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Article

The Expansion of Value Engineering Theory and Its Application in the Intelligent Automotive Industry

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Abstract: Value engineering (VE), as a conceptual approach and management technique, has allowed enterprises to capture value through mass production and market expansion during the industrial economic era. The VE method has enabled companies to produce products that meet user needs at a lower cost, leading to success. However, as the complexity of society and industry development increases, the lack of theoretical expansion in VE has limited its application in today's more complex and macro management systems. With the development and evolution of vehicle–road collaborative intelligence, the intelligent automotive industry has become a complex system with multiple entities and interwoven values across different dimensions. Intelligent connected vehicles (ICVs), along with the external intelligent environment, will jointly participate in the realization of system functions. It is no longer sufficient to apply VE methods to analyze ICVs from a single product perspective. The pursuit of "maximizing value" is always the core driving force of industrial development. This study, building on the fundamental ideas of VE, expands and extends the connotation and theory of VE in three aspects: research objects, value dimensions, and associated entities, to adapt to the current situation. It also provides a new analysis process for the VE theory to better address systemic and complex issues. Taking the intelligent automotive industry as a case study, this study analyzes it based on the expanded VE theory. It considers not only the cost of system function realization and the product value of ICVs but also the external benefits of the system across different dimensions. The social value, user value, enterprise value are introduced in entity value analysis, and the relevant indicators are organized. This approach can better guide the collaboration and division of labor among multiple participating entities such as governments, enterprises, and users, achieving overall value maximization.

Keywords: value engineering (VE); intelligent connected vehicle (ICV); vehicle–road collaborative intelligent system; systemic value; product value; entity value

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1. Introduction

The intelligent connected vehicle (ICV) refers to a new generation of vehicles equipped with advanced sensors, controllers, actuators, and other devices, integrating the latest communication and network technologies and realizing information exchange and vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) sharing. It possesses the functions of environmental sensing, intelligent decision-making, cooperative control, etc., which can serve for assisting or even substituting human operation [1]. With the collaborative intelligent technology route gradually becoming an industry consensus [2,3], ICVs will serve as interconnected nodes, data carriers, intelligent terminals, and mobile intelligent spaces, as well as energy storage and supply units [4]. They will generate benefits on a larger scale in terms of traffic safety, traffic efficiency, energy saving, and carbon emission reduction [5–8]. The product form of the ICV is generalized, involving many elements that are coupled with each other. For example, the realization of autonomous driving also depends on the empowerment of the external intelligent environment such as roadside perception, edge computing, cloud computing, high-precision maps, and high-performance communication networks [9]. The boundaries of the automobile industry are continuously expanding and becoming blurred, involving more participants. In the future, ICVs will not merely be single products manufactured by OEMs to satisfy consumer demands. Governments and other related enterprises will also need to rethink the higher-dimensional value of collaborative intelligent systems from a social value perspective, rather than confining themselves to the value of individual products.

Value engineering (VE), which emerged in the 1950s, is a modern management method proposed by the American General Electric engineer L.D. Miles and has gradually developed [10]. It is dedicated to providing the most effective function with the least cost, thereby achieving the highest value for products. As an application-driven theory, VE is primarily used as a means of scheme selection, product creation, and management, and it has been widely applied in various fields such as industrial manufacturing, construction, transportation, and chemical engineering. However, as the complexity of society and industry increases, the insufficiency of its theoretical expansion has limited its application in today’s more complex and macroscopic management systems. As a complex system with multiple stakeholders and interwoven values across various dimensions, the pursuit of “value maximization” is always the core driving force of the automotive industry. This study continues the basic ideas of VE and extends its adaptive connotations and theoretical extensions to address complex and systemic issues, which can guide decision optimization among multiple participants such as governments, enterprises, and users in the intelligent automotive industry ecosystem.

2. Basic Theory and Development Status of Value Engineering

2.1. Basic Theory of Value Engineering

Value engineering is a thought method and management technique, whose basic idea is to achieve the functions required by users reliably at the lowest lifecycle cost, i.e., to maximize the functional value of the product [11]. Its conceptual formula is illustrated in Equation (1).

$$V = \frac{F}{C} = \frac{F_k/\sum F_i}{C_k/\sum C_i} \tag{1}$$

V represents the value, F represents the function, and C represents the cost incurred in acquiring the function. This conceptual formula emphasizes the dialectical relationship between the value, function, and cost. It can be seen that if costs cannot be effectively used to enhance the necessary function, they cannot generate value, because value is realized through the function. VE’s initial practice mainly focused on material substitution, such as replacing an asbestos board with lower-cost fireproof paper when there was a shortage of materials in the wartime [12].

In the classic book *Techniques of Value Analysis and Engineering*, published in 1961, L.D. Miles further systematized the methodology of VE and put forward the standardized process of “selecting the analysis object→collecting data and information→function sorting and definition→function evaluation→cost analysis→value analysis→scheme innovation and optimization→scheme evaluation", with the core content including functional evaluation and cost analysis [13]. The U.S. Department of Defense promoted the institutionalization of VE at this stage. In 1962, it incorporated VE into the procurement process and standardized the implementation process through MIL-STD-490. At the same time, Germany, France, and other European countries began to formulate national standards, such as DIN 69910 (1973) in Germany and XO-150 (1984) in France, to promote the standardization of VE [14].

Since the end of the 20th century, VE has formed a global network. Japan combined VE with total quality management (TQM) and developed a "VIQ" (Value Engineering, Industrial Engineering, Quality Management) system, which was popularized by 84.5% of enterprises in 1978 [15]. Europe promotes the combination of VE and sustainable design through interdisciplinary collaboration. For example, the German VDI 2801 standard emphasizes the integration of functional analysis and environmental impact assessment [16]. At this stage, VE is beginning to form a consensus structure and principles. As shown in Figure 1, a product is composed of multiple elements, each of which has a corresponding cost. The combination of different elements enables the product to exhibit various functions. The cost is what users need to pay, and it is also what enterprises hope to reduce by cutting elements or optimizing element combinations. The function is the essential need of users and the necessary goal of enterprise development. The basic principles of VE mainly include the principle of functional essence, the principle of dynamic correlation between function and cost, and the principle of value standardization, which play a guiding role throughout the entire process of VE activities [17].

