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Environmental impact assessment of urban roads construction

April 2021

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Master Dissertation
Master in Urban Engineering

Work carried out under the supervision of
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April 2021

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ACKNOWLEDGMENT

This thesis was completed under the supervision of Professor Hugo Silva. From the topic selection, data collection, thesis writing, revision and finalization of the thesis, he put much effort into it. Professor Hugo Silva's rigorous teaching attitude and care for students deeply moved me. Upon completing this thesis, I would like to express my heartfelt thanks to Professor Hugo Silva.

During my master's degree in urban engineering, due to my poor language, which brought much inconvenience to study, I would like to thank all the professors and classmates who gave me help.

When developing the work for writing this thesis, a large number of questionnaires were applied. Thanks to the municipal environmental protection department and construction department for providing me with all the conveniences during this process. Many thanks for your enthusiastic help, from environmental experts and road construction engineers to several former colleagues and many workers and citizens involved in the road construction who helped me a lot during the data acquisition process.

Thanks to the authors of the references in this thesis. Your documents were infinite enlightenment for me when developing this work.

Finally, I would like to thank my family for their support and help during my master's degree.

DECLARATION OF INTEGRITY

I declare to have acted with integrity in the preparation of this academic work. I confirm that I did not resort to the practice of plagiarism or any form of misuse or falsification of information or results in any stage leading to its elaboration.

I further declare that I know and have respected the Code of Ethical Conduct of the University of Minho.

Environmental impact assessment of urban roads construction

ABSTRACT

With the continuous development of the economy, urban road construction has achieved rapid development, which at the same time has brought severe environmental problems. Therefore, carrying out an environmental impact assessment of urban roads construction projects is of great significance to achieve the harmonious coordination of road construction with society, economy, and environment and promote road traffic sustainable development.

This thesis aims at studying the environmental impact assessment method of road construction projects based on analyzing and summarising many previous research results. Then, it suggests a comprehensive fuzzy matter-element assessment method combining fuzzy theory and matter-element analysis. This method provides a new way for a comprehensive evaluation of the environmental impact of road construction.

The results of this work led to the following main conclusions of the dissertation. First, by systematically analyzing the impact of road construction projects on the social, ecological, atmospheric, acoustic and water environments, it is possible to lay the foundation for a comprehensive environmental impact assessment of road construction projects. Secondly, by analyzing the road construction environmental assessment's ideas and principles, it was possible to establish an index system for environmental impact assessment of road construction. Simultaneously, a new weight determination method, established by a consistent fuzzy matrix and an analytic hierarchy process (AHP), improved the weight's rationality. Finally, a fuzzy matter-element comprehensive evaluation model was established, tested and verified on different road places, conditions and projects using different environmental protection measures to understand its potential use.

Keywords:

Environmental impact assessment, Fuzzy matter-element model, Index system, Urban roads construction, Weight determination

Avaliação do impacto ambiental da construção de estradas urbanas

RESUMO

Com o contínuo desenvolvimento da economia, a construção de estradas urbanas alcançou um rápido desenvolvimento, o que ao mesmo tempo trouxe sérios problemas ambientais. Portanto, a avaliação do impacto ambiental nos projetos de construção de estradas urbanas é de grande importância para alcançar a coordenação harmoniosa da construção de estradas com a sociedade, a economia e o meio ambiente e promover o desenvolvimento sustentável do tráfego rodoviário.

Esta tese tem como objetivo estudar o método de avaliação de impacto ambiental de projetos de construção de estradas com base na análise e resumo de muitos resultados de investigação anteriores. Depois, propõe um método abrangente de avaliação de elementos difusos, combinando a teoria *fuzzy* (difusa) e a análise de elementos materiais. Este método fornece uma nova maneira de avaliar de forma abrangente o impacto ambiental da construção de estradas.

Os resultados deste trabalho deram origem às seguintes conclusões principais da dissertação. Primeiro, ao analisar sistematicamente o impacto dos projetos de construção de estradas no ambiente social, ecológico, atmosférico, acústico e aquático, é possível criar as bases para uma avaliação abrangente do impacto ambiental do projeto de construção de estradas. Em segundo lugar, ao analisar as ideias e princípios da avaliação ambiental na construção de estradas, foi possível estabelecer o sistema de índice de avaliação de impacto ambiental para construção de estradas. Simultaneamente, um novo método de determinação do peso, estabelecido pela matriz consistente difusa e pelo processo de análise hierárquica (AHP), melhorou a racionalidade do peso. Finalmente, foi estabelecido um modelo abrangente de avaliação de elementos difusos, que foi testado e verificado em diferentes estradas, condições e projetos usando diferentes medidas de proteção ambiental para se compreender o seu potencial de utilização.

Palavras-chave:

Avaliação de impacto ambiental, Modelo de elementos difusos, Sistema de índices, Construção de estradas urbanas, Determinação do peso.

INDEX

LIST OF ABBREVIATIONS

AC – Asphalt concrete

AHP – Analytic Hierarchy Process

ASTAE – Asia Sustainable and Alternative Energy Program

EIA – Environmental impact assessment

FAHP – Fuzzy analytic Hierarchy Process

SMA – Stone Mastic Asphalt

NEPA – National Environmental Policy Act

NAP – Noise action plans

OGFC – Open Graded Friction Course

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background and significance of the study

Urban roads construction and social, economic, and environmental benefits constrain and promote each other. As an essential infrastructure for urban economic development, urban roads play a vital role in the national economy and social life.

On the positive side, urban roads construction is a large and complex project that has led to many related industries and increased employment opportunities. Urban roads construction has formed a good transportation network, shortened the world distance, reduced transportation and travel costs, promoted urbanization, accelerated the logistics industry's rise, optimized resource allocation, and developed tourism and urban economy.

According to the statistics of the International Road Federation’s statistical yearbook and the statistics departments of various countries, the total mileage of roads has reached 6,853,024 kilometres in the United States (2017), around 6,100,000 kilometres in the European Union (2016), 5,929,293 kilometres in India (2019), and 4,846,500 kilometres in China (2018). Roads have played a vital role in the development of the world economy.

On the negative side, roads construction will inevitably affect the environment. Like other construction projects, urban roads construction will have a specific impact on the environment during the construction process and operation, such as social, ecological, atmospheric, water and acoustic environment, leading to an urban healthy development crisis.

Therefore, how to correctly analyze and evaluate the impacts of roads construction on the environment and what measures can be applied to reduce or avoid environmental pollution is a long-term and arduous task for roads construction and environmental protection workers.

Environmental impact assessment is an essential task for environmental protection, and it is also an effective means and method for implementing sustainable development strategies in decision-making and development and construction activities (Zhang, 2001). The environmental impact assessment (EIA) of urban roads construction is used to identify, predict and evaluate its environmental impacts. EIA proposes environmental protection measures to be taken during construction and operation, analyzes its technical feasibility and economic rationality, provides the scientific basis for engineering construction and environmental protection, and promotes the coordinated development of urban roads construction, economic development and environmental protection.

With the continuous progress of society and the increase in people's awareness of environmental protection worldwide, environmental impact assessment plays an increasingly important role in sustainable development.

Environmental impact assessment of urban roads construction is instrumental for sustainability, but it is a time-consuming process due to many dependent and independent variables (El-Gafy *et al.*, 2011). Besides, due to the late start of environmental protection on urban roads construction, since the environmental action plan of the 1970s, EIA has become the cornerstone of the European Community's preventive environmental policy. The European Community Environmental Impact Assessment Directive 85/337 emphasizes that all technologies, planning and decision-making must consider environmental issues as early as possible (Directive 85/337/EEC, 1985). Although EIA of roads construction has developed rapidly in recent years, there is still a long way for it because of the diversity of evaluation factors and the short development time. So it is of great significance to explore a comprehensive environmental assessment system which can satisfy the current needs.

1.2. Objectives

This work's primary objective is to construct the fuzzy matter-element comprehensive assessment methods by combining fuzzy theory and matter-element analysis method. By studying the international literature, materials, laws, and regulations about environmental impact assessment on urban roads construction, analyzing and summarizing the theoretical knowledge and the latest research results, this work drew inspiration to construct a comprehensive assessment method of environmental impact for roads.

Nevertheless, there are other specific objectives pursued in this work:

- establish an environmental impact assessment index system through analysis of urban road construction projects and environmental impacts;
- establish a fuzzy analytic hierarchy process through the analysis and improvement of the analytic hierarchy process, and to find a method for determining the weights in combination with expert consultation;

- establish a fuzzy matter-element comprehensive evaluation model through fuzzy theory and matter-element analysis;
- apply the model under different scenarios, namely by using different methods to reduce the environmental impact in different road conditions, to evaluate the environmental protection measures for road construction.

1.3. Organization of the dissertation

This thesis is divided into five different chapters. The first chapter introduces this dissertation, with its background, significance, objectives, and framework.

The second chapter refers to a literature review. In this chapter, the environmental impact of road construction and the development of environmental impact assessment are introduced separately. Besides, the construction of the environmental impact indicator system and the determination of indicator weights are introduced. Finally, the methods of environmental impact assessment are introduced, and in the 40 years since the development of environmental impact assessment, the methods of comprehensive environmental impact assessment and their respective advantages and disadvantages are summarized and compared. In the sustainable development of road construction, a more accurate and convenient comprehensive assessment method is vital.

In the third chapter, the latest fuzzy matter-element comprehensive evaluation method is obtained by combining fuzzy theory and matter-element analysis method. This chapter mainly introduces the basic concepts, model establishment, and case study around the method. It also tests the model in different ways (i.e., after using different reducing environmental impact methods, in different road conditions, among others) to verify the model's application and evaluate potential improvements.

The fourth chapter is the analysis of different results obtained by EIA fuzzy matter-element comprehensive evaluation. It mainly includes three aspects: analysis of different environmental impacts of road construction, analysis of environmental impacts under different road conditions, and analysis of evaluation results after using different methods to reduce environmental impacts.

Chapter five introduces the conclusions and analyzes the results obtained. Moreover, given the continuous development of road engineering and environmental impact assessment methods and some limitations of this thesis, this chapter put forward a prospect for future work.

2. LITERATURE REVIEW

2.1. Environmental impact of urban roads construction

Road projects are generally intended to improve the economic and social welfare of people. Increased road capacity and improved pavements can reduce travel times and lower vehicle use costs while increasing access to markets, jobs, education, and health services and reducing transport costs for freight and passengers. All the positive aspects of road projects may also negatively impact nearby communities and the natural environment. People and assets may be in the direct path of road works, being affected significantly. People may also be affected indirectly by projects, through the disruption of livelihood, loss of accustomed travel paths and community linkages, increases in respiratory problems due to air pollution, and injury from road accidents. Disturbances to the natural environment may include soil erosion, changes to streams and underground water, and interference with animal and plant life. Roads are agents of change and can be responsible for both benefits and damage to the existing balance between people and their environment (Koji and Christopher, 1997; Buckley, 2000).

The international environmental assessment standards are slightly different, but with similar principles. According to China's national industry standards, road construction projects' environmental impact is divided into the social, ecological, atmospheric, acoustic and water environments according to its environmental factors (JTG B03-2006, 2006).

2.1.1. Impacts on the social environment

Impacts on the social environment refer to the interdependence, mutual restraint and mutual development of the social environment that human activities have built. It mainly includes the impacts on communities and their economic activity, impacts arising from land acquisition and resettlement, and employment and safety impacts.

Concerning the impacts on communities and their economic activity, the road construction projects can cause changes in the communities' environment around the road, affecting lifestyles, travel patterns, and all aspects of social and economic activity. Communities owe much of their vitality to the ease with which economic and social interactions take place. Roads are central to this continuing interaction, since the introduction of a road construction project may well cause disruptions to local interactions and bring benefits to surrounding communities as well, for example, through lower transport costs, better access to markets, goods, jobs, or services such as health and education (Koji and Christopher, 1997).

