs and second in importance for ICEVs. This shift suggests a reevaluation of their role in performance and durability. Several engineering literatures affirm this re-prioritization. Tian et al. (2024) demonstrated the performance benefits of a nylon-polyester hybrid cord, noting that tire cord serves as the structural skeleton of the tire, playing a pivotal role in maintaining the tire's shape under load. Ghoreishy (2006) highlighted how key structural parameters (belt cord angle, spacing, and thickness) in tire design affect cornering dynamics. Additionally, Meng et al. (2024) analyzed how different belt angles influence grounding and stress distribution, which are key factors in tire longevity and safety. Meng et al. (2024) also mentioned that the belt angle of the cord directly affects the lateral rigidity of the tread and is a critical consideration in tire structural design. These insights confirm the relevance of cord characteristics in tire design, especially in the context of evolving vehicle technologies. The elevation in importance of cord attributes in this study is both empirically and technically supported.

In summary, the findings affirm the enduring significance of tread pattern and compound formulation as foundational tire design elements. Meanwhile, the elevated role of cord characteristics reflects growing consumer and industry interest in attributes that enhance ride comfort. The study provides specific design recommendations, thereby offering direct strategic guidance for tire manufacturers, especially in the context of product development for the EV market.

5. Conclusions

As technology continues to advance in the global passenger car industry, customers remain the primary stakeholders who determine which features are necessary and valued (Kohli and Singh, 2021). Empirical studies have yielded critical insights into consumer preferences that provide tire design suggestions for automotive tire manufacturers. Tires represent a distinctive product category, with market dynamics shaped by regional climatic conditions, infrastructure characteristics, and geographic variability (Hadi et al., 2017). Furthermore, production and product design should be tailored to address these particular consumer demands, followed by the formulation of suitable marketing and promotional strategies (Chen, 2024).

The study develops a comprehensive framework that prioritizes consumer needs and expectations, enabling tire manufacturers to effectively navigate the challenges of the EV market and maintain competitiveness in a technology-driven landscape. The continuous integration of consumer insights will be essential to cultivating a customer-centric innovation culture, ultimately supporting sustained success in the tire industry.

Theoretically, this research underscores the importance of incorporating structured methodologies, such as the Kano model and QFD, into tire development processes. Notably, there exists a lack of research in the current literature, as no prior studies have specifically applied the Kano model within the context of the tire industry. Utilizing HoQ tools facilitates the systematic conversion of consumer expectations into engineering specifications, thereby aligning innovation more closely with market needs. Furthermore, the analytical application of S-CR and S-CR+ relationship functions displays precision of assessing the relationship between CS and requirement fulfillment.

Practically, by identifying key CRs, such as "Service Life" and "Ride Quality," manufacturers can prioritize their research and development investments. Enhancing these attributes can directly contribute to improved CS. Moreover, recognizing the importance of "Attractive" features such as "Smart Tire Features" informs manufacturers where to direct their innovation efforts to capitalize on emerging consumer trends. Through QFD analysis, tread pattern and compound characteristics were found to be more critical for EV tires, due to their greater vehicle weight and heightened sensitivity to noise. These findings offer valuable insights into tire manufacturers aiming to innovate in the rapidly evolving EV sector. By aligning company resources with the VOC, QFD enables the development of higher-quality products at lower costs in shorter timeframes, making it increasingly attractive to product development practitioners (Mehelmi, 2017).

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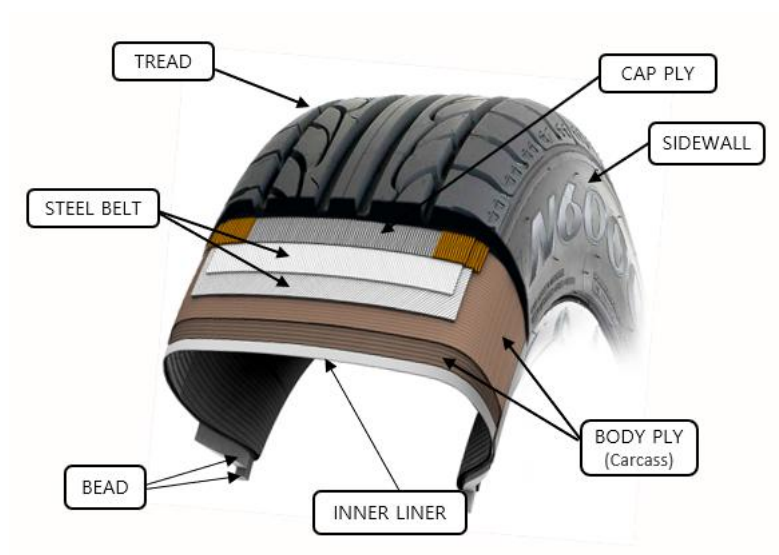