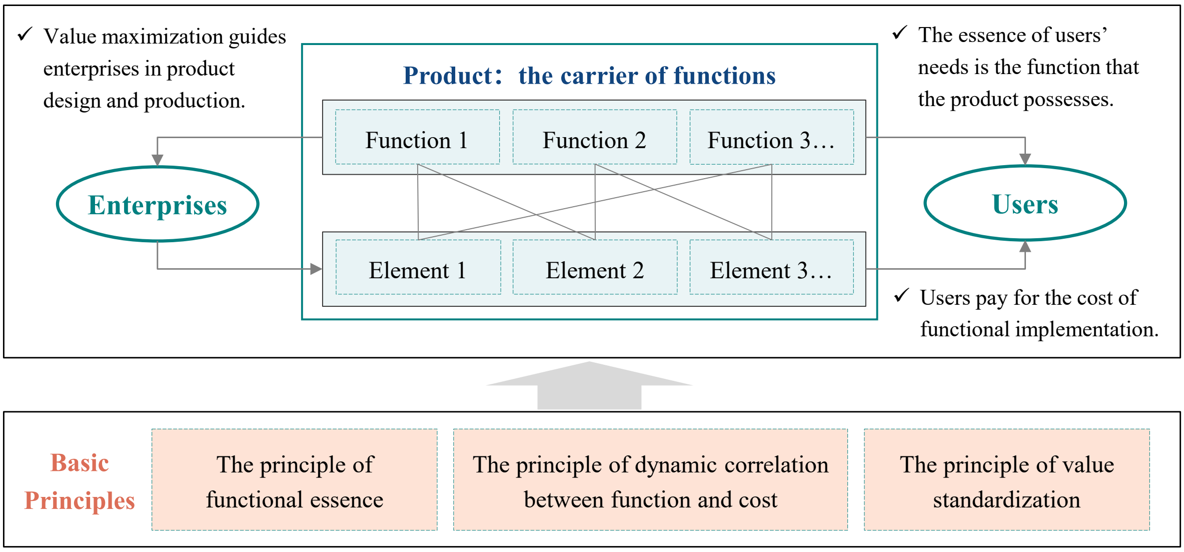

Figure 1. Basic theory of VE.

The principle of functional essence. Function is the essence of a product, and the product is the carrier of the function. The essence of users' needs is also the function that the product possesses. Enterprises should focus on the functions required by users to conduct research, design, and production of the product.

The principle of dynamic correlation between function and cost. Due to differences in production scale, production processes, and technical equipment among various enterprises, the correlation between function and cost is uncertain at the micro level, but statistically correlated at the macro level. That is, products with higher levels of functionality tend to have higher production costs.

The principle of value standardization. The common criterion for users and enterprises to measure the merits of a product is its value, which is to maximize the ratio of function to cost.

With the demand of digital transformation and sustainable development, in recent years, related research mainly focuses on the integration of VE and Industry 4.0. VE has developed from wartime material substitution to an interdisciplinary system methodology, and its evolution reflects the transformation from single cost optimization to full lifecycle value creation [18].

2.2. Existing Extensions and Expansions of VE Theory

Currently, both the industry and academia, in the practical application of VE theory, have made certain extensions and expansions on the basis of inheriting the core ideas of VE. This includes not only the development of traditional methods but also the integration with other theories such as systems engineering and decision-making techniques. Bytheway proposed the concept of the FAST diagram method in 1965, which has become a general method for functional organization [19]. By combining with systems engineering thinking, it provides a concise and effective method for analyzing complex assemblies or processes, determining the required functions of the object through a layered analysis approach [20]. However, this method mostly stays at the level of deconstructing and analyzing the functions of the product, without considering its externalities. Willians et al. added analyses on user value orientation and value composition in the application of VE, but these are mostly limited to the qualitative analysis level [21]. Boudreau et al. expanded the research boundary of VE from the product manufacturing stage to the research and development stage, focusing on cost issues from the overall level of the enterprise. Hines et al. researched management theories and methods of considering the “Value Stream”, involving a strategic review of a business or supply chain’s activities, the delimitation of key processes, and the mapping of these processes [22].

VE research and application in the automotive field mainly focus on the value linkage between vehicle manufacturers and users through their products, including how vehicle manufacturers design, develop, and produce vehicles with lower lifecycle costs to reliably satisfy the functions demanded by users. It includes the substitution of high-cost parts, process analysis and improvement, etc. This is because the vehicle is the carrier for realizing all the functions. The realization of vehicle functions solely depends on the hardware and software configuration on the vehicle side. Shen Bin et al. established an economic evaluation model for automotive energy-saving technologies based on the VE method, which more closely links technology and the economy and seeks the best match between cost and function [23]. Ibusuki et al. proposes a structured methodology for the product development process within an automotive company, focusing on the proper application of VE and target-costing strategies to effectively manage costs, and the engine starter system of vehicles was used as a case study [24]. Liu introduced the VE method into the procurement system of vehicle manufacturers to reduce the cost of components’ and parts’ procurement and conducted practical application and analysis [25]. Hui utilized VE theory and methodology to conduct research on shared car products and the application of shared cars in green mobility. Through value analysis, she identified the main problems with shared cars and proposed targeted innovative solutions [26].

2.3. Dilemmas in the Development of VE Theory

VE emerged in the industrial economic era, characterized by “production-led market and consumption, mass production and large-scale sales.” It met the corporate demand for “how to design and produce products needed by users at a lower cost,” and it was widely applied as enterprises gained value through scale production and market expansion. In today’s knowledge-based economy era, VE is gradually facing challenges, with its application scale decreasing year by year [27]. The reasons for the reduction in the application of VE can be summarized as follows.

Limitations of the definition of “value”. Value is the primary concept of VE theory, which is understood from the “user’s” perspective as the “functional value” of a product. It is equated with the ratio of “function” to “cost,” which actually limits the connotation of “value” and its application expansion. Expanding the ′function/cost′ relationship from encouraging a single product/process/activity to encompass product chains/value chains will become a development trend [28].

Insufficiency of the theoretical depth. When facing various complex entities, the singular mathematical model is not conducive to better and more effectively utilizing its role in the analysis of systems. This is especially the case with the development of industrial ecology, where the interconnections between various modules, elements, and participating entities in the system are strong. The application of VE in addressing industrial division, corporate value, and social value is limited.

3. The Extension and Expansion of VE Theory

The scientific problem to be solved in this study is how to extend VE theory to solve the complexity of the smart car system, including multi-entity cooperation, intertwined value dimensions, and system externality. It is assumed that by expanding the research objects, value dimensions, and related entities of virtual enterprises, the new theory can realize the overall optimization of the vehicle–road collaborative intelligent system, guide the decision-making of multi-stakeholders, and maximize the overall value.

This research adopts a systematic theoretical extension combined with case-driven analysis, structured in three phases. The first phase is theoretical analysis. In Section 3.1, the gap between traditional VE theory and practical problems in the intelligent automotive industry is identified. The second phase is conceptual innovation. In Section 3.2, a multidimensional expansion framework is proposed, and in Section 3.3, a step-by-step VE analysis process is redesigned. The third phase is verified by the case (application) of the intelligent automotive industry in Sections 4 and 5.

3.1. The Complexity and Uniqueness of ICV Research

With the development and evolution of the vehicle–road collaborative intelligent system, the realization of ICV functions requires the empowerment of the external intelligent environment. For example, the implementation of autonomous driving will require roadside perception devices from a high-dimensional perspective, addressing the “long-tail problem” of vehicle-side perception and enhancing the safety of autonomous driving. At the same time, edge computing, cloud computing, and other external computing infrastructure will participate and optimize fleet planning and decision-making, improving traffic operation efficiency. The information exchange requires high-performance communication networks with low latency and large bandwidths as supports.