Concerning the impacts of land acquisition and resettlement, the road construction project often requires privately owned land procurement. This land has to be acquired by the government from its current owners. While it is sometimes possible to negotiate a price for a property's voluntary sale, governments often have to use their rights to compulsory acquisition of properties for public projects (expropriation). By its nature, expropriation causes economic loss and social and psychological disruption for the affected individuals and their families. Naturally, the greater the number of people are involved, the more significant the disruption and loss are (Koji and Christopher, 1997).

Concerning employment and safety impacts, road construction projects occupy the land of people who depend on agriculture and make them lose employment opportunities. However, after land acquisition compensation, they receive funds and may find other employment opportunities. At the same time, the road construction project itself will bring many employment opportunities.

The new transport infrastructure attracts transport intensive establishments to an area and leads to some reorganization of production in existing businesses, which has a substantial positive effect on area level employment and the number of establishments (Gibbons *et al.*, 2019).

After the road project is completed, it will increase the traffic volume along the line, increase traffic accidents in the area, and interfere with people's travel to a certain extent.

Road mileage has a significant impact of the number of road traffic casualties. The increase in road mileage has increased the number of road traffic casualties. For every 10,000 km of new road mileage in China, the number of traffic accident casualties has increased by 284 (Sun *et al.*, 2019).

2.1.2. Impacts on the ecological environment

Ecological environment refers to the living conditions and environment of the living creature and is the material basis for living creature. It is a vast and complicated system. Road construction is closely related to the ecological environment and will inevitably cause damage to the ecological environment. Road construction's impact on the ecological environment mainly includes impacts on vegetation loss, soil erosion impacts, and impacts on aesthetics and landscape.

Concerning the impacts on vegetation, the road construction project is a strip project involving a wide range. During the construction and operation of roads, vegetation (including crops and wild animals) along the route will undergo varying degrees of damage.

During the construction of roads, the occupation of land and the deforestation of vegetation along the line changes the growth environment of vegetation and indirectly affects the biological diversity and the balance of the ecological environment. During road operations, a large amount of air pollution, noise pollution, water pollution, among others, can seriously harm the living environment of the surrounding vegetation and bring severe damage to the ecological environment.

Concerning the soil erosion, that is mainly manifested in the road construction stage. Many engineering activities such as earth excavation, roadbed backfill, material transportation, temporary facility construction, among others, have damaged the geological features along the road, disturbed the land structure, and reduced the corrosion resistance of the land and aggravated soil erosion.

Soil erosion during the operation period is mainly reflected in the early stage of operation because the soil erosion caused by the construction process has not been completely repaired. The degree of soil erosion in the operation period is much lighter than that during the construction stage (Lu, 1999).

The road impacts on aesthetics and landscape are related to the landscape formed by the fusion of natural and human landscapes along the road through the artificial structures such as roads, pavements, structures along the line, facilities along the lines, and appendages.

It is now becoming more widely accepted that ecology is essential for environmental planning in the larger, regional landscape. Stemming from that acceptance is a growing recognition of the fact that human respect for the biophysical determinants of any given physical setting is a significant consideration in attaching aesthetic value to a landscape or any structure, such as a road, that is introduced into that landscape (Koji and Christopher, 1997).

Road construction changes aesthetics and landscape elements, destroying many landscapes and but also merging new landscapes. Road construction is a large structure that forms a barrier between adjacent landscapes, which creates a splitting effect on the landscape. Therefore, we must fully consider the coordination between road construction, aesthetics, and landscape in the road planning and design stage.

2.1.3. Impacts on the atmospheric environment

The atmospheric environment impacts of urban roads construction are mainly divided into two phases: construction and operation.

During road construction, air pollution mainly comes from dust (Figure 1) generated by construction materials and mechanical transportation, and asphalt fume (Figure 2) generated by asphalt mixing and laying.

Figure 1 - Dust pollution from road construction (https://image.baidu.com/)

Figure 2 - Asphalt fume from road construction (https://image.baidu.com/)

Roads construction activities constitute a significant source of particulate matter (PM) into the atmosphere and substantially temporarily impact air quality (Font *et al.*, 2014).

Air pollution during road operation mainly comes from pollutants emitted by traffic vehicles (Kumar *et al.*, 2012), such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbon (HC), among others (Figure 3).

Road transport is one of the primary sources of atmospheric emissions especially in urban areas where the exceedance of NO_2 or PM limit values is anticipated, which has evident health implications (Dzikuć *et al.*, 2017; Pérez *et al.*, 2019).

The direct emission of nitrogen dioxide (NO_2) from road vehicle exhaust has been a chief contributor to near-road ambient concentrations of NO_2 in many European cities (Carslaw *et al.*, 2019).

Figure 3 - Air pollution during road operation (https://image.baidu.com/)

Rapid global urbanization and explosive overall population increase generate high demand for new road networks. Paved surfaces contribute to greenhouse gas emissions and climate change at both the urban and global scales (White *et al.*, 2010). Between 2000 and 2010, the annual greenhouse gas emissions of transport sector have increased from 10% to 14% of global emission of which approximately 72% is attributed to road construction, rehabilitation, maintenance, service, and usage (World Bank and ASTAE, 2010).

2.1.4. Impacts on the acoustic environment

The impacts of acoustic environmental of urban roads construction mainly include mechanical noise and material processing noise during the construction phase and traffic vehicle noise along the road during the operation period.

Road traffic noise is one of the most significant environmental impacts generated by transport systems. The recent implementation of the European Environmental Noise Directive by Public Administrations of the European Union member countries has led to various noise action plans (NAPs) for reducing the noise exposure of EU inhabitants (Ruiz-Padillo *et al.*, 2016).

The impact of noise during the road construction phase is transient, temporary, and local, so the impact has limited characteristics. However, during the construction of urban roads, due to the construction site is close to the residents and the degree of construction mechanization is high, the noise impact in the stage period can be enormous. It is necessary to strictly follow the corresponding standards to reduce noise and ensure a healthy urban environment.

The traffic noise during the operation period has high intensity, wide influence range and long duration. It will affect people's everyday life, interfere with rest and sleep. Simultaneously, traffic noise will also affect economic development, reduce economic efficiency and production efficiency along the line, and affect the surrounding land's value. Therefore, the noise must be strictly controlled.

2.1.5. Impacts on the water environment

Due to earth excavation and backfill, potential impacts on the surrounding groundwater level will arise in the early stage of road construction, which will affect the surrounding vegetation and residents.

Construction wastewater and domestic sewage generated during the construction process and polluted water washed by chemical materials into the soil or water body will cause soil and water pollution.

Extensive construction of roads has a significant impact on the landscape and its structure. It can also influence local climate and heat fluxes in the surrounding area. After removing vegetation due to road construction, the amount of solar radiation energy used for plant evapotranspiration (latent heat flux) decreases, bringing about an increase in landscape surface temperature, changing the local climate, and increasing the road runoff (Nedbal and Brom, 2018). During road operation, on the impervious pavement, the pavement's pollution, including dust, oil, and others, will enter the water body with the surface runoff, which will cause pollution to the surface water.

2.2. Environmental impact assessment in general and of urban roads construction

Every country attaches great importance to the environmental impact of road construction. One of the World Road Association Technical Committee goals was to address the environmental impact of road construction. The committee's core purpose in the environmental aspect is to create a compelling and comprehensive assessment method for road environmental systems and provide specifications for guiding road design, construction, planning, and management (PIARC, 2020).

2.2.1. Development of environmental impact assessment of road construction

As a linear transportation infrastructure that crosses different areas and spaces, roads will affect the surrounding environment during construction and operation. Due to its wide range of influence and long duration, it has always been a popular research object in various countries worldwide.

The earliest highway in the world was from Germany, completed in 1931, between Cologne and Bonn. Therefore, the environmental protection of expressways has experienced the development of nearly 90 years, which has a reference effect on the environmental protection of urban roads. Since the 1930s and 1940s, developed countries such as the United States have recognized the importance of protecting ecological balance and have begun experiments such as planting lawns on highway slopes. In 1969, a famous British garden designer McHarg applied ecological concepts to road design, opening a new chapter in road environmental protection. He pointed out that the choice of road route should not only consider the general physical geography, transportation and engineering standards, but also consider the value of resources, society and aesthetics, and pay attention to its impact on the natural biology and society in the region (McHarg, 1969).

In German, Dr Lorenz expounded road construction and environmental coordination problems from multiple perspectives in a book on road linearity and environmental design completed in 1970. It is proposed that the close relationship between people and the natural environment should be considered in road design, and strive to make the designed road not only have fast and safe driving lines, and right driving environment, but also have measures to protect the environment (Lorenz, 1970).

Since the 1990s, Lamont, Blyth and other scholars have taken the lead in studying the division, interference and destruction of natural ecosystems by road networks and transportation corridors (Lamont and Blyth, 1995). Forman and other scholars have proposed that the impact of the ecological environment on road construction includes the impact on living environments of living creatures, geology, water and soil, climate, and road pollution caused by traffic vehicles (Forman and Deblinger, 1998). They also pointed out that the construction of many roads, the density and traffic volume continue to increase, and the environment's impact is also increasing. Therefore, the research of environmental impact of road construction has become a crucial subject (Forman and Alexander, 1998).

In road laws, regulations and technical specifications, the impact of road construction on the environment aroused more and more attention from society after the 1950s. Therefore, developed countries have begun to formulate laws requiring environmental protection for new roads. In 1969, the United States Congress enacted the National Environmental Policy Act, the first legal requirement for an environmental impact assessment. It requires establishing an environmental quality committee, preventing and reducing environmental damage, and promoting harmonious development of man and environment (NEPA, 1969).

After the United States formulated a special environmental impact assessment law, many countries such as Canada, Australia, Germany, France and other countries had successively established different environmental impact assessment systems and then expanded to developing countries. In 1985, the adoption of the European Community Environmental Impact Assessment Directive accelerated the establishment of environmental impact assessment legal systems in European countries (Directive 85/337/EEC, 1985). The Netherlands established the statutory Strategic Environmental Assessment system in 1987 improved it in 1989. The Ministry of Communications of China issued measures for environmental protection management of road construction in 1987, and the environmental impact assessment of road construction was officially launched.

The adoption of the Environmental Impact Assessment Law of the People's Republic of China in 2002 marked the improvement of China's environmental impact assessment from project evaluation to strategic evaluation (EIAL, 2002).

The United Kingdom proposed the Standing Advisory Committee on Trunk Road Appraisal in 1992 and proposed that traditional environmental impact assessment procedures should be further developed to consider specific cumulative or long-term effects (SACTRA, 1992). In the early 1990s, South America and Africa also developed many environmental impact assessment regulations.

In 1999, Enea and Salemi introduced the fuzzy concept into environmental impact assessment and tried to quantify the evaluation results (Enea and Salemi, 2001). By the beginning of the new century, more than 100 countries had established environmental impact assessment systems.

In road construction, environmental protection high-tech developed countries have had numerous environmental assessment software, such as German environmental noise prediction and simulation software system Cadna/A, British atmospheric diffusion model system ADMS and the United States System QUAL2E used in numerical simulation of environmental water pollution. Simultaneously, many countries have made significant progress in applying GIS, GIS/CAD to road environmental protection. They have perfectly combined noise pollution, air pollution, water pollution and GIS methods.

Practices in various countries worldwide have proven that if any road construction project only considers economic and technical factors and ignores environmental factors' influence, it will ultimately be difficult to achieve the intended purpose. Therefore, environmental impact assessment plays a vital role in promoting the coordinated development of road construction and the environment.

2.2.2. The environmental impact assessment procedure

The "Environmental Impact Assessment Law of the People's Republic of China", implemented in 2002, stipulates that environmental impact assessment refers to the analysis, prediction, and evaluation of environmental impacts that may be caused after the implementation of planning and construction projects, and proposes countermeasures to prevent or reduce adverse environmental impacts and proposes methods and systems for tracking and monitoring. The law compulsorily stipulates that environmental impact assessment is necessary to guide people's development activities, and it has become an environmental impact assessment system and an essential means to implement the "prevention-oriented" environmental protection policy (EIAL, 2002).