Figure 1. The basic structure of radial tire

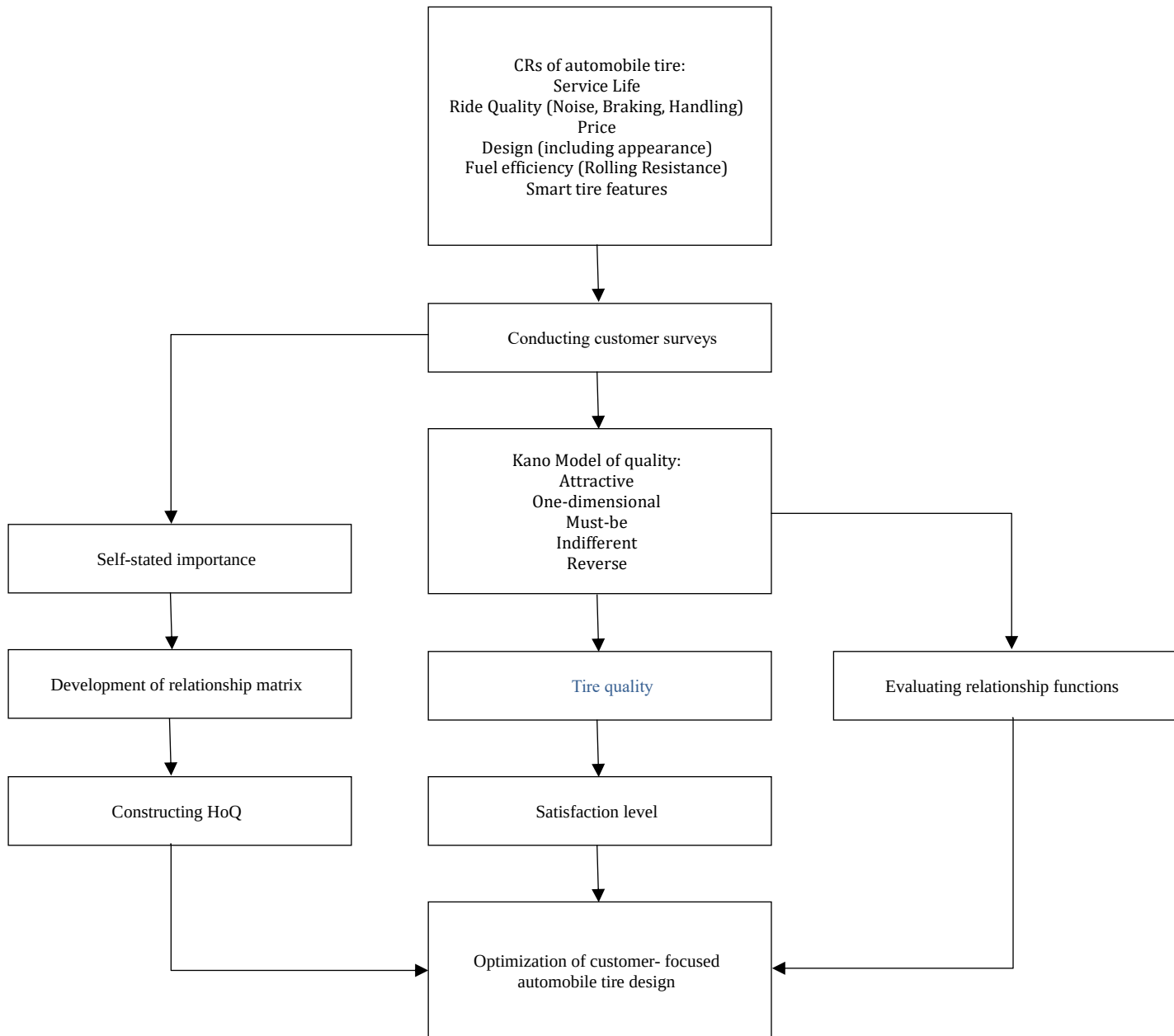


Figure 2. Research framework of this study

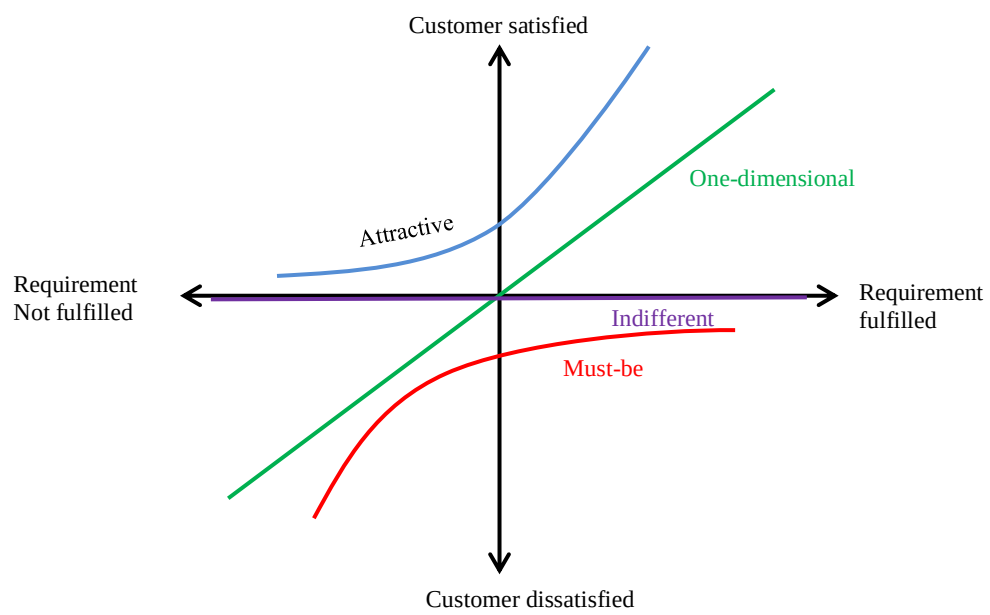