The collaborative intelligent system constituted by ICVs and external intelligent infrastructure will generate greater social benefits in terms of traffic safety, traffic efficiency, energy saving, and carbon emission reduction. It is necessary to analyze the system value from the dimensions of cities or society. At the same time, the participation and collaboration of more external entities, such as governments, communication operators, cloud platform operators, and high-precision map operators, will allow for sharing the cost of the collaborative intelligent system over a longer time span. It can be said that the intelligentization and network connectivity of automobiles have led to the continuous expansion and blurring of industry boundaries, resulting in a network-like structure of the industrial ecosystem [29].

VE theory, by guiding enterprises to design, develop, and produce products at low costs, still has application value for the analysis and improvement of parts and processes in automobiles. However, it falls short and has deficiencies when studying "new-generation vehicles" and solving "newly emerging problems". These shortcomings stem from three core gaps between the traditional VE framework and the complexity and uniqueness of ICVs:

① Narrow focus on single-product analysis in a multi-entity system: Traditional VE centers on optimizing individual vehicle components by balancing function and cost within a product's lifecycle. However, ICVs operate as nodes in a vehicle–road collaborative intelligent system, where functions like autonomous driving rely on external infrastructure and cross-entity collaboration, the dependencies that traditional VE—confined to product-level analysis—cannot model. This limitation hinders holistic optimization of system-wide cost allocation and functionality sharing.

② Inadequate representation of multi-dimensional value and externalities: VE's classic formula reduces value to a product's functional efficiency, ignoring the systemic external benefits generated by ICVs. New-generation vehicles create value in non-product dimensions: traffic safety, energy savings, and carbon emission reduction, which traditional VE does not quantify. Additionally, the theory lacks mechanisms to assess "implicit values" (e.g., long-term urban mobility optimization) and "inter-entity value correlations" (e.g., how government investments in infrastructure impact enterprise production costs).

③ Failure to address collaborative decision-making across diverse entities: Traditional VE assumes a single decision-maker optimizing the product value for users. In contrast, ICV development involves interdependent entities with conflicting objectives. Governments prioritize social welfare, enterprises seek profitability, and users focus on experience. Traditional VE cannot model how these entities share costs or coordinate benefits.

In summary, traditional VE's theoretical rigidity—rooted in its product-centric, single-entity, and static-value framework—renders it insufficient for analyzing ICVs as complex, multi-stakeholder, and externally dependent systems.

3.2. The Extension of VE Theory

VE, as a method of thinking, has the advantages of high flexibility and expandability, providing many conveniences in the aspects of theoretical expansion and innovative application. Our study expands the VE theory in three dimensions: research/application object, value dimension, and associated entities, as shown in Figure 2.

Expansion of the application object. The application object is extended from the "product" to "system". On the basis of fully considering the systematization, comprehensiveness, and hierarchy, the functions, modules, elements, and entities of the entire system are sorted out, rather than being limited to the product itself. The original product in the traditional VE theory may only serve as a module for the implementation of system functionality in the extension of VE theory.

Expansion of the value dimension. Traditional VE theory equates "value" to the ratio of "function" to "cost". Our study expands the concept of "value" to "system value" and "entity value", understands "cost" as "sacrifice", and expands "function" to "benefits". The benefits include several dimensions such as safety, efficiency, energy saving, carbon emission reduction, industrial economy, and user experience. Different entities have different concerns regarding benefits, costs, and values. "Value" can be divided into "explicit value" and "implicit value" based on the degree of manifestation, and into "long-term value" and "short-term value" based on the speed of manifestation.

Expansion of the associated entities. While the "system" generates benefits and value at a higher dimension, different entities will have different value perceptions of the "system" and participate in the construction of the system. It is necessary to redefine the value of the "system" to multiple entities, expanding the original "product function value" to "user value", "enterprise value", and "social value", rather than only understanding it as the functional value of the product to the user. User value, enterprise value, and social value, respectively, represent the benefits and related cost inputs that users, enterprises, and governments, as three different entities, focus on over a certain period of time. It is worth noting that for a particular entity, greater value means that the entity has a stronger willingness to participate in the construction of the system. Changes in the system's state will affect the value of other entities. Therefore, the values of entities are interrelated and intertwined.

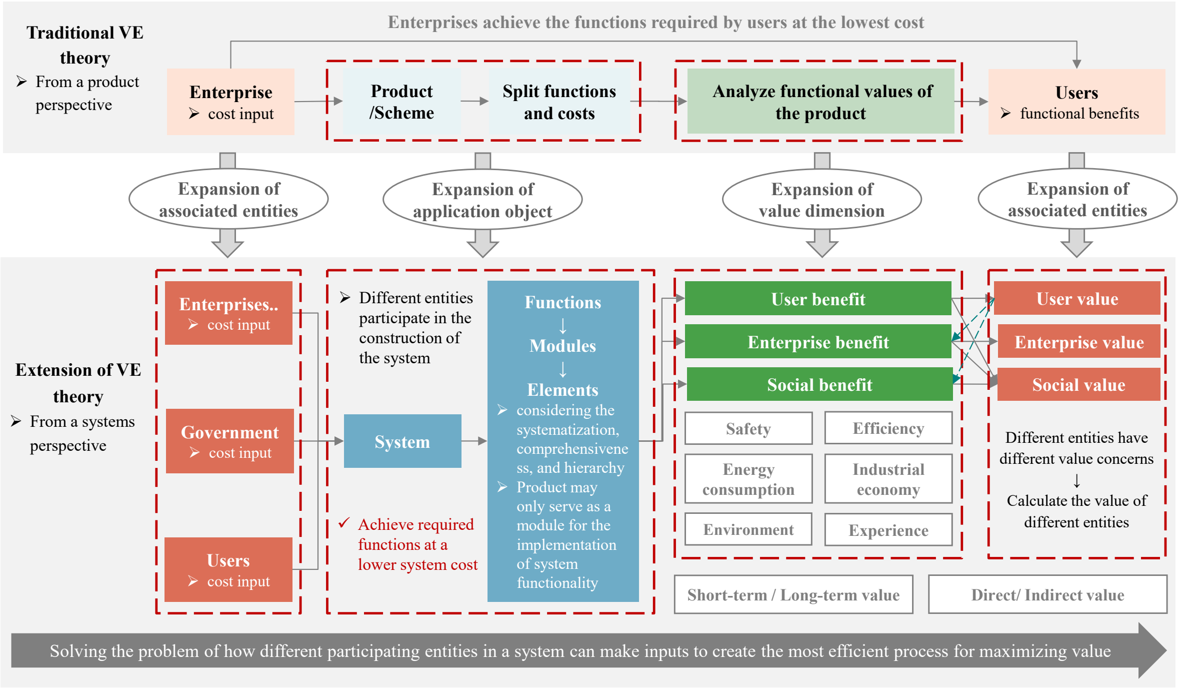

Figure 2. The extension of VE theory.

3.3. Extension of the VE Analysis Process

Traditional VE emphasizes enhancing the functional value of products, involving simple elements and a single entity. The original analysis process is not suitable for complex systems involving multiple entities in collaborative division of labor. The original analysis process is expanded and optimized to adapt to systematized and ecological research objects, as shown in Figure 3.