The essence of environmental impact assessment is a combination of a series of procedures and methods. It is a legal system. The environmental impact assessment procedure refers to completing the environmental impact assessment in a specific order or step, and it can be divided into management and working procedures. The former is mainly used to guide the supervision and management of environmental impact assessment, and the latter to guide the work content and process of environmental impact assessment. The working procedure of environmental impact assessment (Figure 4) is usually divided into three phases: i) the preliminary preparation, investigation and work plan; ii) the analysis, demonstration and forecast assessment, and; iii) the final document preparation.

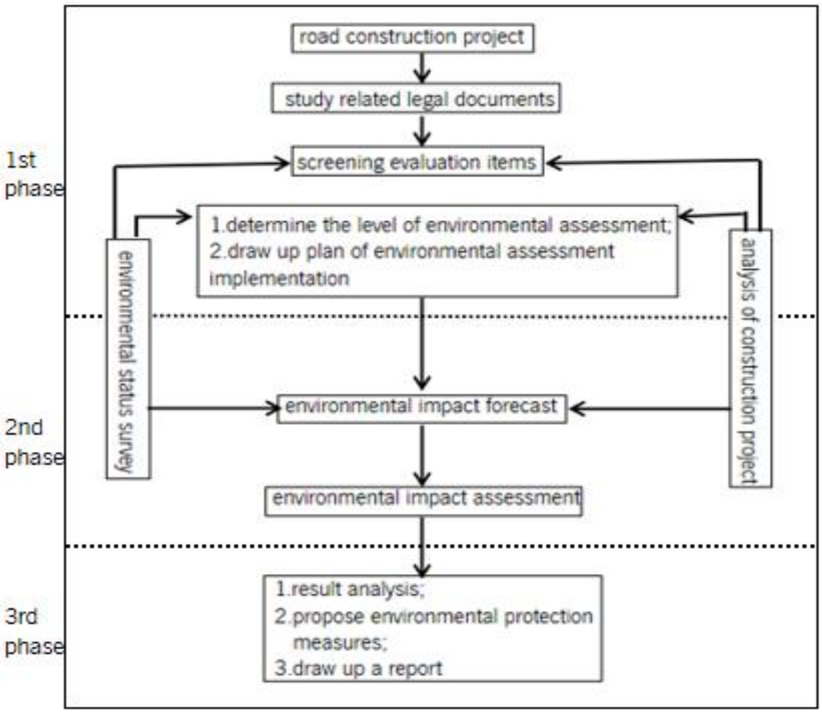


Figure 4 - The working procedure of environmental impact assessment (EIAL, 2002)

Phase 1 - Preparation phase

Study relevant documents to conduct preliminary engineering analysis and environmental status survey of the environmental impact zone of the construction project, identify environmental impact factors of the construction project, select significant environmental impact assessment factors, define the focus of the evaluation, determine the scope and the grade of environmental impact assessment.

Phase 2 - Formal working phase

Further engineering analysis sufficient environmental status investigation and monitoring, environmental quality status assessment, environmental impact prediction, environmental impact assessment of construction projects, public opinion survey, and environmental management and engineering measures to reduce environmental pollution and ecological impact.

Phase 3 - Preparation phase of the environmental impact report

Analyze and summarize all kinds of information and data obtained at the formal stage, determine the feasibility of project construction from the environmental protection perspective, give evaluation conclusions, put forward suggestions for further mitigating environmental impacts, and complete the report.

2.3. Indicator system of environmental impact assessment of urban roads construction

2.3.1. Construction idea for the indicator system

The first idea for the indicator system is to analyze the object of evaluation systematically. When establishing an evaluation index system, it is necessary to carry out an in-depth and comprehensive analysis of the evaluation object (road construction project) to determine its function, characteristics, key issues, impact scope, and project goals.

The second idea for the indicator system is to draft the assessment indicator. Based on a systematic analysis of the evaluation project, the project objective is decomposed according to its internal causality, affiliation, other logical relationships, and the corresponding evaluation indicators are determined for each level of the project target generated by the decomposition, which initially constitutes the level of the project evaluation index structure. When choosing to establish a rating index system, it is necessary to ensure the overall optimum and comprehensively select various evaluation indexes to determine the evaluation index system.

The third idea is screening and optimizing the assessment indicator system. The assessment indicator system established through the above contents should be further screened and optimized and comprehensively optimized through merger, elimination, replacement, among others, to modify and improve the indicators.

2.3.2. Construction principles for the indicator system

This work's indicator system will be based on seven construction principles described in the following paragraphs.

Scientific principle (1): The established indicator system can reflect the nature and complexity of the road construction environment. The evaluation indicators must be based on science and genuinely reflect the level of environmental quality of highway construction. Each indicator must have a clear concept and scientific meaning, and there must be a clear relationship (inner connections) between the indicators to avoid duplication.

The system should be representative (2): The indicators involved in environmental impact assessment of road construction are very extensive. In actual assessment, it is neither necessary nor possible to select all. Therefore, when determining the assessment indicators, it is only necessary to select a factor with particular representativeness that genuinely reflect the road construction environment's status and changes as the assessment indicators.

The system should be comprehensive (3): A road construction project's environment is a hybrid environmental system, and the indicator system should be comprehensive. Then it can reflect partial, current, and individual, as well as global, long-term, and comprehensive characteristics to ensure the comprehensiveness and credibility of the comprehensive assessment.

The system should be systematic (4): As a hybrid environmental system, road construction must have intricate and hierarchical relationships in structure. To this end, it is necessary to determine the corresponding evaluation levels, consider each evaluation index from a system theory perspective, and form a complete evaluation index system.

Operability of the system (5): Setting indicators should serve the analysis and evaluation. Therefore, the selected indicators should have an exact meaning and have a particular external expression form. They should be able to be calculated or observed to be applied in actual work with operability. Simultaneously, it should also be considered that they can be determined as much as possible using existing or conventional statistical data and survey methods to ensure the assessment indicators' applicability and effectiveness.

The system should be dynamic (6): The environmental assessment of road construction projects itself is a dynamic process with the development of construction projects, and the objectively set indicator system has dynamic characteristics (Nouri *et al.*, 2009). It can show the historical status and current situation of the surrounding environment of road construction projects, maintain stability for a certain period and assess the future changes and development of the environment.

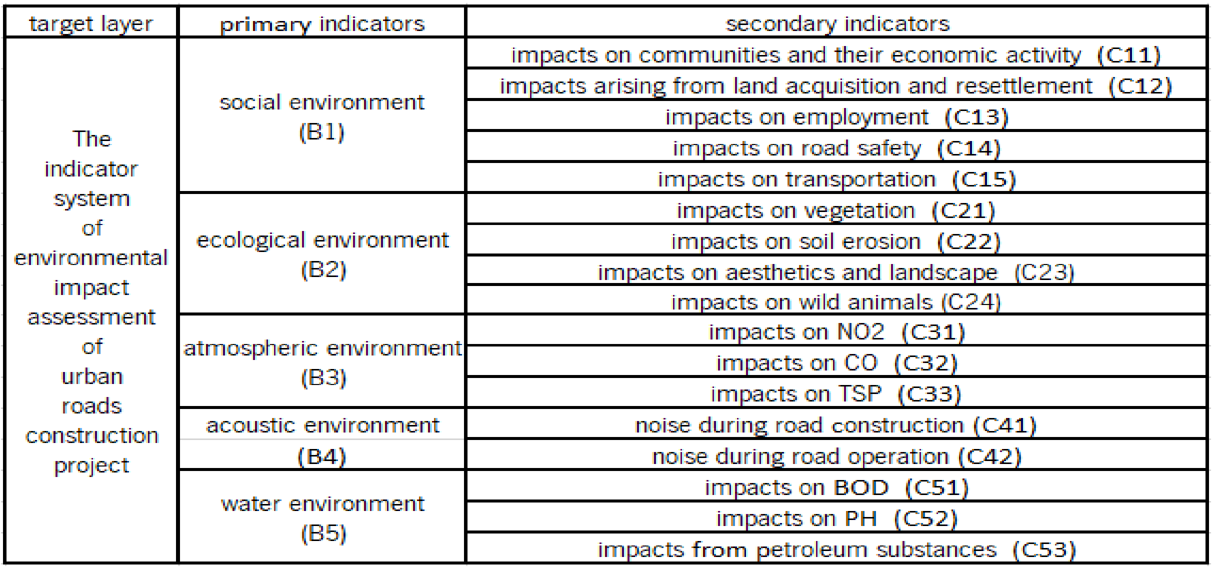
Territoriality principle (7): In different regions, the geographical locations along the road, the economic conditions, meteorological, hydrological conditions, and the environmental factors of road construction on the environment all are different. Therefore, when establishing the evaluation index system, it should be selected according to the principle of adapting to local conditions and according to the area under study and its main environmental problems.

2.3.3. Construction of indicator system of environmental impact of urban roads construction

This thesis is guided by the construction ideas and principles of environmental impact assessment indicator system to scientifically and comprehensively assess the environmental impact of road construction projects, combined with the research status and existing results, according to the general characteristics of road construction projects. Thus, a preliminary environmental impact assessment index system for road construction projects has been established to be used in this work.

The indicator system of environmental impact assessment of urban roads construction is divided into three levels or layers. The first layer is the target layer, that is the comprehensive impact of urban road construction on the environment. The second layer includes five first-level indicator layers, including social environment, ecological environment, atmospheric environment, acoustic environment, and water environment. The third layer is a secondary indicator layer composed of several related secondary indicators below each primary indicator layer. The specific indicator system structure is presented in Table 1.

Table 1 - Indicator system of environmental impact assessment of the urban roads construction project



target layer	primary indicators	secondary indicators
The indicator system of environmental impact assessment of urban roads construction project	social environment (B1)	impacts on communities and their economic activity (C11)
		impacts arising from land acquisition and resettlement (C12)
		impacts on employment (C13)
		impacts on road safety (C14)
		impacts on transportation (C15)
	ecological environment (B2)	impacts on vegetation (C21)
		impacts on soil erosion (C22)
		impacts on aesthetics and landscape (C23)
		impacts on wild animals (C24)
	atmospheric environment (B3)	impacts on NO2 (C31)
		impacts on CO (C32)
		impacts on TSP (C33)
	acoustic environment (B4)	noise during road construction (C41)
		noise during road operation (C42)
	water environment (B5)	impacts on BOD (C51)
		impacts on PH (C52)
		impacts from petroleum substances (C53)

2.4. Weight of environmental impact assessment of urban roads construction

In the process of comprehensive environmental impact assessment of urban road construction projects, the indicator weight determination is critical. It reflects each index's status and role in the evaluation process and directly affects the evaluation results. Therefore, scientifically and reasonably determining the indicator weight is related to the comprehensive evaluation results' reliability and correctness.

2.4.1. Concepts of weight

In the environmental impact assessment of road construction projects, the weight reflects the indicators' relative importance. It has the following characteristics:

i) fuzzy: because importance cannot be quantified, it lacks a precise definition and transparent extension. There is no clear boundary in the description of each degree, so it has fuzzy characteristics;

ii) subjectiveness: when determining the weight, it is impossible to thoroughly and objectively reflect the thing's inherent nature. For large differences, therefore, the determination of weights will necessarily be restricted by specific issues, expert opinions, weighting methods and other factors;

iii) uncertainty: the uncertainty of weights includes the uncertainty of quantitative and semi-quantitative indicators and the weighting method's uncertainty (e.g., how many indicators are selected, the variable nature of the indicators with different issues, different evaluators, and accuracy requirements).

2.4.2. Methods for determining the weight

At present, there are many methods for determining weights. According to the original data source when calculating weights, they can be divided into subjective weighting method, objective weighting method and comprehensive weighting method.