Figure 3. Kano's Model

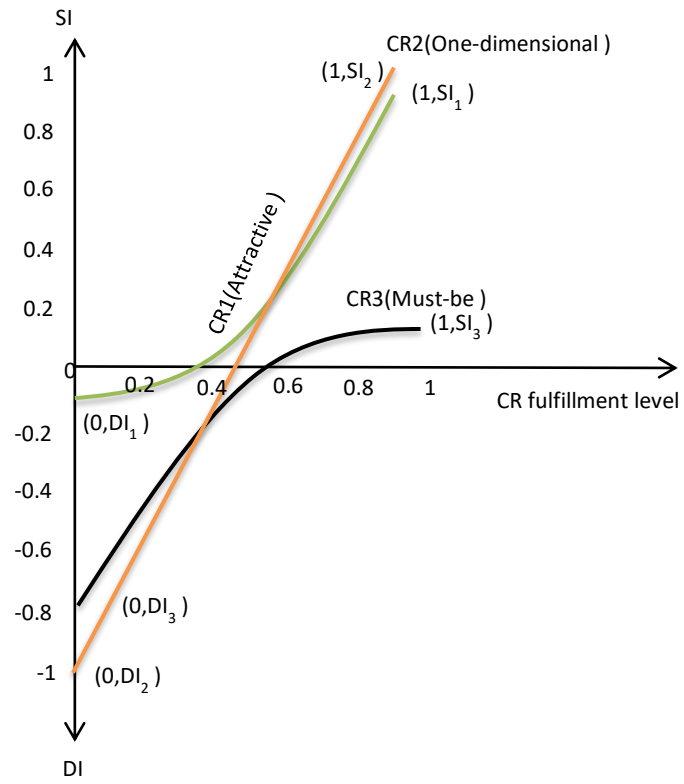


Figure 4. Relationships between CR fulfillment and CS by S-CR relationship functions