Define the target functions to be achieved by the system. System value is realized based on specific functions, with the difference that the carriers of function realization will no longer be limited to a single product. This can be compared to the traditional VE approach to sorting out product functions and sub-functions.

Key elements and coupling relationship sorting. From the system perspective, identify the key modules/elements within the product and the associated and supporting modules/elements outside the product to achieve the system's target functions. On the basis of meeting technical feasibility, judge the coupling and substitution relationships between modules, elements, and sub-functions to determine a set of system solutions that meet the target functions.

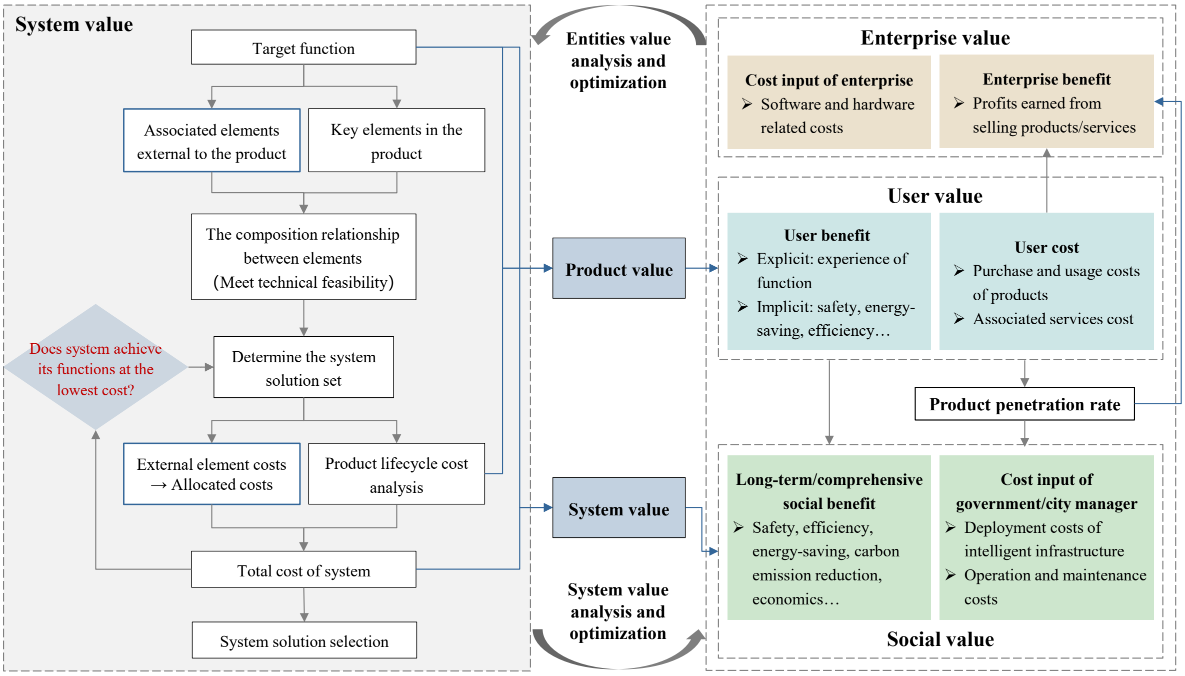

Figure 3. Extension of the VE analysis process.

Cost analysis for function realization. Conduct a lifecycle cost analysis for all system solutions, including both product lifecycle cost analysis and external environment lifecycle cost analysis. The product lifecycle cost mainly consists of two parts: one is the general price represented by the human resources and materials consumed during the production, manufacturing, and sales process of the product, and the other is the energy consumption and service-related costs during the actual use of the product. The external environment lifecycle cost can be analyzed by analogy. The unit apportioned cost of the external environment can be obtained based on the utilization rate corresponding to the actual use scenario. It is worth noting that the costs of different modules in the system will be paid by different participating entities.

Selection of the optimal system solutions that satisfy the target functions. From the system solution sets that meet the technical feasibility of the target functions, the one with the lowest total system cost and the one that minimizes the product lifecycle cost can be selected, respectively. In other words, under the premise of achieving the same functionality, the system solutions that yield the highest product value and the highest system value were obtained.

Entity value analysis. ① User value: User value is defined as the ratio of the benefits obtained by users in terms of experience, safety, efficiency, energy savings, etc., based on product functions to the costs paid by users for acquiring and using the product. ② Social value: Social value is defined as the ratio of the benefits generated by the system (product + external environment) in terms of social safety, traffic efficiency, energy saving, carbon emission reduction, etc., to the total system cost. City managers should fully consider the long-term social value brought by the system, play a guiding role in key links/modules, and guide initial investments. ③ Enterprise value: Enterprise value is defined as the ratio of the product value produced to the total cost paid by the related enterprises. In real scenarios, the ability to produce high-value products at a lower cost is also the key for enterprises to win market competition and achieve profitability.

Analysis of the correlation between entity values. Different collaboration and division of labor models among entities will directly affect the costs of achieving the same product functions. The related costs will be passed on to the user end or affect the profitability of the industry. The product value will affect the willingness of users to purchase, which in turn affects the market sales and ownership volume of the product, ultimately influencing the social value generated by the product.

Iterative optimization of the linkage between entity value and system value. While ensuring the low-cost realization of the system's target functions, external benefits should be fully considered. Based on the analysis of different entity values under various system solutions, a comprehensive evaluation of the system solutions should be conducted. This will clarify the division of labor and collaboration relationships and models among multiple participating entities, addressing issues of resource sharing, industrial division of labor, and cost allocation within the industrial ecosystem, ultimately achieving the maximization of overall value.

By constructing a value network for multiple entities, VE theory is extended into a methodology that is oriented towards complex systems with multiple elements and entities, where different values are interwoven and integrated throughout the entire process of design, operation, and innovation improvement. This methodology can analyze how multiple entities can input and output to create the most efficient process for maximizing overall value/utility, thereby optimizing the cost input and value distribution of the various entities.

4. The Application of Extended VE in the Intelligent Automotive Industry

4.1. Vehicle–road Collaborative Intelligent System

ICVs, together with the external intelligent environment, constitute a complex collaborative intelligent system, as shown in Figure 4.