Method 1 - Subjective weighting

The system presents different characteristics during the operation, or by the influence of the environment, or the appraiser's wishes, making it difficult to determine the weight coefficients. Therefore, in many cases, it is often subjective to determine the weight coefficient, that is, to determine the weight coefficient according to the subjective importance people attach to each evaluation indicator. Subjective weighting is mainly determined by expert consultation through the comprehensive quantitative determination of indicator weights, such as Delphi method, analytic hierarchy process, or others. Because this method is based on the evaluator's subjective preferences, it can reflect the evaluator's experience and intuition, making the results subjective and arbitrary.

Method 2 - Objective weighting

The objective weighting method determines the corresponding indicator's weight coefficient according to the degree of variation of each indicator in the overall indicator and the impact on other indicators, which can avoid artificial interference when determining the weight coefficient, such as component analysis method and standard deviation coefficient method. This method can overcome the main factors' adverse effects and reduce the calculation workload, even though it does not fully consider the indicator's relative importance. Moreover, objective weighting method might easily ignore the personal information of decision-makers.

Method 3 - Comprehensive weighting

Comprehensive weighting combines subjective weighting and objective weighting so that the determined weight coefficient can reflect both subjective and objective information. This method first finds the most reasonable weight coefficients within subjective and objective weighting, determines the proportion of the two according to the specific situation, and calculates the comprehensive evaluation weight coefficient. This method is rarely used in practice due to considerable calculation effort and lack of opportunities for implementation.

2.4.3. Calculation of weight

The calculation of weights can be carried out using two analytical processes described below.

Process 1 - Analytic hierarchy process (AHP)

The analytic hierarchy process was proposed by American operations researcher, Professor Saaty, in the 1970s. The AHP determines each evaluation index's initial weight at the same level, thereby quantifying the qualitative factors and layering various influencing factors, which reduces the personal impact to a certain extent and makes the evaluation more scientific.

The AHP is designed to structure a decision process in a scenario affected by multiple independent factors. In the analysis, a complex problem can be divided into several sub-problems organized according to hierarchical levels (Figure 5), where each level denotes a set of criteria or attributes related to each subproblem. The top level of the hierarchy denotes the problem's goal, and the intermediate levels denote the factors of the respective upper levels. Meanwhile, the bottom level contains the alternatives or actions considered when achieving the goal. The AHP permits factors to be compared, with the importance of individual factors being relative to their effects on the problem solution, and the priority list of the considered alternative to be reached (Saaty, 1980; Saaty and Vargas, 1990).

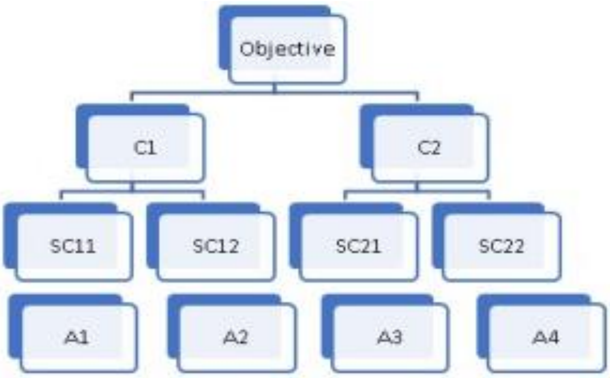
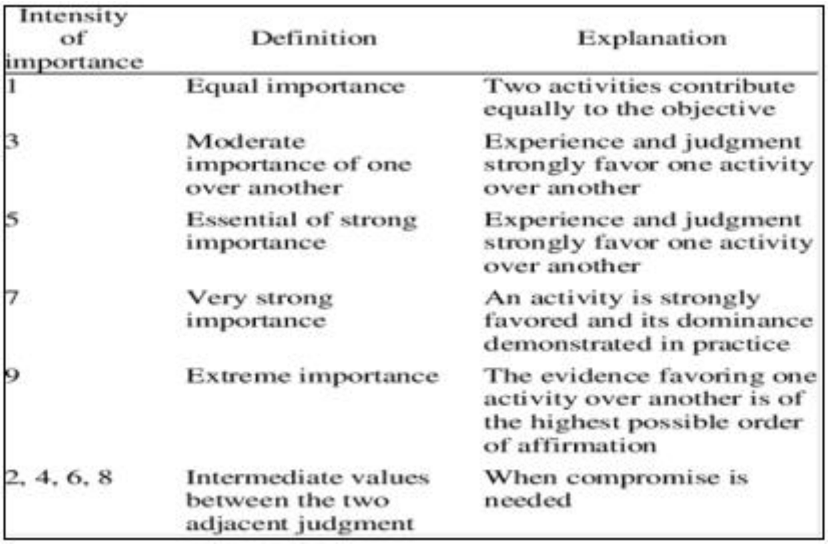


Figure 5 - Example of hierarchies (Leal, 2020)

The analysis is based on three fundamental principles: breaking down the problem, pairwise comparison of the various alternatives, and synthesizing the preferences. The first step of the analysis consists of subdividing the decision-making problem into several levels to form a hierarchy with unidirectional hierarchical relationships between levels. The decomposition is carried out from top to bottom, starting from the objective, going on to the criteria and sub-criteria, and then to the final alternatives. As soon as the hierarchy is constructed, the decision elements are compared pairwise regarding their control criterion's importance. The values of relative importance are determined on a 9-point scale, the so-called "Saaty's Fundamental Scale" (Table 2). The numerical judgments established at each level of the hierarchy make up pair matrices. After the comparison matrices are created, each level's relative weights to an adjacent upper-level element are computed as the largest normalized eigenvector components associated with their comparison matrix (Bologa *et al.*, 2018).

Table 2 - Saaty's Fundamental Scale (Saaty, 1980)



Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential of strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgment	When compromise is needed

Process 2 - Fuzzy analytic hierarchy process (FAHP)

There are many deficiencies in AHP, and to overcome all these shortcomings, such as it is difficult to judge the consistency matrix, fuzzy analytic hierarchy process (FAHP) was developed to construct a consistent fuzzy matrix for solving these problems. The FAHP method is used to determine weights for decision-makers' evaluation criteria (Khashei-Siuki *et al.*, 2020).

If the fuzzy matrix $R = \left(r_{ij}\right)_{nm}$ satisfies $r_{ij} = r_{ik} - r_{jk} + 0.5$, then the matrix is called a consistent fuzzy matrix. The fuzzy consistent judgment matrix R indicates comparing the relative importance between the elements in the current layer and the related elements for the upper layer. It is assumed that the element C in the previous layer is related to the elements a_1, a_2, ..., a_n in the next layer. The fuzzy consistent judgment matrix can be expressed by Equation 1. In that matrix, r_{ij} represents elements a_i and a_j have a membership degree of fuzzy relationship (the degree to which element a_i is more or less important than a_j) when they are compared with each other.

$$\begin{array}{c|cccc} C & a_1 & a_2 & \cdots & a_n \\ \hline a_1 & r_{11} & r_{12} & \cdots & r_{1n} \\ a_2 & r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_n & r_{n1} & r_{n2} & \cdots & r_{nn} \end{array} \tag{1}$$

To quantitatively describe the relative importance of any two schemes concerning a criterion, this thesis used the scale shown in Table 3.

Table 3 - Quantity scale of the weight (improvement of Saaty's Fundamental Scale)

FAHP indicator weight scale	
number scale	description
0.5	element i and j are equally important
0.6	element i is slightly more important than j
0.7	element i is obviously more important than j
0.8	element i is much more important than j
0.9	element i is extremely important than j
0.1, 0.2, 0.3, 0.4	back comparison

Through the quantity scale, the elements a_1, a_2, ..., a_n are compared with the element C in the previous layer, and the following fuzzy judgment matrix R is obtained, which is also a fuzzy consistent matrix.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{2}$$

By comparing the elements $(a_1, a_2, ..., a_n)$ in pairs, the fuzzy consistency matrix $R = \left(r_{ij}\right)_{nn}$ can be obtained and the weights $(w_1, w_2, ..., w_n)$ of all elements $(a_1, a_2, ..., a_n)$ of the previous layer calculated. The weight can be calculated with Equation 3, where $a = \frac{n-1}{2}$ and n is the order of R.

$$w_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na} \times \sum_{k=1}^{n} r_{ik} \tag{3}$$

2.5. Comprehensive environmental impact assessment methods for road construction

With the development of science and technology and the deepening of environmental assessment work, the technical, environmental impact assessment methods have extensively developed in theoretical structure and data processing. Since the environmental impact of urban road construction projects is involved and fuzzy affected by many factors, comprehensively evaluating the environmental impact of road construction projects requires further research and discussion. The environmental impact assessment methods of road construction projects mainly include unusual analysis (single item) assessment methods and comprehensive assessment methods.

The comprehensive assessment method of environmental impact of road construction is mainly used to comprehensively describe, identify, analyze, and evaluate the impact of road development projects on environmental factors or changes in the overall environmental quality. Since comprehensive assessment method requires a large amount of data and information, it is necessary to obtain information through testing, surveys and collecting information from other literature or using other unique analysis and assessment methods. Commonly used comprehensive assessment methods are checklist, matrix, network, overlay, AHP, and fuzzy comprehensive assessment. Each method can be developed into many improved methods to adapt to different objects and evaluation tasks (Lu, 1999).

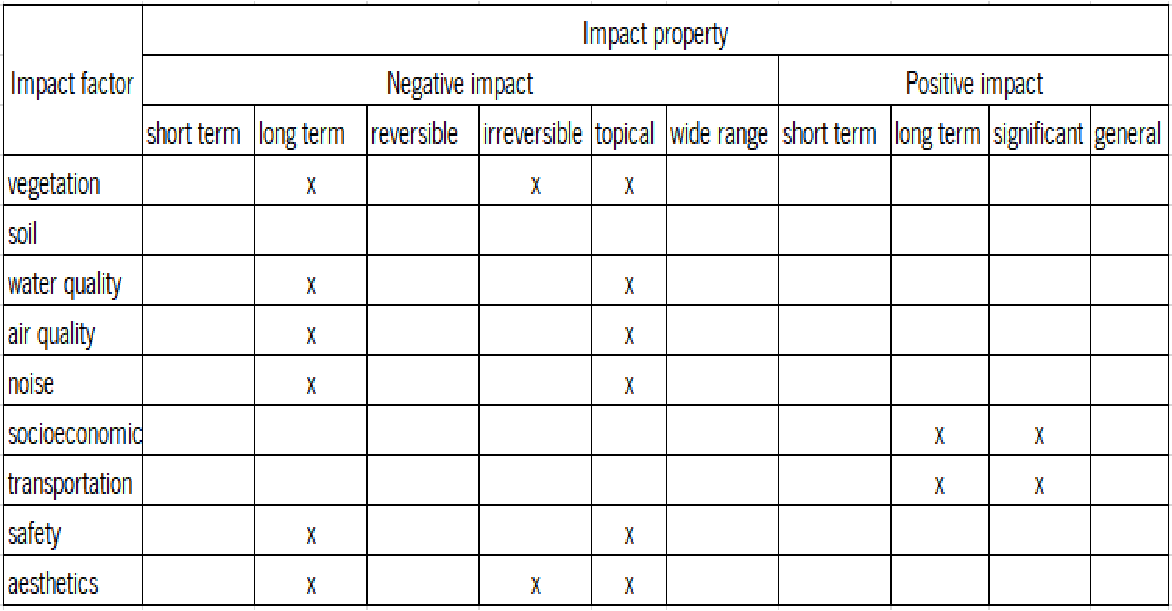
2.5.1. Checklist method

The checklist is the earliest method used for environmental impact identification, evaluation and decision-making. It is the most common and straightforward comprehensive assessment method and was initially used by Little in 1971 (Borri *et al.*, 1998).

The checklist method lists the factors that must be considered in the environmental assessment, then makes a judgment after checking these factors one by one, and finally gives a qualitative or semi-quantitative conclusion to the verification results. The checklist's complexity can be divided into simple checklists, descriptive checklists, and scoring checklists.