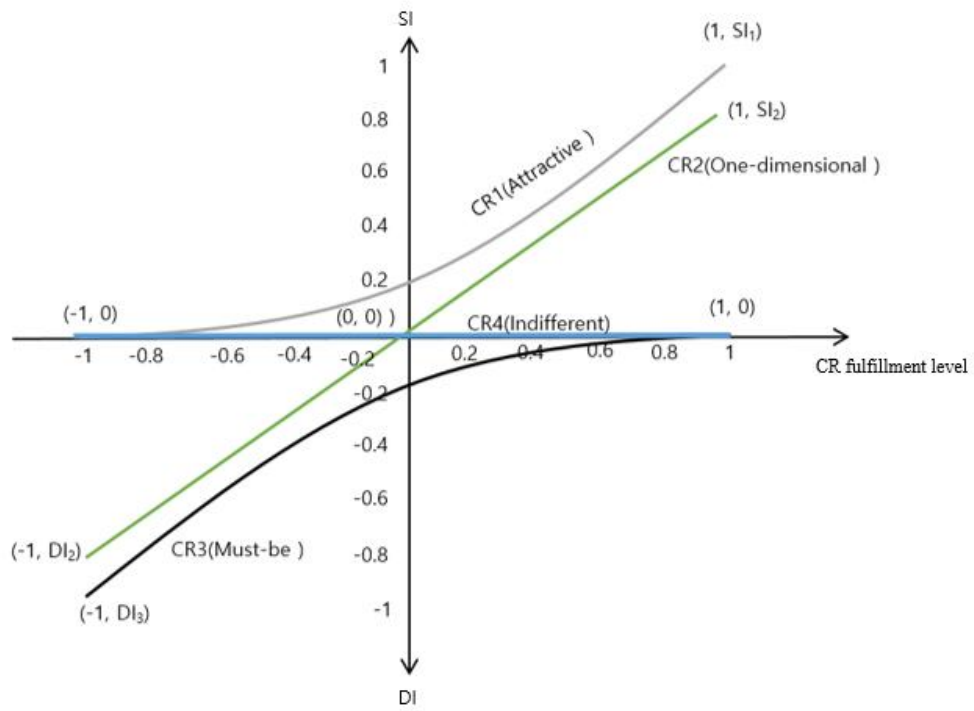


Figure 5. Relationships between CR fulfillment and CS by S-CR+ relationship functions

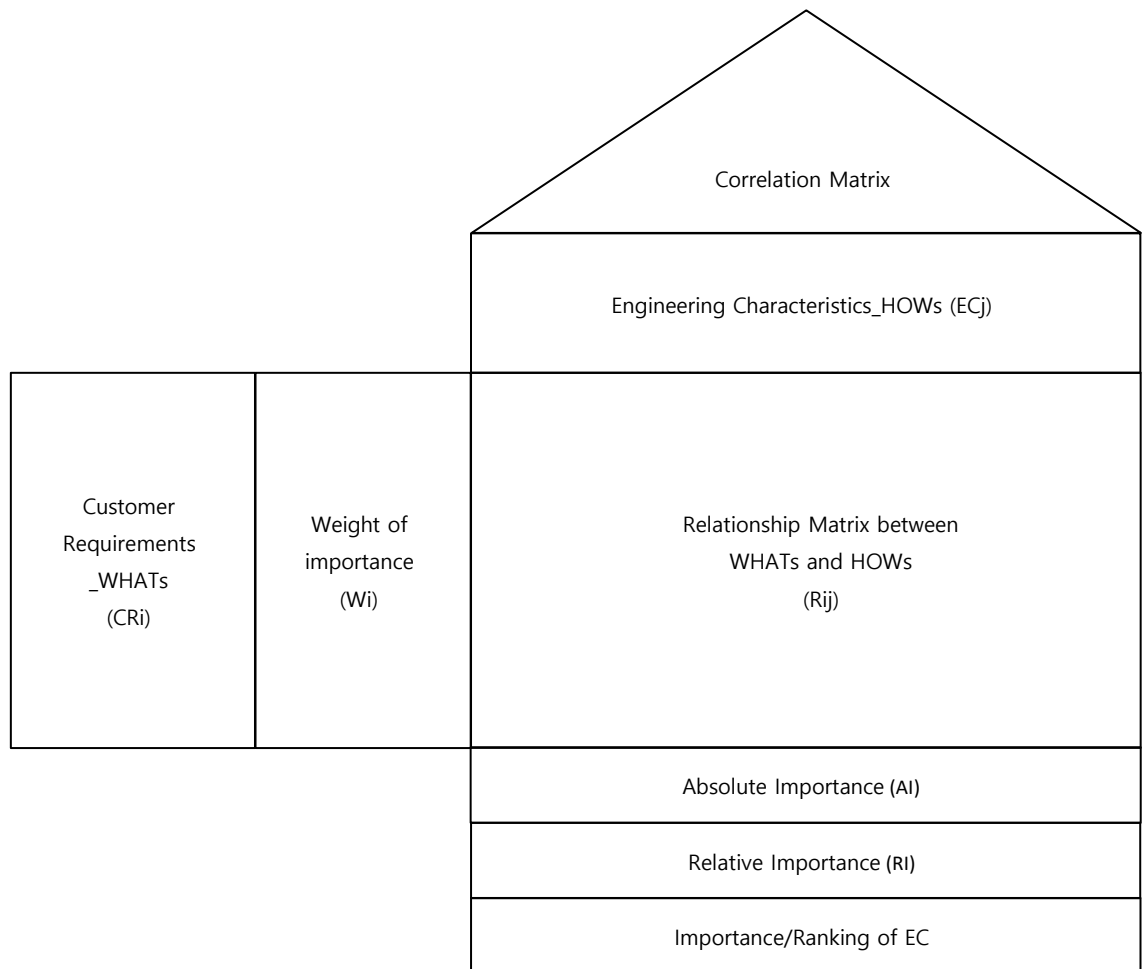


Figure 6. House of Quality (HoQ)