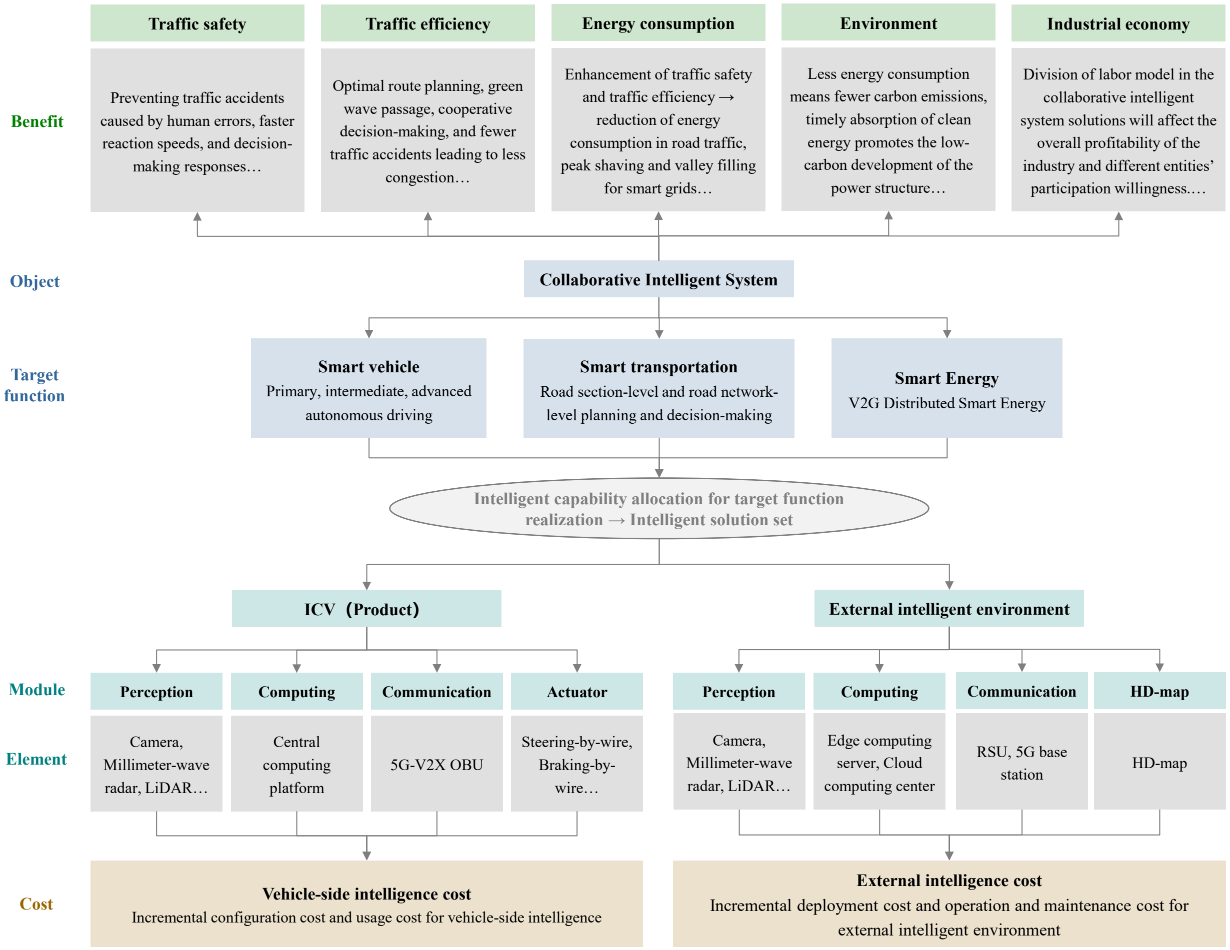

Figure 4. Vehicle–road collaborative intelligent system.

In the system value analysis part of the collaborative intelligent system, the key modules and elements of ICVs and the external intelligent environment required by the system can be analyzed for the purpose of realizing primary, intermediate, and advanced autonomous driving, the smart transportation functions of the road section level and the road network level, as well as the smart energy functions. The key elements of ICVs mainly include onboard perception equipment such as cameras, millimeter-wave radars, Lidars, central computing units, 5G-V2X OBU (On-Board Unit), and actuation devices like steer-by-wire and brake-by-wire systems. The key elements of the external intelligent environment mainly include roadside perception equipment, MEC (mobile edge computing), central cloud, RSU (Roadside Unit), 5G base station, HD maps, etc. On the basis of satisfying the technical feasibility of different target functions, clarify the coupling and substitution relationships between elements. For example, roadside high-dimensional perception equipment can provide ICVs with more comprehensive perception information, expanding the range and capability of vehicle-side perception, and effectively reducing the demand for vehicle-side perception capabilities. Roadside high-dimensional computing can offer ICVs global route planning and optimized decision-making, addressing mixed traffic scenario issues such as autonomous driving game theory, reducing the demand for vehicle-side computing capabilities [30,31]. On this basis, obtain a set of collaborative intelligent solutions that meet technical feasibility [30].

By analyzing the lifecycle costs of ICVs and the costs of the external intelligent environment, the total cost of the collaborative intelligent system can be obtained. Through the assessment and comparison of the total costs corresponding to several intelligent solutions, the optimal system-level solution for achieving target functions can be obtained. ICVs offer lower costs at the same level of functionality, which also implies a higher product value of ICVs. The realization of the collaborative intelligent system's functions will also generate external benefits in dimensions such as traffic safety, traffic efficiency, energy consumption, environment, and industrial economy.

4.2. Extended VE Analysis Process of Vehicle–road Collaborative Intelligent System

Next, conduct a value analysis for three different participating entities: users, governments, and enterprises. The overall process of applying the extended VE theory to conduct a value analysis of the vehicle–road collaborative intelligent system is illustrated in Figure 5.

Social benefits encompass the incremental gains generated by the vehicle–road collaborative intelligent system in overall traffic safety, traffic efficiency, and environment dimensions. Social costs include the deployment and operation and maintenance costs of the external intelligent environment, as well as the incremental configuration cost and usage costs of the ICV fleet. Specific social benefit indicators and social cost indicators are shown in Tables 1 and 2, respectively. Different benefit and cost indicators can be quantitatively assessed through the design of corresponding sub-models.

Table 1. Social benefit indicators.

Classification	Indicator	Notes
Traffic safety related	b_1: Reduction in the economic loss of social labor force/productivity	➢ The productivity loss caused by traffic accidents represents the disappearance of the victims' social productivity due to premature death, while severe or minor injuries may result in a discount or even loss of the victims' ability to work.
	b_2: Reduction in societal medical costs	➢ Traffic accidents and casualties lead to an increase in societal medical costs. Varying degrees of severity in traffic accidents result in different medical costs.
	b_3: Reduction in direct property losses	➢ Direct property loss includes the damage to vehicles, cargo, and other related facilities, as well as the costs associated with on-site handling.
	b_4: Reduction in congestion delay losses	➢ Traffic accidents lead to congestion time losses of fleet, with accidents of different severity levels causing different processing times and congestion durations.
	b_5: Reduction in energy consumption losses	➢ Traffic accidents lead to congestion energy consumption losses of fleet. During congestion, vehicles are generally in an idling state.
Traffic efficiency related	b_6: Economic benefit of time saving	➢ Improved traffic efficiency results in less travel time of fleet.
	b_7: Economic benefit of energy saving	➢ Improved traffic efficiency results in less energy consumption of fleet.
Environment related	b_8: Reduction in carbon emission	➢ Reduction in energy consumption results in lower corresponding carbon emissions.