In the simple checklist method (Table 4), only the factors that must be considered in the assessment need to be listed, and the evaluators will judge whether the environmental impact factors of the road construction have an impact and the simple nature of the impact. The principles of other improved checklist methods are similar to the simple checklist method. In addition to the environmental factors, the descriptive checklist method also provides a preliminary explanation of the extent and nature of environmental factors. The scoring checklist will evaluate the value of each environmental factor's impact and then accumulate the total score to select the best solution based on the total score.

Table 4 - The simple checklist of environmental impact caused by road construction



Impact factor	Impact property									
	Negative impact						Positive impact			
	short term	long term	reversible	irreversible	topical	wide range	short term	long term	significant	general
vegetation		x		x	x					
soil										
water quality		x			x					
air quality		x			x					
noise		x			x					
socioeconomic								x	x	
transportation								x	x	
safety		x			x					
aesthetics		x		x	x					

Note: X indicates an impact

2.5.2. Matrix method

The matrix method is another early and very widely used method of environmental analysis, assessment and decision-making. It mainly includes two categories, the simple interaction matrix method and the iterative matrix method.

Leopold was the first to use this method, and he established the Leopold interaction matrix in 1972. The matrix is suitable for almost all infrastructure projects (Lind *et al.*, 2001).

The horizontal axis of the matrix lists the various environmental impact activities included in the development project, and the vertical axis lists all environmental factors that may be affected by various activities of the development action. Each element in the matrix is divided into two. The left half of the grid represents the magnitude of environmental impact, and the right half of the grid represents the weight of the impact. The positive impact is “+”, the negative impact is “-”, and the method gets the sum of final algebra (Table 5).

Table 5 – Example of a matrix analysis on the interaction of road construction project

Project activity Impact factor	demolition, resettlement	earthwork excavation, backfill	material processing, transportation	pavement laying	road operation	......	$\sum M_{ij}.W_{ij}$
vegetation	-1(2)	-4(5)		-1(2)			-24
soil		-5(6)	-1(1)	-1(1)			-32
water quality		-1(1)		-2(2)			-5
air quality		-2(2)	-2(2)	-3(2)	-6(6)		-50
noise	-1(1)	-3(3)	-2(2)		-6(6)		-50
employment	2(2)	2(2)	2(2)	2(2)	5(4)		36
safety	-1(1)	-1(1)	-1(1)	-1(1)	-2(3)		-10
economy	2(2)	5(5)	2(2)	2(2)	8(10)		117
aesthetics	1(1)			2(2)			5
transportation				4(5)	8(10)		100
......							
$\sum M_{ij}.W_{ij}$	5	-36	-2	18	102		87

Leopold divided the magnitude of the impact into ten levels, with "10" being the largest and "1" the smallest. The importance of impact is also divided into ten levels, where "10" means the impact is the most important, "1" means the impact is the least important, and $\sum M_{ij}\, W_{ij}$ is the final score of the comprehensive evaluation. This method forms a matrix of the project and the affected environmental characteristics and establishes a direct causal relationship between the project and the environmental impact.

2.5.3. Network method

Sorensen developed the network method in 1971. Its principle is to use a cause-effect relationship tree to represent the environmental impact chain. The relationship between primary, secondary and tertiary impacts is reflected through the relationship tree.

The network can identify the direct and indirect environmental impacts of road construction projects, but for developing areas with more construction activities and complex environmental elements, the network may be complex and quickly lead to confusion.

2.5.4. Map overlay method

The map overlay method is used by superimposing two or more pictures representing environmental characteristics on a picture to form a composite picture. The map overlay method was pioneered by

McHarg (1969) and developed by KransKopf. It is used to indicate the affected environment characteristics and the relative magnitude of the impact within the scope of project development activities. Its fundamental significance lies in explaining, evaluating or predicting the affected status of a specific area and the degree of suitability for development, and providing selected locations and routes.

With the development of computer technology, geographic information systems are increasingly used in environmental impact assessment. The GIS-based overlay method uses spatial analysis functions such as overlay and buffer analyses of the GIS system and processing attribute data functions. It overlays environmentally sensitive area level maps and route plans of various evaluation factors and can be graded and evaluated hierarchically. It can be used to evaluate a wide range of complex environments and compare options for route plans.

2.5.5. Analytic hierarchy process

The analytic Hierarchy Process (AHP) is a muti-indicator comprehensive assessment method proposed by Saaty, a famous American operations researcher and Professor at the University of Pittsburgh in the 1970s. This method's main idea is: first, the entire system is hierarchically divided into different levels of subsystems according to the overall goals of the system and according to the relationship between the factors and constraints, making it a structure model with multilevel. Different factors in each level are compared pair by pair, the relative importance of the factors is determined, and a judgment matrix is constructed. Hierarchical single-ranking is performed by obtaining the feature vector of the judgment matrix, the total ranking is performed based on the single-ranking of each hierarchy, and finally, a comprehensive evaluation is performed.

The analytic hierarchy process can quantify some qualitative problems that are difficult to quantify based on strict mathematical calculations, and comprehensively analyze some mixed quantitative and qualitative problems. It is suitable for a comprehensive evaluation and decision-making of multi-index and multilevel systems.

2.5.6. Fuzzy comprehensive assessment

An essential constituent of human decision-making is the ability to reason and act on imprecise and subjective information. Vagueness, ambiguity, and imprecision have not deterred human beings from taking actions. Zadeh created the fuzzy set theory to recognize this need to model the human mind, accounting for subjective and imprecise factors.

A fuzzy comprehensive evaluation is a comprehensive evaluation method based on fuzzy mathematics. It uses the theory of membership degree in fuzzy mathematics to change the qualitative evaluation into a quantitative evaluation, making a comprehensive evaluation of different factors using fuzzy mathematics. It is the right solution for the challenging problems to quantify and is suitable for solving non-deterministic problems. The specific application process of a fuzzy comprehensive evaluation is as follows: first, set up to evaluate factors of different levels; second, determine the evaluation rules which can determine the correspondence (function) between the value and the evaluation factors; then give out the weight distribution for different evaluation factors using the AHP, considering that the sum of the weights of the evaluation factors in each stage is one. The last part is to calculate the comprehensive evaluation value (Zhang *et al.*, 2016).

In addition to the comprehensive assessment method, there are also special evaluation and analysis methods for qualitatively and quantitatively determining the degree, magnitude and importance of environmental impacts. The impact size is sorted and graded to describe the limits or changes in the quality of individual environmental factors and various evaluation factors. It can also normalize the impact of different properties according to environmental value judgments. This type of method mainly includes expert judgment method, Brainstorming, Delphi technique, and Battle environmental evaluation system. It also contains many methods such as field monitoring and reconnaissance and statistical and multivariate analysis.

For the environmental impact assessment of road construction projects, many factors need to be considered, and the results are difficult to quantify. Therefore, the fuzzy comprehensive evaluation method that applies fuzzy mathematical theory, combining quantitative and qualitative evaluation, is of great significance to obtain comprehensive quantitative results in the environmental impact assessment of road construction.

2.6. Comparison of comprehensive assessment methods

At present, there are many comprehensive methods for environmental impact assessment of road construction projects. Each method has its application background, and each has its advantages and disadvantages. The specific comparison is presented in Table 6.

Table 6 - The comparison of comprehensive assessment methods of a road construction project

Method	Characteristic	Advantages	Disadvantages
checklist	Systematically presents all possible environmental impacts on the tabular form.	Comprehensive, systematic, easy to understand and use, the weight-based checklist can realize a semi-quantitative environmental assessment.	Creating lists is tedious. Most lists are non-special, non-static and non-quantitative, and it is easy to overlook some critical effects.
matrix	The matrix consists of two columns representing various activities and environmental elements and characteristics. The intersections show the possible impacts of the project activities on the environment, and the corresponding evaluations are carried out according to the degree of impact displayed at the intersections.	Quantitative analysis is available, which is helpful for in-depth research. It is practical and straightforward, intuitive and obvious, broad in content, easy to understand, and low in cost.	Cannot deal with indirect and potential impacts, cannot reflect time and space characteristics, cannot reflect complex causality and accumulation pathways. If too many factors are considered, the matrix may become complicated and inconvenient to use.
network	Seek direct correlations between environmental factors or factors, and chart the significant impacts of project activities, including higher-level and indirect impacts.	Emphasizes indirect effects and can clearly express the correlation and complexity of environmental factors.	Lack of feedback mechanism between causality, no quantitative description of magnitude or significance of the impact, and lack of space-time scale.
overlay	Overlay analysis using thematic maps, often combined with GIS technology.	Intuitive, visual, concise, easy to understand, can visualize the spatial distribution of various single and composite effects.	The causal relationship between the source and the recipient cannot be expressed, and it is not easy to comprehensively evaluate the rank of environmental factors.
AHP	Muti-objective, muti-criteria decision analysis is an organized process of human subjective thinking.	Reflects the combination of qualitative and quantitative evaluation, easy to implement, useful in many cases.	The calculation result depends on the constructed judgment matrix. Expert judgment may be one-sided and inconsistent.
fuzzy comprehensive assessment	Use fuzzy exchange principle and maximum membership principle to consider various factors related to the thing being evaluated and make a comprehensive assessment of it.	Strong discriminability and comparability, simple model, good judgment effect on multi-factor, multilevel complex problems. Suitable for evaluation with less relevant data, uneven influence, and the existence of vagueness.	The judgment of the maximum membership principle may cause loss of information, even leading to unrealistic conclusions.

By comparing various road construction environmental impact assessment methods, it becomes evident that most environmental impact assessment methods start with a single evaluation and qualitative description. From the perspective of a comprehensive evaluation, it is not easy to comprehensively evaluate road construction projects' environmental impact. Although there are some more effective multi-objective comprehensive evaluation methods widely used in the environmental impact assessment of road construction projects, they still have certain limitations and lack of data on road construction's environmental impacts. Therefore, it is urgent to establish a more concise and practical model for a comprehensive environmental impact assessment of road construction projects.

3. METHODOLOGY

3.1. The fuzzy matter-element comprehensive evaluation model

Fuzzy mathematics is a mathematical theory and method for studying and dealing with ambiguity. In 1965, American cybernetics expert Zadeh published a paper entitled "Fuzzy Sets", which proposed using "membership function" to describe the intermediate transition of phenomenon differences, thereby breaking through the absolute relationship of belonging to or not belonging to the classic set theory. This pioneering work by Professor Zadeh marked the birth of a new branch of fuzzy mathematics. Fuzzy mathematics uses uncertain things as its research object. The basic idea of fuzzy mathematics is to use precise mathematical methods to describe and model many fuzzy concepts and fuzzy phenomena in the real world to achieve the purpose of proper handling (Gupta and Ragade, 1977).

Chinese mathematician Cai put forward Matter-element analysis method in the 1980s. In 1983, he published the paper "Extension Sets and Incompatible Problems" marking the birth of matter-element analysis. Matter-element analysis develops based on classical mathematics and fuzzy mathematics, but it is a new discipline that is different from them. The logic basis of classical mathematics is formal logic, the logic basis of fuzzy mathematics is fuzzy logic, and the logic basis of the matter-element analysis is the combination of formal logic and dialectical logic. The matter-element analysis is the theory that studies the problem of incompatibility. Quality and quantity analysis are the two most essential components of matter-element analysis (Cai, 1983).

Applying a matter-element method to establish a multi-index evaluation model can establish a visualization model for complex problems and quantify the evaluation results to reflect the comprehensive level of things more thoroughly and accurately (Cai, 1998). When people deal with incompatible problems, they must consider matters, characteristics, and corresponding composed quantities to form a solution to the problem, describe the changing law of objectives more appropriately, and formalize solving contradictory problems. This idea describes things with three elements of matter, characteristics, and values to form an ordered triplet, i.e., a matter-element.

3.1.1. Basic concepts of fuzzy matter-element

Matter-element analysis is an effective method for studying matter-element and its change planning laws and is used to solve incompatible problems in the real world. If the value in the matter-element is fuzzy, it constitutes a problem of fuzzy incompatibility. Fuzzy matter-element is a combination of fuzzy mathematics and matter-element analysis. It analyzes and synthesizes the fuzziness of the corresponding magnitude of things' characteristics and the incompatibility between many factors affecting things, to obtain a new way to solve such problems.