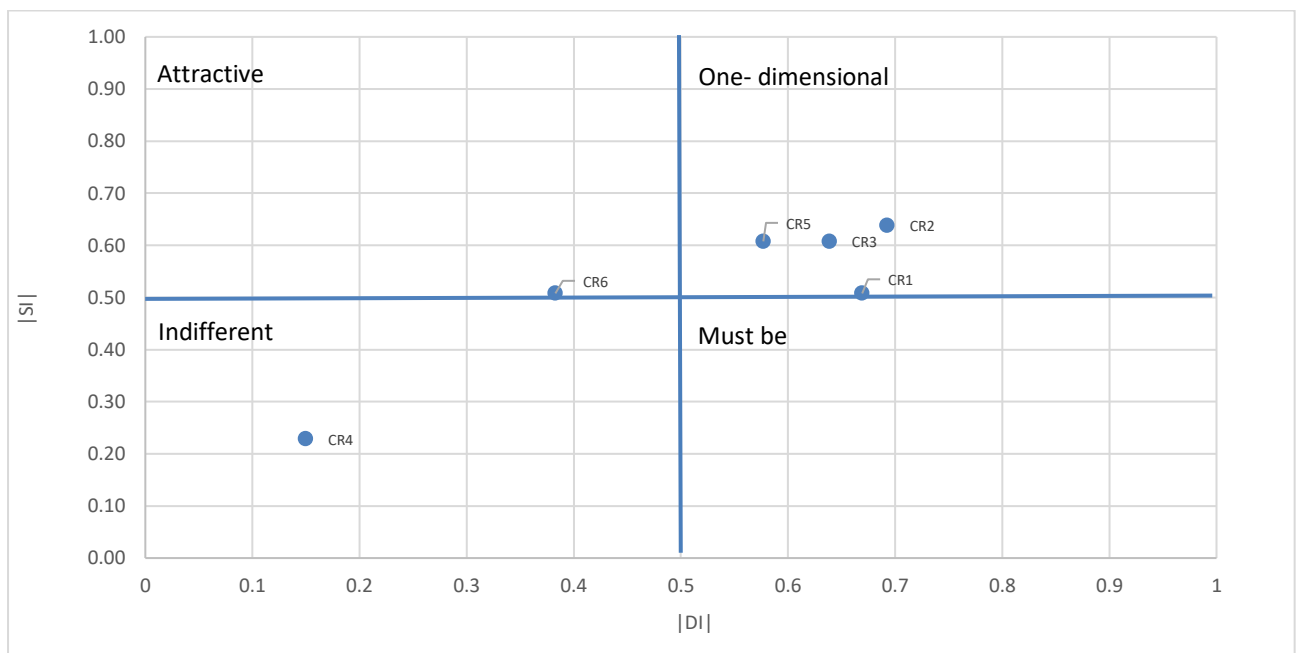
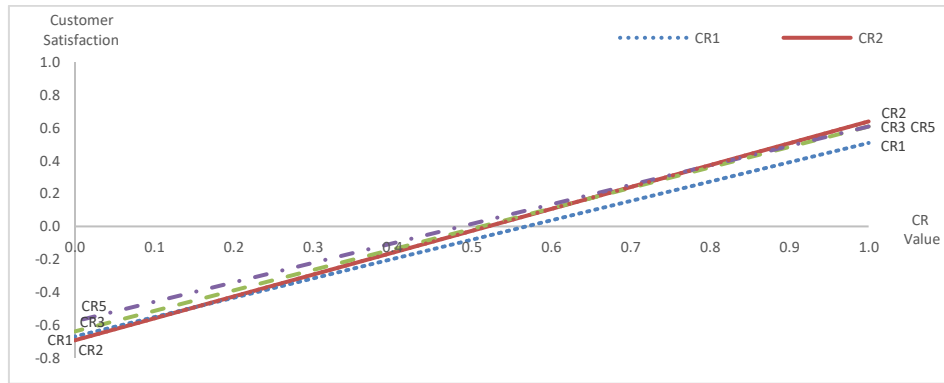
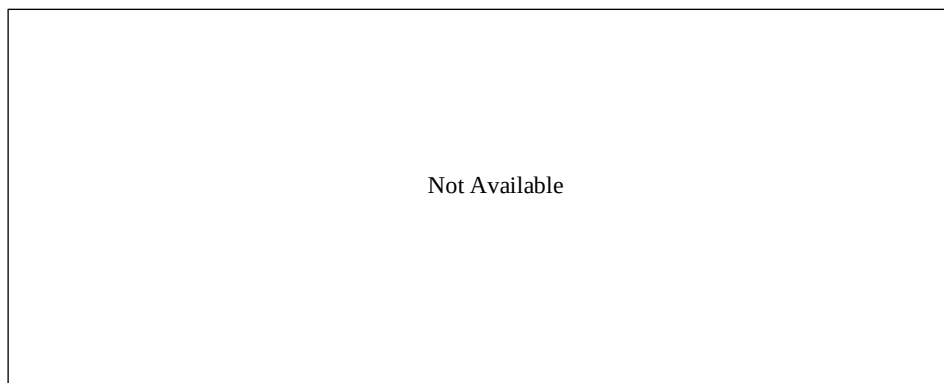