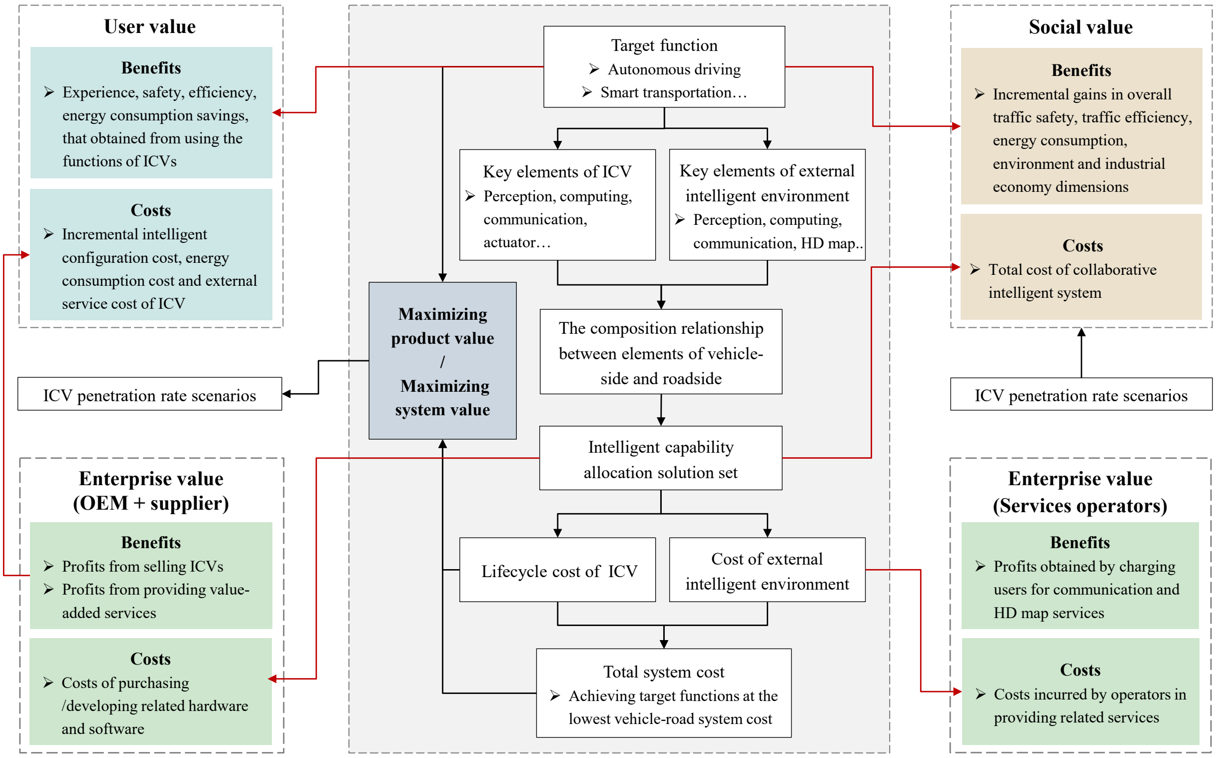

Figure 5. Extended VE analysis process of collaborative intelligent system.

Table 2. Social cost indicators.

Classification	**Indicator**	**Notes**
Roadside related	p_1: Deployment costs of external intelligent environment	➢ Including the deployment costs of roadside perception equipment, MEC, central cloud, RSU, 5G base station, as well as the acquisition cost of HD map.
	p_2: Operation and maintenance costs of external intelligent environment	➢ Including the operation and maintenance costs of roadside perception equipment, MEC, central cloud, RSU, 5G base station, as well as the update cost of HD map.
Vehicle-side related	f_1: Incremental intelligent configuration cost of ICV fleet	➢ Including incremental configuration cost of onboard perception equipment, central computing units, V2X T-Box, and actuation devices like steer-by-wire and brake-by-wire systems.
	f_2: Incremental energy consumption cost of ICV fleet	➢ Including incremental energy consumption cost of onboard perception equipment, central computing units, V2X T-Box, and actuation devices like steer-by-wire and brake-by-wire systems.

Together, these indicators determine the social value of the vehicle–road collaborative intelligent system, as shown in Equation (2). Social value is a systematic assessment of the overall cost input and comprehensive benefit output under different intelligent system solutions, which can guide different participating entities to construct the system in a way that maximizes the output–input ratio.

$$V_{society,VR} = \frac{\sum_{i=1}^{8} F_{society,vr,b_i}}{\sum_{j=1}^{2} C_{society,p_j} + \sum_{k=1}^{2} C_{society,f_k}} \quad (2)$$

$F_{society,VR,b_i}$ represents the social benefits generated by the vehicle–road collaborative intelligent system VR under the indicator b_i. $C_{society,p_j}$ and $C_{society,f_k}$, respectively, represent the incremental social costs of the vehicle–road collaborative intelligent system under the indicators p_j and f_k.

User benefits are the experience, safety, and efficiency that users obtain from using the functions of ICVs. User costs include the incremental purchase cost of intelligent configurations and its energy consumption costs, and external service costs (including communication services, HD map services, etc.) paid during the usage phase. Specific user benefit indicators and user cost indicators are shown in Tables 3 and 4, respectively. User benefits are distinguished into direct benefits and indirect benefits. Direct benefits represent the parts that users can directly benefit from during the use of ICVs' functions. ICVs of different autonomous driving levels imply different user experiences and varying degrees of in-vehicle travel time release. ICVs can achieve safer autonomous driving through intelligent functions, reducing the probability of traffic accidents, which also means lower insurance costs for users. Indirect benefits represent the parts that users indirectly benefit from due to the improvement of the system's intelligence level. For example, even if a vehicle has high safety-level autonomous driving functions, it cannot avoid traffic congestion and energy consumption loss caused by accidents involving other vehicles. Travel time savings also depend on the overall improvement of traffic efficiency, which requires an increase in the penetration rate of ICVs in traffic flow. At this point, each ICV can be considered an element of the collaborative intelligent system, participating in the generation of indirect benefits.

Table 3. User benefit indicators.

Classification	Indicator	Notes
Experience related	d_1: Release of in-vehicle travel time	➢ As the level of autonomous driving increases, intelligent vehicles will better and replace humans in performing driving tasks, achieving the release of drivers' in-vehicle travel time and improving their experience. (direct benefit)
Safety related	d_2: Reduction in vehicle's insurance expense	➢ Reduction in traffic accidents leads to reduction in vehicle's insurance expense. (direct benefit)
	id_1: Reduction in congestion delay losses	➢ Dependent on the improvement of the overall traffic safety level of the fleet. (indirect benefit)
	id_2: Reduction in energy consumption losses	➢ Dependent on the improvement of the overall traffic safety level of the fleet. (indirect benefit)
Efficiency related	id_3: Economic benefit of time saving	➢ Dependent on the improvement of the overall traffic efficiency level of the fleet. (indirect benefit)
	id_4: Economic benefit of energy saving	➢ Dependent on the improvement of the overall traffic efficiency level of the fleet. (indirect benefit)

Table 4. User cost indicators.