The fuzzy-matter element is the ordered element triples "matter, characteristic, value" as the fundamental element to describe things, denoted by Equation 4, where R is a fuzzy matter-element, M is things, C is the feature of things M and $V(x)$ is the fuzzy value of things M about C, that is, the degree of membership of thing M to the corresponding fuzzy value of feature C.

$$R = \begin{bmatrix} & M \\ C & V(x) \end{bmatrix} \tag{4}$$

If thing M can be characterized by features C_1, C_2, $\cdots$, C_n and the corresponding fuzzy values are $V(x_1)$, $V(x_2)$, $\cdots$, $V(x_n)$, then R is called an n dimensional fuzzy matter-element, which is shown in Equation 5.

$$R_n = \begin{bmatrix} & M \\ C_1 & V(x_1) \\ C_2 & V(x_2) \\ \vdots & \vdots \\ C_n & V(x_n) \end{bmatrix} \tag{5}$$

Where:
- R_n is an n-dimensional fuzzy matter element;
- C_1, C_2, ..., C_n are n features of thing M;
- x_i (i = 1, 2, ..., n) is the corresponding magnitude of feature C_i of thing M;
- $V(x_i)$ is the degree of membership of the corresponding value x_i of the feature C_i of thing M.

If m things are described by their n features C_1, C_2, $\cdots$, C_n and their corresponding fuzzy value $V_1(x_{1i})$, $V_2(x_{2i})$, ..., $V_m(x_{mi})$ (i = 1, 2, ..., n), then they are called n dimensional fuzzy composite matter elements of m things, as shown in Equation 6.

$$R_{mn} = \left[\begin{array}{ccccc} & M_1 & M_2 & \cdots & M_m \\ C_1 & V_1(x_{11}) & V_2(x_{21}) & \cdots & V_m(x_{m1}) \\ C_2 & V_1(x_{12}) & V_2(x_{22}) & \cdots & V_m(x_{m2}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & V_1(x_{1n}) & V_2(x_{2n}) & \cdots & V_m(x_{mn}) \end{array}\right] \tag{6}$$

Where:
- R_{mn} is an n dimensional fuzzy matter element of m things;
- M_j (j = 1, 2, ..., m) is the j^{th} thing;
- x_i (i = 1, 2, ..., n) is the corresponding value of the feature C_i of thing M;
- $V_j(x_{ji})$ is the degree of membership of the corresponding value x_{ji} (j = 1, 2, ..., m; i = 1, 2, ..., n) of the feature C_i of thing M_j.

When a specific thing gives the specific values, the equation's fuzzy value can be replaced with specific values, as shown in Equation 7.

$$R_{mn} = \left[\begin{array}{ccccc} & M_1 & M_2 & \cdots & M_m \\ C_1 & x_{11} & x_{21} & \cdots & x_{m1} \\ C_2 & x_{12} & x_{22} & \cdots & x_{m2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & x_{1n} & x_{2n} & \cdots & x_{mn} \end{array}\right] \tag{7}$$

3.1.2. Establishment of a fuzzy matter-element comprehensive evaluation model

The fuzzy matter-element comprehensive evaluation model established and used in this work for EIA of a series of road construction sites comprises five main phases, as presented in Figure 6.

Phase 1 - Establishment of composite matter-element for the environmental impact

There are both qualitative and quantitative indicators in the indicator system of environmental impact of urban roads construction. The value of the qualitative index can be obtained directly through the expert consultation method. For the quantitative index value, the evaluation result can be calculated by a single factor prediction model first and then obtained by the expert consultation method. In order to facilitate the evaluation, according to the standard of evaluation level, $V = \{100, 80, 60, 40 , 20\}$ is assigned to each evaluation level, then the experts combined the evaluation level to assign values to each evaluation index. Based on these, a composite matter-element of each primary index of environmental impact is established.

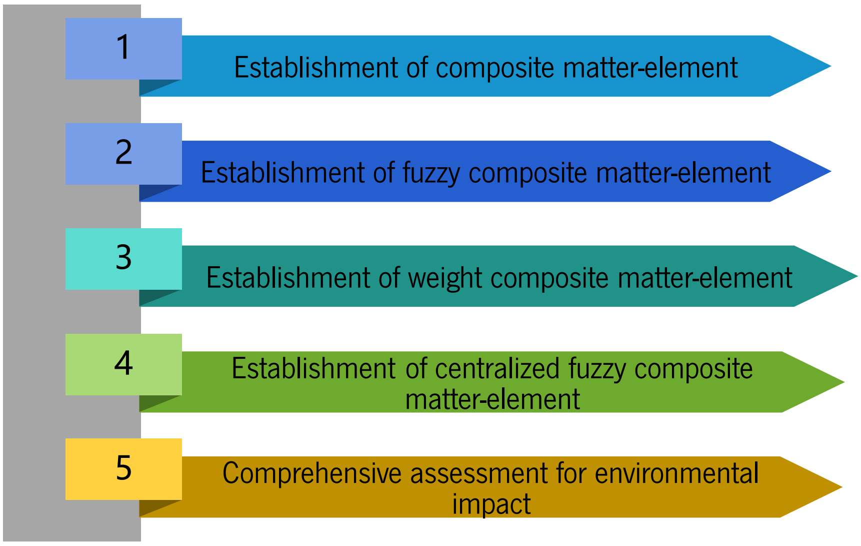


Figure 6 - Fuzzy matter-element comprehensive evaluation model

Phase 2 - Establishment of fuzzy composite matter-element for the environmental impact

The degree of membership of each evaluation index to each evaluation level must be determined to establish a fuzzy composite matter-element for the environmental impact of road construction. In this thesis, the evaluation index membership function is constructed by establishing descending half of trapezium function, where V_k and V_{k+1} are two adjacent classification standards. Obviously, V_k is greater than V_{k+1}. Then, the membership function for V_k is given by Equation 8.

$$r(x) = \begin{cases} 0 & x < V_{k+1}\,, x > V_k \\ \dfrac{x - V_{k+1}}{V_k - V_{k+1}} & V_{k+1} \leq x \leq V_k \end{cases} \tag{8}$$

The membership function for V_{k+1} is given by Equation 9.

$$r(x) = \begin{cases} V_{k-x} & V_{k+1} \leq x \leq V_k \\ 0 & x < V_{k+1}\,, x > V_k \end{cases} \tag{9}$$

Where:
- $r(x)$ is a membership function;
- x is the score of the evaluation index.

By substituting the expert's score for the evaluation index into the membership function constructed above, the membership degree of the evaluation index corresponding to the equivalent level can be obtained, thereby obtaining a fuzzy membership degree matrix.

Phase 3 - Establishment of weight composite matter-element for the environmental impact

In this thesis, the fuzzy analytic hierarchy process is used to determine each evaluation index's weight of road construction projects' environmental impact. That process has three specific steps:

i) Establish a hierarchical structure, that is, a comprehensive environmental impact assessment system for road construction projects;
ii) Construct a fuzzy consistent matrix, and compare the factors of each pair one by one to obtain the membership of the comparison of the two factors;
iii) Determine the index weights, as previously shown in Equation 3.

Phase 4 - Establishment of centralized fuzzy composite matter-element

Based on the above evaluation index's fuzzy composite matter-element and the corresponding weight composite matter-element, a centralized fuzzy composite matter-element of each primary index can be established, as shown in Equation 10, where b_{ji} is the concentrated value of the membership of the i^{th} main factor of the j^{th} level.

$$R_b = \left[\begin{array}{ccccc} & M_1 & M_2 & \cdots & M_m \\ b_1 & b_{11} = \sum_{k=1}^{p} W_{1k} V_{11k} & b_{21} = \sum_{k=1}^{p} W_{1k} V_{21k} & \cdots & b_{m1} = \sum_{k=1}^{p} W_{1k} V_{m1k} \\ b_2 & b_{12} = \sum_{k=1}^{p} W_{2k} V_{12k} & b_{22} = \sum_{k=1}^{p} W_{2k} V_{22k} & \cdots & b_{m2} = \sum_{k=1}^{p} W_{2k} V_{m2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_n & b_{1n} = \sum_{k=1}^{p} W_{nk} V_{1nk} & b_{2n} = \sum_{k=1}^{p} W_{nk} V_{2nk} & \cdots & b_{mn} = \sum_{k=1}^{p} W_{nk} V_{mnk} \end{array}\right] \tag{10}$$

Phase 5 - Comprehensive assessment for environmental impact

First, determine the fuzzy composite matter-element of single evaluation index (represented by R_x), as shown in Equation 11.

$$R_x = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ x_1 & x_{11} = W_1 b_{11} & x_{21} = W_1 b_{21} & \cdots & x_{m1} = W_1 b_{m1} \\ x_2 & x_{12} = W_2 b_{12} & x_{22} = W_2 b_{22} & \cdots & x_{m2} = W_2 b_{m2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_n & x_{1n} = W_n b_{1n} & x_{2n} = W_n b_{2n} & \cdots & x_{mn} = W_n b_{mn} \end{bmatrix} \tag{11}$$

Then, the composite fuzzy matter-element for comprehensive evaluation is established. The average, maximum and minimum values of the fuzzy matrix under the corresponding weights of the main factors are used as the evaluation indicators to overcome the one-sidedness and are denoted as d_{j1}, d_{j2}, d_{j3}, as shown in Equation 12.

$$\begin{cases} d_{j1} = \frac{(x_{j1} + x_{j2} + \cdots + x_{jm})}{n} \\ d_{j2} = max(x_{j1}, x_{j2}, \cdots, x_{jm}) \\ d_{j3} = min(x_{j1}, x_{j2}, \cdots, x_{jm}) \end{cases} \quad , j = 1,2, \cdots, m \tag{12}$$

The fuzzy composite matter-element for evaluation is presented in Equation 13.

$$R_d = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ d_{j1} & d_{11} & d_{21} & \cdots & d_{m1} \\ d_{j2} & d_{12} & d_{22} & \cdots & d_{m2} \\ d_{j3} & d_{13} & d_{23} & \cdots & d_{m3} \end{bmatrix} \tag{13}$$

The composite fuzzy matter-element for comprehensive evaluation is presented in Equation 14.

$$R_D = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ d_j & d_1 & d_2 & \cdots & d_m \end{bmatrix} \tag{14}$$

Where d_j is comprehensive evaluation value of the j^{th} evaluation level, as shown in Equation 15.

$$d_j = \frac{1}{3} \sum_{i=1}^{3} d_{ji} \;, \qquad j = 1, 2, \cdots, m \tag{15}$$

The level corresponding to the maximum value d_{max} of the centralized evaluation value d_j is the level to which the environmental impact of the urban roads construction project belongs.

3.2. Case study of environmental impact assessment of urban roads construction

3.2.1. General situation of the project

The Jialing District Industrial Concentration Zone is located in the southwest of Nanchong City, next to the Jialing River. The planned area has 30 square kilometres, where more than 150 enterprises with more than 25,000 employees have been settled. In 2014, it achieved sales revenue of 23 billion yuan, forming automobile and auto parts, silk spinning clothing, food and beverage, construction materials, and mechanical processing of several major industrial clusters.

The industrial park's completed area has formed a road pattern that crosses the southeast to northwest, and the backbone road network has been completed. As the industrial park is close to the main railway and highway junctions, there are many employees in the park, schools (university and various schools), residents nearby, and the continuous expansion of trade, the existing road traffic can no longer meet the current needs. To promote the development of Jialing Industrial Park, promote the rapid development of regional economy, improve land utilization rate, accelerate urban infrastructure construction, and improve road traffic network, this road project's construction will be of great significance.

The planned road, namely the extension of Geely road (Figure 7), has a total length of 3,689 meters, of which the west section is 2,120 meters long, 24 meters wide, and two-way 4-lane roads, while the east section is 1,569 meters long, 32 meters wide, and two-way six lanes, with a design speed of 40 km/h. The road construction project is in the east-west direction, and the construction content includes road engineering and its auxiliary facilities.