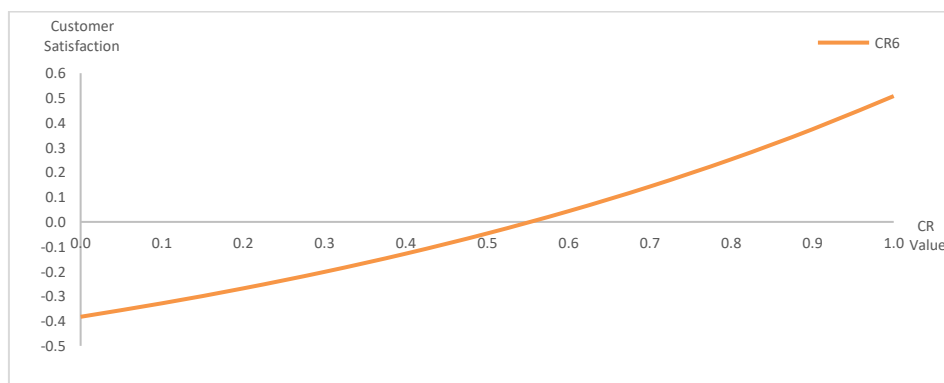
Figure 7. Kano Category for Customer Requirements



(a) Relationship functions of One-dimensional CRs

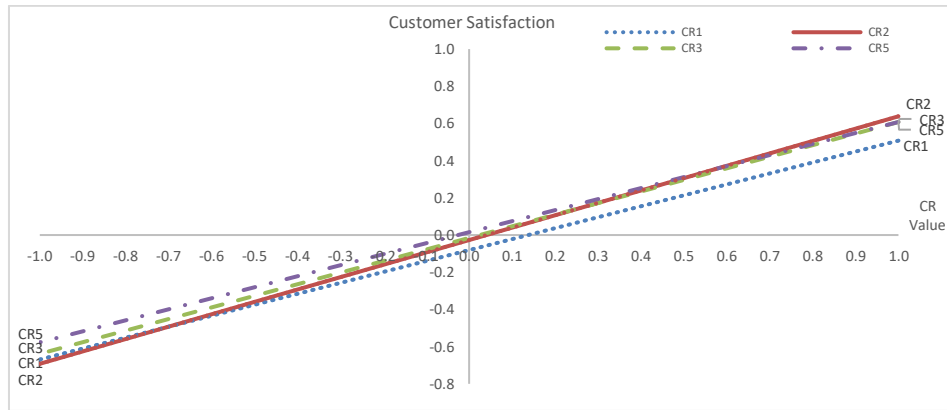


(b) Relationship function of Indifferent CR



(c) Relationship function of Attractive CR

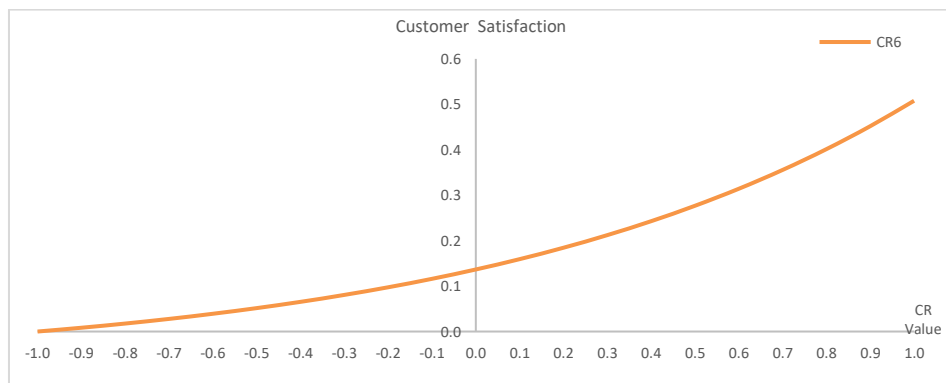
Figure 8. S-CR Relationship Graphs for Automobile Tire Design