Classification	Indicator	Notes
Purchase phase	p_1: Incremental intelligent configuration cost of ICV	➢ Including incremental configuration cost of onboard perception equipment, central computing units, V2X T-Box, and actuation devices like steer-by-wire and brake-by-wire systems.
Usage phase	u_1: Incremental energy consumption cost of ICV	➢ Including incremental energy consumption cost of onboard perception equipment, central computing units, V2X T-Box, and actuation devices like steer-by-wire and brake-by-wire systems.
	u_2: Incremental external service cost of ICV	➢ Including the service fees that users need to pay to obtain high-precision maps and high-performance communication.

Together, these indicators determine the user value of the intelligent connected vehicle, as shown in Equation (3). The user value is an assessment of the user cost input and relevant benefit output. The user value is a comprehensive assessment of the user's cost inputs and related benefit outputs over the lifecycle of an ICV. It influences users' willingness to purchase ICVs, ultimately affecting their market penetration rate. In the actual vehicle purchasing decision-making process, users often focus more on the experience brought by intelligent driving functions and the incremental costs incurred at the time of purchase.

$$V_{user,ICV}=\frac{\sum_{i=1}^{2}F_{user,ICV,d_i}+\sum_{j=1}^{4}F_{user,vr,id_j}}{C_{user,p_1}+\sum_{k=1}^{2}C_{user,u_k}} \tag{3}$$

F_{user,ICV,d_i} represents the direct user benefits generated by the ICV under the indicator d_i. F_{user,vr,id_i} represents the indirect user benefits generated by the vehicle–road collaborative intelligent system under the indicator id_i. C_{user,p_1} and C_{user,u_k}, respectively, represent the incremental energy consumption cost and external service cost of the ICV.

In the intelligent automotive industry ecosystem, the enterprise value of two main types of companies can be primarily analyzed. One is automotive companies and suppliers of hardware and software, who mainly provide ICV products. The other is operators of HD map and communication services, who primarily offer supportive services. While it is challenging to discuss the profitability of different enterprises, the specific financial situation of an enterprise is related to its pricing strategy and the competitive environment in which it operates. However, the construction of an external intelligent environment will affect the cost investment of vehicle manufacturers in achieving the same level of intelligent functions in intelligent vehicle products. Additionally, it will impact the cost investment required by external service providers, such as HD map services, to offer the same services. Within the framework of market laws, it is possible to analyze and discuss the potential profit margins for related companies and the range of changes in consumers' purchase costs.

Attention should be paid to the correlation between product value and the values of different entities. An ICV fleet can improve travel efficiency, save energy, reduce carbon emissions, and lower the rate of traffic accidents, especially when the penetration rate of intermediate and advanced ICVs reaches a certain scale, at which their traffic and safety benefits will be more significant [32,33]. At the current stage, since the perception, planning, and decision-making tasks of advanced intelligent vehicles are all completed by the vehicle itself, vehicles need to be equipped with a large amount of redundant perception and computing devices to avoid functional failure, leading to high intelligentization costs and a lower product value of advanced intelligent vehicles. Consumers often focus more on the costs they pay and the functional experience they gain when choosing intelligent vehicles. In the early stages of industry development, it is difficult for consumers to realize the potential safety and efficiency benefits in the future use process. Coupled with the high cost of functional implementation, this leads to a lower willingness of consumers to purchase. At the same time, the development of an advanced autonomous driving function involves a large investment in hardware and software, and related participating entities such as vehicle manufacturers and hardware and software suppliers will fall into a predicament of difficult profitability.

Governments or city managers should fully consider the long-term social value that ICVs bring to aspects such as traffic safety, traffic efficiency, and traffic decarbonization (even if the short-term value is not significant), and can guide and participate in the investment and deployment of the external intelligent environment in an orderly manner [34,35]. The deployment of the external intelligent environment will reduce the performance requirements for vehicle-side perception and computing. The industry ecosystem, centered around vehicle manufacturers, collaborates in the design, research and development, and production of ICV products, making full use of the external intelligent environment to continuously reduce costs related to the product intelligence configuration and enhance its product value. Consumers can obtain a better experience of intelligent vehicle products at a lower price. By integrating the guidance and promotion from governments and enterprises, consumers can fully recognize the implicit value of intelligent vehicles in terms of safety and efficiency, accelerating the market penetration of advanced intelligent vehicles, and addressing the profitability challenges faced by related enterprises (OEMs and suppliers). Due to the higher stability and reliability of roadside perception equipment compared to map crowdsourcing collection vehicles, the cost of map data traffic and data processing is correspondingly reduced [31]. Therefore, the deployment of roadside perception and computing will greatly reduce the real-time map update costs for map operators. The popularization of ICVs will also expand the application scenarios and application value of 5G communication networks, solving the profitability issues for communication operators in the deployment and operation of 5G base stations. While achieving "technology equality", governments can further enhance the social benefits of collaborative intelligent systems in aspects such as traffic efficiency, traffic safety, energy consumption saving, and carbon emission reduction.

5. Case Application

To verify the feasibility of the framework proposed in this study, this section takes Beijing as a case to apply the framework for evaluating the social value and user value generated by the deployment of vehicle–road collaborative intelligent systems.

The basic data are derived from the authors' previous research [36], including the vehicle–road intelligent deployment scheme and functions, the annual vehicle ownership and intelligent vehicle penetration rate in Beijing, the mileage scale and usage intensity of various types of roads in Beijing, etc. The time period selected in this study is 2025–2040. According to the *Research White Paper on the Industrialization Path and Timeline of C-V2X* [37], it is assumed that all new intelligent vehicles are equipped with networked terminals. The intelligent transformation of urban expressways will be completed to 25% in 2025 and achieve 100% coverage in 2028; the intelligent transformation of expressways, arterial roads, and secondary roads in urban areas will start in 2025 and achieve 100% coverage in 2030; first-class highways will start intelligent transformation in 2030 and achieve 100% coverage in 2035; and second-class highways will start intelligent transformation in 2030 and achieve 100% coverage in 2040.

In terms of the overall calculation logic, the procurement costs are mainly calculated from the bottom up based on hardware and software configurations. The operation and maintenance costs are primarily determined by hardware power consumption and usage duration, with considerations for maintenance and replacement of certain equipment. Safety-related benefits are economically converted according to the collision avoidance rate achieved by intelligent driving functions and the scale of traffic accidents in Beijing. Traffic efficiency-related benefits are economically converted based on the speed increase and road capacity improvement in Beijing enabled by intelligent driving functions. User experience-related benefits are economically converted according to the time liberated for drivers. Due to the limitation of the current paper's length, this study does not elaborate on the calculation models of various value indicators, which can be obtained from the published papers of the research team [30,33,36,38]. Figure 6 shows the evaluation results of the indicators in Tables 1–4 in the case.

As shown in Figure 6, both at the social and user levels, the cumulative benefits obtained from deploying the vehicle–road collaborative intelligent system in Beijing during 2025–2040 far exceed the cumulative costs. At the enterprise level, as long as the pricing is not lower than the cost, its value will also be greater than 1. That is to say, the government, enterprises, and users will all be willing to promote the implementation of the vehicle–road collaborative intelligent system in Beijing. However, different cities and different deployment scenarios may lead to different conclusions in the framework proposed in this study.