3.2.2. Environmental status of the project

The first topic to be observed is the geographical location. The geographic coordinates of Nanchong City are between 30°35′ and 31°51′ North Latitude and 30°35′ and 31°51′ East Longitude. Nanchong is located in the northeast of Sichuan, and the middle reaches of the Jialing River. Nanchong has a population of 7,596,400 inhabitants and an area of 125,000 square kilometres. It is the second-most populous city in Sichuan Province and an excellent tourist city in China, with a national garden city, a national clean energy demonstration city, and the prestigious "Silk Capital". The city in the north of Chengdu-Chongqing Economic Zone and the northeast of Sichuan is the central city.

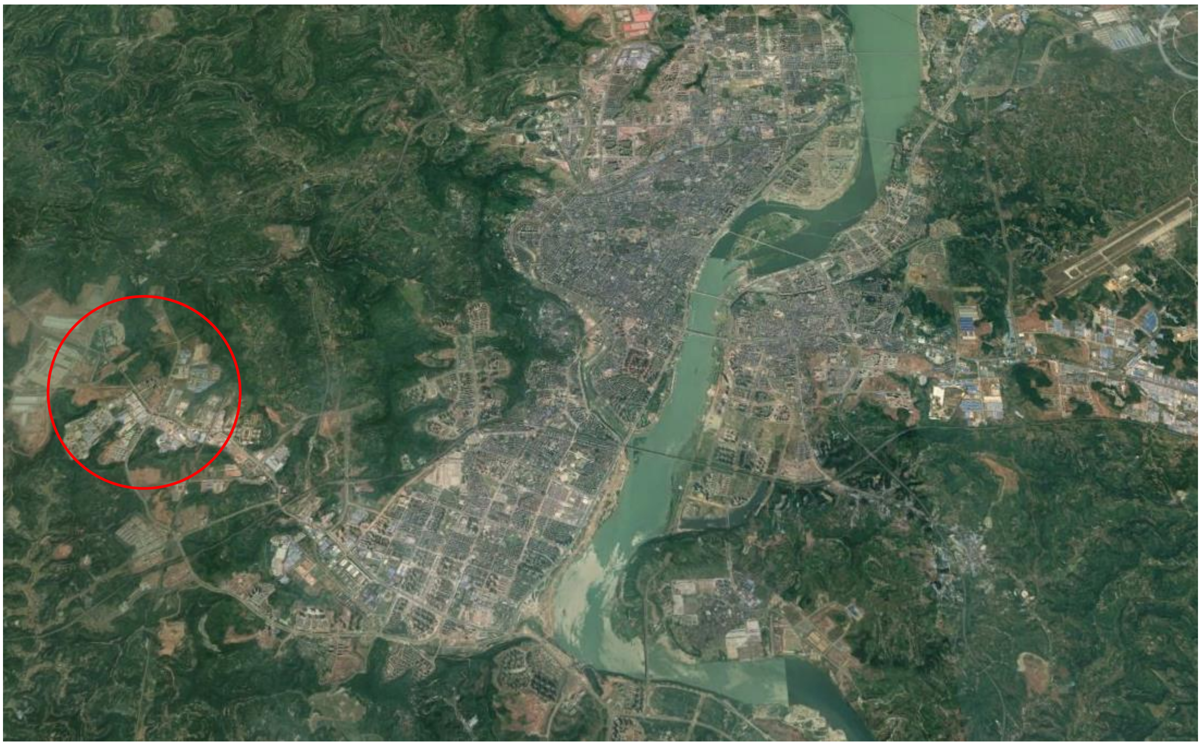


Figure 7 - Geely road new construction project (Google Earth)

The second topic is geology, terrain, and landform. The area belongs to hills and low mountains, and there are no substantial adverse geological phenomena. The surface is cultivated, with cohesive alluvial soil, an underlying pebble layer, and the bedrock is Middle Jurassic sand mud. The geological structure is simple, and the recent crustal movement is stable. The area is located at the intersection of the mountainous areas in the Sichuan Basin's northern edge and the hills in the middle of the Sichuan Basin. The landforms in the area are mainly affected by erosion and accumulation during the flood period.

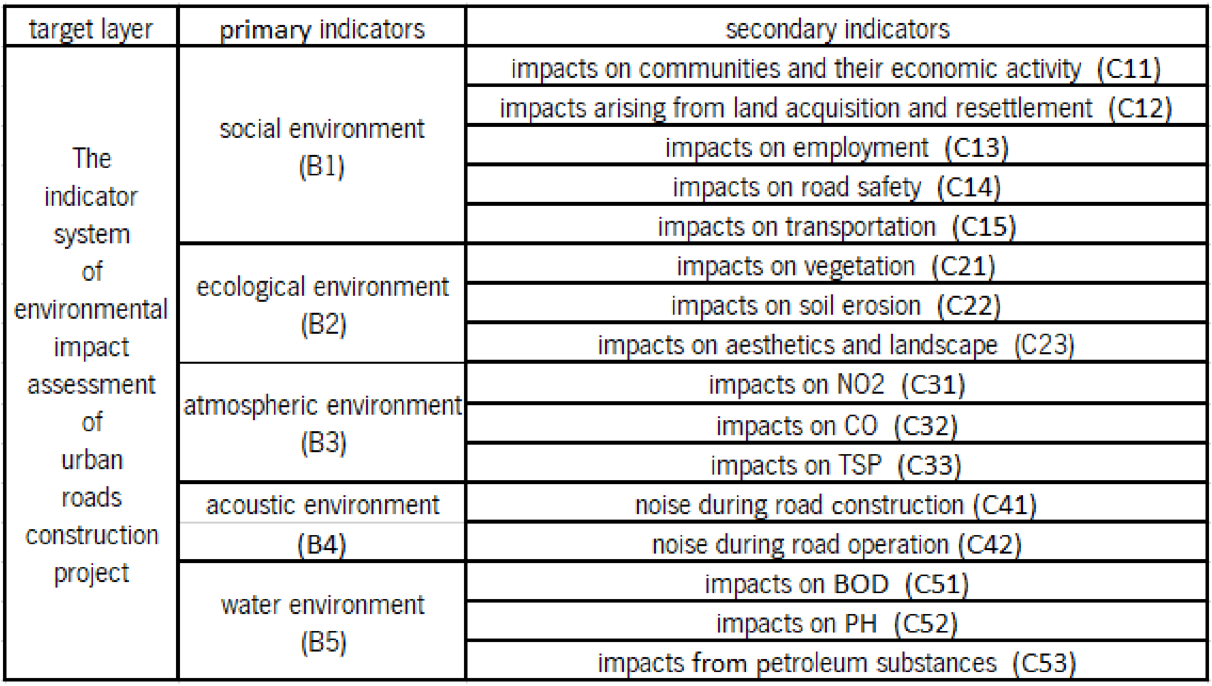
The climate and weather is the third topic observed. The project is set in a subtropical humid monsoon climate zone with a mild climate and abundant rainfall. Cold air activities are frequent in spring, and precipitation reduces, while summers are hot, and there are torrential rains. Autumn temperatures fall fast and rain increases, followed by foggy and more dry winters. According to the Nanchong Weather Bureau statistics, the average annual temperature is 17 °C, the extreme maximum is 40.1 °C, the extreme minimum is -2.8 °C, the average annual rainfall is 1021 mm, the annual maximum precipitation is 1529 mm, and the maximum rainfall for 24 h is 209 mm. The evaporation is 1088 mm, the average annual wind speed is 1.1 m/s, the maximum wind direction is N, the maximum wind speed is 16.0 m/s from NE, the average relative humidity is 79%, and the annual average sunshine is 1267 h.

The fourth topic to be observed is hydrogeology. The groundwater on the site is the upper stagnant water in the soil layer and the pore diving in the sandy pebble layer. The upper layer of stagnant water mainly exists in the upper artificial filling layer, replenished by atmospheric precipitation and surface water. There is no uniform free water surface, and the amount of water is enormous. The primary type of groundwater is pore diving in sand and pebble, which is slightly pressure-bearing. It mainly occurs in sand and pebble layers. Groundwater is recharged laterally by atmospheric precipitation and surface water and is discharged by evaporation and underground seepage. According to regional hydrogeological data, the in-site groundwater's annual variation ranges from 2.00 to 3.00 m. The dry season is from November to March, and the wet season is from July and August.

3.2.3. Comprehensive assessment of the environmental impact

The first step of the method is the establishment of the environmental impact assessment index system. According to the objective of a comprehensive assessment of the environmental impact of urban roads construction, and combined with the actual situation of Geely road, a screening method combining qualitative and quantitative methods was selected to establish the index system (Table 7).

Table 7 - Index system of environmental impact assessment of Geely road



target layer	primary indicators	secondary indicators
The indicator system of environmental impact assessment of urban roads construction project	social environment (B1)	impacts on communities and their economic activity (C11)
		impacts arising from land acquisition and resettlement (C12)
		impacts on employment (C13)
		impacts on road safety (C14)
		impacts on transportation (C15)
	ecological environment (B2)	impacts on vegetation (C21)
		impacts on soil erosion (C22)
		impacts on aesthetics and landscape (C23)
	atmospheric environment (B3)	impacts on NO2 (C31)
		impacts on CO (C32)
		impacts on TSP (C33)
	acoustic environment	noise during road construction (C41)
	(B4)	noise during road operation (C42)
	water environment (B5)	impacts on BOD (C51)
		impacts on PH (C52)
		impacts from petroleum substances (C53)

Note: The establishment of the Geely road construction project's environmental impact indicator system combines the expert consultation questionnaire's relevant data.

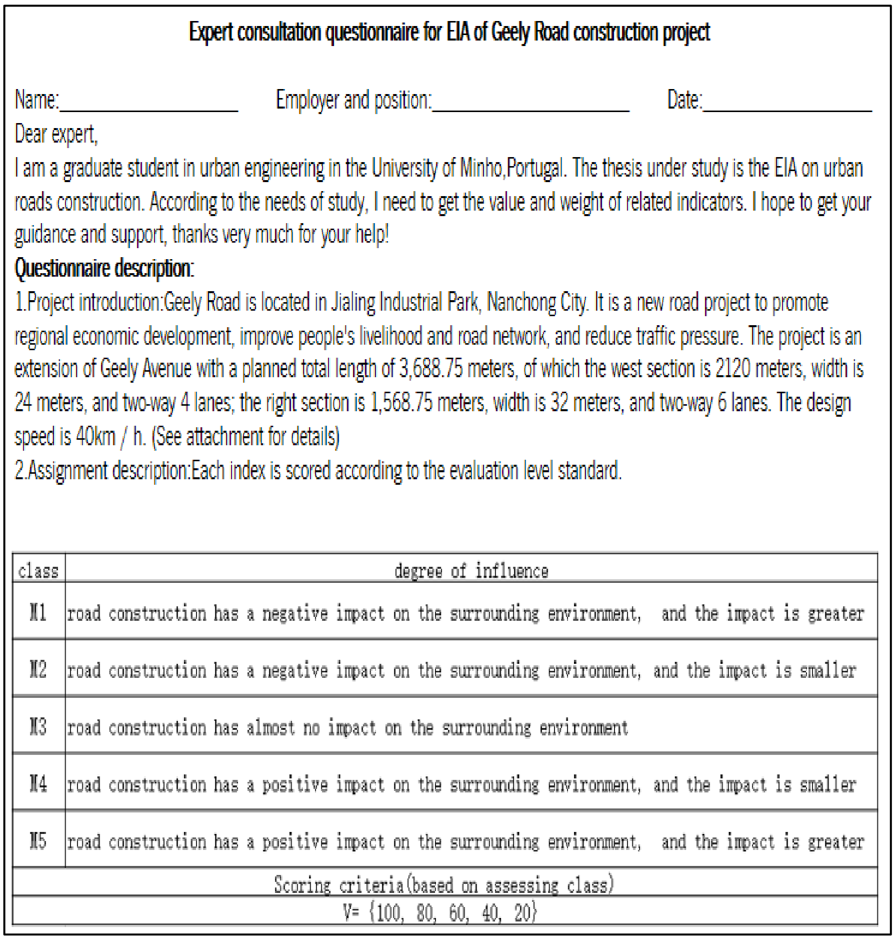
The second step of the method is the classification of environmental impact assessment standards. The EIA of road construction projects objectively gives the degree of road construction's environmental impact and gives intuitive evaluation conclusions through quantitative analysis. The model divides the evaluation results into five levels (Table 8).