(a) Relationship functions of One-dimensional CRs



(b) Relationship function of Indifferent CR



(c) Relationship function of Attractive CR

Figure 9. S-CR+ Relationship Graphs for Automobile Tire Design

Table 1 Questionnaire items used in this study

Customer requirements	Description
1. Service life	Long mileage, long durability, high wear resistance
2. Ride Quality	No noise while driving, good tire braking performance, wet and high-speed driving performance, Tire durability at high speeds, vehicle steering performance
3. Price	Reasonable price, competitive pricing
4. Design	Tire appearance does not fade, tire exterior has various surface designs and aesthetic elements
5. Fuel Efficiency	Low rolling resistance, high fuel efficiency
6. Smart Tire Features (Intelligent Tire)	Equipped with smart sensors to monitor tire conditions (i.e., tread wear, air pressure, internal temperature, road surface conditions)

Table 2 Kano two-way questionnaire format (using service life as an example)

If the automobile tire is designed for a long service life (Long mileage, long durability, high wear resistance), how do you feel?
☐ I am satisfied ☐ That my expectations were met ☐ I am neutral (Indifferent)
☐ I can live with it that way ☐ I am dissatisfied
If the automobile tire is not designed for a long service life (Short mileage, short durability, low wear resistance), how do you feel?
☐ I am satisfied ☐ That my expectations were met ☐ I am neutral (Indifferent)
☐ I can live with it that way ☐ I am dissatisfied

Table 3 Kano table for attribute classification

Criteria/attribute		Insufficiency				
		Satisfied	Must-be	Indifferent	Live with it	Dissatisfied
Sufficiency	Satisfied	Q	A	A	A	O
	Must-be	R	I	I	I	M
	Indifferent	R	I	I	I	M
	Live with it	R	I	I	I	M
	Dissatisfied	R	R	R	R	Q

A-attractive, O-one-dimensional,M-must-be,I-indifferent,R-reverse,Q-questionable

Table 4. S-CR relationship functions

KC	a_i	b_i	$f(x_i)$	$Si = a_i f(x_i) + b_i$
O	$SI_i - DI_i$	DI_i	x	$Si = (SI_i - DI_i)x + DI_i$
A	$\frac{SI_i - DI_i}{e - 1}$	$-\frac{SI_i - eDI_i}{e - 1}$	e^x	$Si = \frac{SI_i - DI_i}{e - 1}e^x - \frac{SI_i - eDI_i}{e - 1}$
M	$\frac{e(SI_i - DI_i)}{e - 1}$	$\frac{eSI_i - DI_i}{e - 1}$	$-e^{-x}$	$Si = -\frac{e(SI_i - DI_i)}{e - 1}e^{-x} + \frac{eSI_i - DI_i}{e - 1}$

Table 5. S-CR+ relationship functions

KC	a_i	b_i	$f(x_i)$	$Si = a_i f(x_i) + b_i$
O	$\frac{SI_i^* - DI_i^*}{2}$	$\frac{SI_i^* + DI_i^*}{2}$	x	$Si = \frac{1}{2}(SI_i^* - DI_i^*)x + \frac{1}{2}(SI_i^* + DI_i^*)$
I	0	0	x	$Si = 0$
A	$\frac{eSI_i^*}{e^2 - 1}$	$-\frac{SI_i^*}{e^2 - 1}$	e^x	$Si = \frac{eSI_i^*}{e^2 - 1}e^x - \frac{SI_i^*}{e^2 - 1}$
M	$\frac{eDI_i^*}{1 - e^2}$	$\frac{DI_i^*}{1 - e^2}$	$-e^{-x}$	$Si = -\frac{eDI_i^*}{1 - e^2}e^{-x} + \frac{DI_i^*}{1 - e^2}$

Table 6. Respondent demographics (N=130)

		No. of respondents	%	Total Sample size	Cumulative percentage
Gender	Male	90	69.2	130	69.2
	Female	40	30.8		100
Age	20~29	1	0.8	130	0.8
	30~39	44	33.8		34.6
	40~49	60	46.2		80.8
	50~59	25	19.2		100
Occupation	Employee	106	81.5	130	81.5
	Homemaker:	1	0.8		82.3
	Self-employed/Business Owner	16	12.3		94.6
	Public Servant	4	3.1		97.7
	Other	3	2.3		100
Driving Experience	Almost None	2	1.5	130	1.5
	More than 1 year	8	6.2		7.7
	Within 3 years	6	4.6		12.3
	Within 5 years	6	4.6		16.9
	Within 10 years	15	11.5		28.5
	More than 10 years	93	71.5		100
Experience with Tire Replacement	YES	116	89.2	130	89.2
	No	14	10.8		100
Degree of Understanding of Tire Product Characteristics	Not at all	17	13.1	130	13.1
	Slightly unaware	28	21.5		34.6
	Neutral	43	33.1		67.7
	Somewhat aware	36	27.7		95.4
	Very aware	6	4.6		100