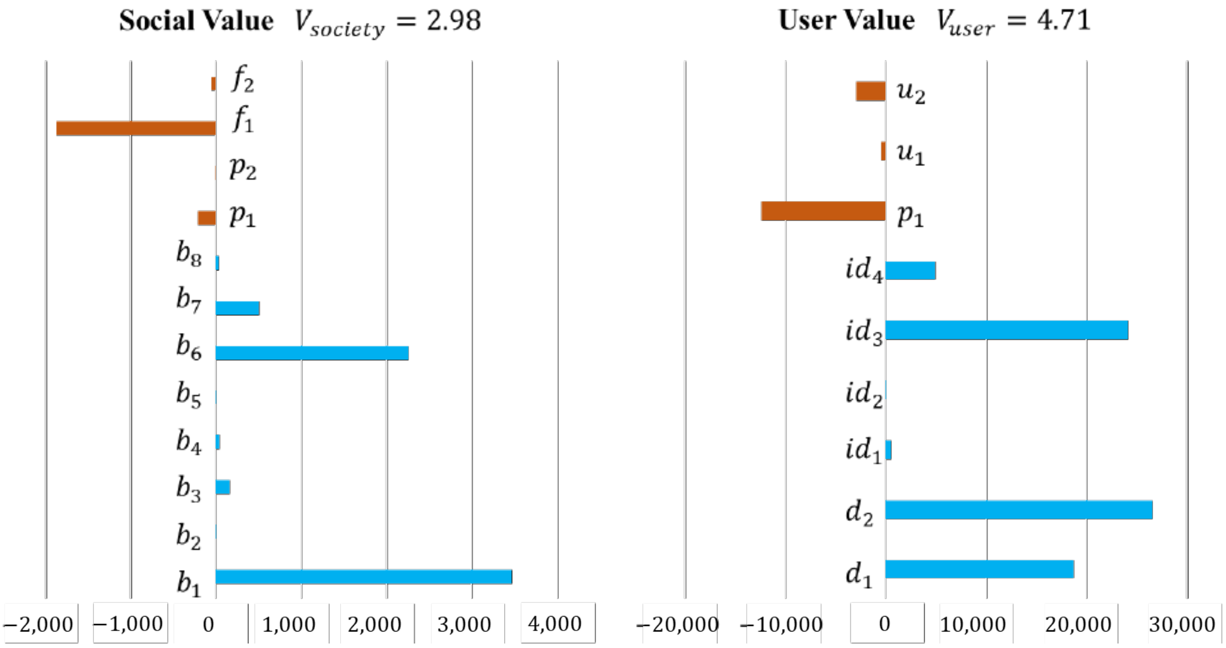

Figure 6. Cumulative benefits and costs of deploying vehicle–road collaborative intelligent system in Beijing from 2025 to 2040.

There are several potential conflicts of interests among different stakeholders. For example, users may prefer lower-cost ICVs with high levels of intelligence, which could put pressure on enterprises to reduce costs. However, enterprises need to ensure sufficient profit margins to sustain their development and innovation. If cost reduction efforts are excessive, it may affect the quality and performance of ICVs, ultimately impacting user experience. Additionally, the deployment of the external intelligent environment may require significant investment from governments and related enterprises. While this can enhance the overall intelligence level of the system and generate social value, it may also increase the financial burden on enterprises and governments.

To address these conflicts of interests and achieve reasonable value distribution, it is necessary to establish a coordination and cooperation mechanism among stakeholders. Through value engineering analysis, we can identify the key modules and elements required to achieve target functions, as well as the costs and benefits associated with each stakeholder. This enables us to optimize the allocation of resources and costs among stakeholders, ensuring that each party's value demands are met to the greatest extent possible. For instance, governments can provide policy support and financial subsidies to encourage enterprises to invest in the research and development of ICV technologies, while also guiding users to adopt ICVs through promotional policies and public education. Enterprises can optimize their product design and production processes to reduce costs and improve product value, thereby enhancing their market competitiveness. Users, in turn, can actively participate in the adoption and use of ICVs, providing feedback to enterprises and governments to help refine products and policies.

6. Conclusions

Value engineering (VE), as a method of thinking and management technique aimed at enhancing the function–cost ratio of products, is extended in this paper beyond its foundational concepts. The traditional VE theory is deepened in three aspects: application objects, value dimensions, and associated entities. Additionally, the original analysis process is expanded and extended to accommodate complex and systematic research subjects. Taking the intelligent automotive industry as an example, a research framework and analysis process oriented towards the value of vehicle–road collaborative intelligent systems and the value of entities is proposed.

As the automotive industry evolves towards intelligence and connectivity, ICVs are set to become the core and link between smart transportation, smart cities, and smart energy. ICVs, along with the external intelligent environment, will create value at a larger urban and societal scale, rather than being recognized and analyzed solely from the perspective of a single product. By applying the extended VE theory to analyze collaborative intelligent systems, we can sort out the key modules and elements required for the realization of target functions from a systemic perspective. Under the guidance of the basic theory of VE, we obtain an intelligent capability allocation plan that achieves the lowest system cost while meeting the system’s target functions, as well as a plan that achieves the lowest product cost. Different modules and elements are often associated with different industry participants who bear the corresponding costs. While considering the cost of realizing collaborative intelligent system functions and the value of ICV products, the discussion introduces the social value, user value, and enterprise value, fully considering the external benefits of the system in different dimensions. It has organized the relevant indicators for user value (user benefits, user costs) and social value (social benefits, social costs). This approach better guides governments, enterprises, and users, among other participants, in a collaborative division of labor and optimized decision-making within the intelligent automotive industry ecosystem, helping to maximize the overall societal value.

The extension of VE theory also has a significant impact on technological innovation in the intelligent automotive industry. By analyzing the cost and value of different modules and elements within the collaborative intelligent system, VE can identify the key areas where technological innovation is needed. For instance, if the cost of vehicle-side perception equipment is found to be excessively high, it may prompt research and development efforts to explore more cost-effective sensing technologies or optimize the integration of roadside perception devices. On the other hand, VE can also prevent over-investing in certain technologies that may not generate proportional value. For example, if the incremental benefits of a certain level of autonomous driving technology are found to be limited compared to its costs, it may guide enterprises to focus on more promising technological directions. However, it should also be noted that the application of VE may potentially constrain technological innovation to some extent. The emphasis on cost-effectiveness might lead enterprises to prioritize short-term cost savings over long-term technological breakthroughs. Additionally, the analysis process of VE, which relies on existing modules and elements, may not fully account for the potential value of disruptive technologies that are yet to emerge. In the future development of the intelligent automotive industry, it is crucial to strike a balance between leveraging VE to optimize costs and values and maintaining sufficient investment and openness to technological innovation. This will ensure the sustainable advancement of intelligent automotive technologies while maximizing overall societal value.

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