Table 7. The self-stated importance of CRs for automobile tires

Customer requirement	Self-stated Importance	
	Mean	Rank
Service Life	6.06	1
Ride Quality (Noise, Braking, Handling)	6.02	2
Price	5.92	3
Design (including appearance)	3.82	6
Fuel efficiency (Rolling Resistance)	5.88	4
Smart tire features	5.48	5

Table 8. The Kano category results of the sample analysis

CR	Customer Requirements	A	O	M	I	R	Q	Total respondents	SI_i	DI_i	KC
1	Service Life	11	55	32	32	0	0	130	0.51	-0.67	O
2	Ride Quality	12	71	19	28	0	0	130	0.64	-0.69	O
3	Price	15	64	19	32	0	0	130	0.61	-0.64	O
4	Design	19	10	9	89	2	1	130	0.23	-0.15	I
5	Fuel efficiency	19	60	15	36	0	0	130	0.61	-0.58	O
6	Smart tire features	28	37	12	51	1	1	130	0.51	-0.38	A

Table 9. S-CR Relationship Functions for automobile tire design

CR	Customer Requirements	KC	Point SI_i	Point DI_i	a_i	b_i	$f(x_i)$	$S_i = a_i f(x_i) + b_i$
1	Service Life	O	(1, 0.51)	(0, -0.67)	1.18	-0.67	x	$S = 1.18x - 0.67$
2	Ride Quality	O	(1, 0.64)	(0, -0.69)	1.33	-0.69	x	$S = 1.33x - 0.69$
3	Price	O	(1, 0.61)	(0, -0.64)	1.25	-0.64	x	$S = 1.25x - 0.64$
4	Design	I	(1, 0.23)	(0, -0.15)	-	-	-	-
5	Fuel efficiency	O	(1, 0.61)	(0, -0.58)	1.18	-0.58	x	$S = 1.18x - 0.58$
6	Smart tire features	A	(1, 0.51)	(0, -0.38)	0.52	-0.90	e^x	$S = 0.52e^x - 0.90$

Table 10. S-CR+ Relationship Functions for automobile tire design

CR	Customer Requirements	KC	Point SI_i^*	Point DI_i^*	a_i	b_i	$f(x_i)$	$S_i = a_i f(x_i) + b_i$
1	Service Life	O	(1, 0.51)	(-1, -0.67)	0.59	-0.08	x	$S = 0.59x - 0.08$
2	Ride Quality	O	(1, 0.64)	(-1, -0.69)	0.67	-0.03	x	$S = 0.67x - 0.03$
3	Price	O	(1, 0.61)	(-1, -0.64)	0.62	-0.02	x	$S = 0.62x - 0.02$
4	Design	I	(1, 0.23)	(-1, -0.15)	0.00	0.00	x	$S = 0$
5	Fuel efficiency	O	(1, 0.61)	(-1, -0.58)	0.59	0.02	x	$S = 0.59x - 0.02$
6	Smart tire features	A	(1, 0.51)	(-1, -0.38)	0.22	-0.08	e^x	$S = 0.22e^x - 0.08$

Table 11. Part of the HoQ for ICEV tires

Customer Requirements	Self-stated importance	Engineering Characteristics					
		Compound characteristic	Cord characteristic	(Joint) index distribution	Tire heating and vulcanization	Tread patten	Sidewall
Service Life	6.06	9	3		3	3	
Ride Quality	6.02	3	9	9	1	9	1
Price	5.92	3	1				1
Design	3.82			3		9	9
Fuel efficiency	5.88	9	9	3	1	3	3
Smart tire features	5.48		1	3	9	1	
Absolute Importance (<i>AI</i>)		83	78	55	47	68	35
Relative Importance (<i>RI</i>)		22.65%	21.44%	14.93%	12.93%	18.50%	9.54%
Ranks		1	2	4	5	3	6

Table 12. Part of the HoQ for EV tires

Customer Requirements	Self-stated importance	Engineering Characteristics					
		Compound characteristic	Cord characteristic	(Joint) index distribution	Tire heating and vulcanization	Tread patten	Sidewall
Service Life	6.06	9	3		3	3	
Ride Quality	6.02	3	9	9	1	9	3
Price	5.92	3	1				1
Design	3.82			3		9	9
Fuel efficiency	5.88	9	9	3	1	9	3
Smart tire features	5.48		1	3	9	1	
Absolute Importance (<i>AI</i>)		83	78	55	47	91	41
Relative Importance (<i>RI</i>)		20.98%	19.85%	13.83%	11.98%	23.01%	10.36%
Ranks		2	3	4	5	1	6