Table 8 - Partition of assessing level

Partition of assessing class	
class	degree of influence
M1	road construction has a negative impact on the surrounding environment, and the impact is greater
M2	road construction has a negative impact on the surrounding environment, and the impact is smaller
M3	road construction has almost no impact on the surrounding environment
M4	road construction has a positive impact on the surrounding environment, and the impact is smaller
M5	road construction has a positive impact on the surrounding environment, and the impact is greater

The third step of the method is the establishment of the fuzzy matter-element comprehensive evaluation model. Initially, the composite matter-element of environmental impact is established. According to the standard, $V = \{100, 80, 60, 40\ , 20\}$ is assigned to each evaluation level to facilitate, and then the experts combined the evaluation level to assign values to each evaluation index (Tables 9 and 10).

Table 9 - Expert consultation questionnaire for EIA of Geely road construction project (first sheet)



Expert consultation questionnaire for EIA of Geely Road construction project

Name:________________ Employer and position:__________________ Date:________________

Dear expert,

I am a graduate student in urban engineering in the University of Minho,Portugal. The thesis under study is the EIA on urban roads construction. According to the needs of study, I need to get the value and weight of related indicators. I hope to get your guidance and support, thanks very much for your help!

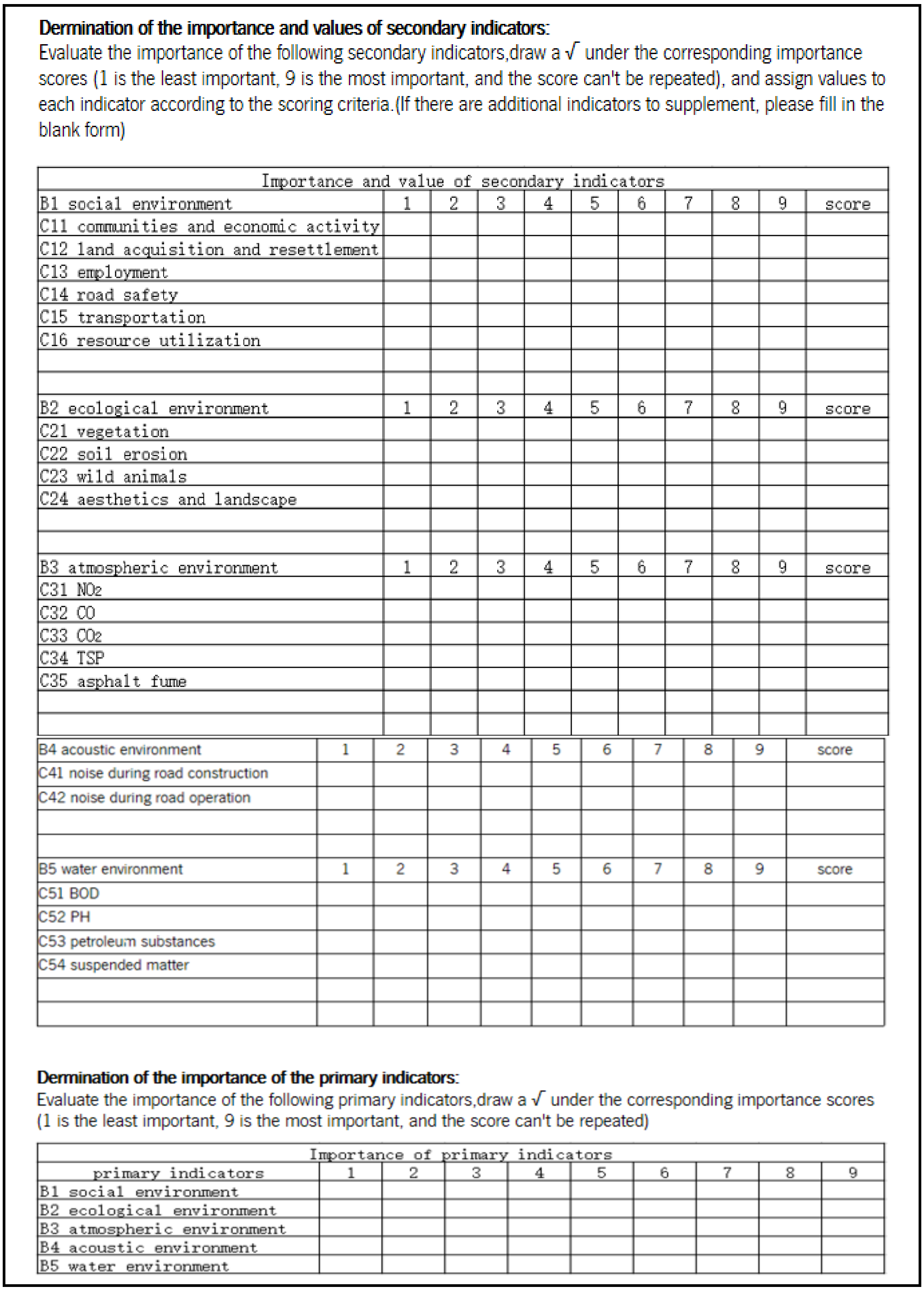
Questionnaire description:

1.Project introduction:Geely Road is located in Jialing Industrial Park, Nanchong City. It is a new road project to promote regional economic development, improve people's livelihood and road network, and reduce traffic pressure. The project is an extension of Geely Avenue with a planned total length of 3,688.75 meters, of which the west section is 2120 meters, width is 24 meters, and two-way 4 lanes; the right section is 1,568.75 meters, width is 32 meters, and two-way 6 lanes. The design speed is 40km / h. (See attachment for details)

2.Assignment description:Each index is scored according to the evaluation level standard.

class	degree of influence
M1	road construction has a negative impact on the surrounding environment, and the impact is greater
M2	road construction has a negative impact on the surrounding environment, and the impact is smaller
M3	road construction has almost no impact on the surrounding environment
M4	road construction has a positive impact on the surrounding environment, and the impact is smaller
M5	road construction has a positive impact on the surrounding environment, and the impact is greater
Scoring criteria(based on assessing class)	
V= {100, 80, 60, 40, 20}	

Table 10 - Expert consultation questionnaire for EIA of Geely road construction project (second sheet)



Dermination of the importance and values of secondary indicators:

Evaluate the importance of the following secondary indicators,draw a √ under the corresponding importance scores (1 is the least important, 9 is the most important, and the score can't be repeated), and assign values to each indicator according to the scoring criteria.(If there are additional indicators to supplement, please fill in the blank form)

Importance and value of secondary indicators										
B1 social environment	1	2	3	4	5	6	7	8	9	score
C11 communities and economic activity										
C12 land acquisition and resettlement										
C13 employment										
C14 road safety										
C15 transportation										
C16 resource utilization										
B2 ecological environment	1	2	3	4	5	6	7	8	9	score
C21 vegetation										
C22 soil erosion										
C23 wild animals										
C24 aesthetics and landscape										
B3 atmospheric environment	1	2	3	4	5	6	7	8	9	score
C31 NO_2										
C32 CO										
C33 CO_2										
C34 TSP										
C35 asphalt fume										
B4 acoustic environment	1	2	3	4	5	6	7	8	9	score
C41 noise during road construction										
C42 noise during road operation										
B5 water environment	1	2	3	4	5	6	7	8	9	score
C51 BOD										
C52 PH										
C53 petroleum substances										
C54 suspended matter										

Dermination of the importance of the primary indicators:

Evaluate the importance of the following primary indicators,draw a √ under the corresponding importance scores (1 is the least important, 9 is the most important, and the score can't be repeated)

Importance of primary indicators									
primary indicators	1	2	3	4	5	6	7	8	9
B1 social environment									
B2 ecological environment									
B3 atmospheric environment									
B4 acoustic environment									
B5 water environment									

The main source of the questionnaire contains experts, engineers and nearby residents. Experts include experts from the environmental protection department, experts from the construction department, and senior engineers. Professional technical person include road engineers, construction engineers, and supervision engineers. In the questionnaire survey of Geely road, 200 questionnaires were sent out, and a total of 116 questionnaires were returned. The composition of the questionnaire is shown in Figure 8.

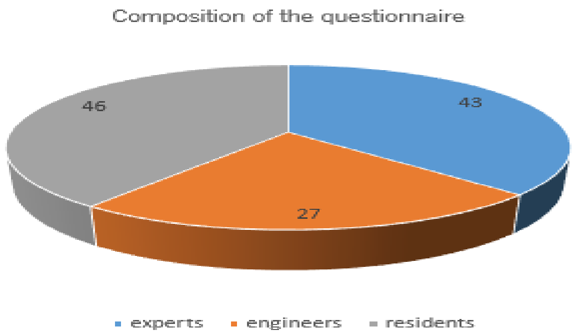


Figure 8 - Composition of the questionnaire on Geely road

Based on these, a composite matter-element of each primary index (social environment, ecological environment, atmospheric environment, acoustic environment and water environment) of environmental impact can be established.

After consulting the experts, the statistical analysis of expert consultation questionnaire data for Geely road construction project was carried out, which is presented in Figure 9.

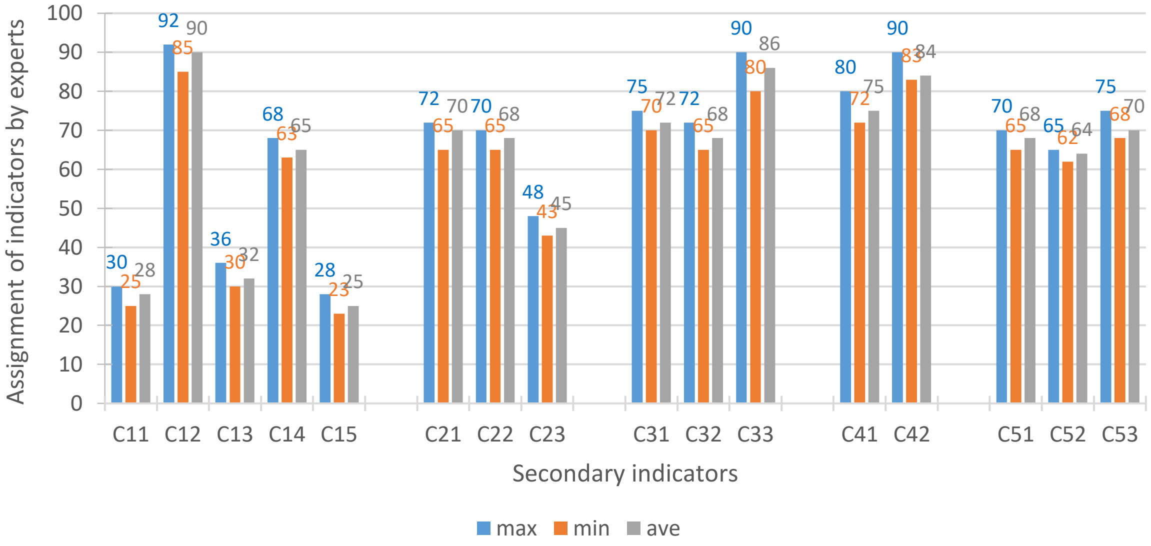


Figure 9 - Questionnaire statistics of experts' consultation on the secondary indicators

Based on those questionnaires, it was possible to establish composite matter-elements of environmental impact for each primary index based on the data. In this thesis, the average value of the questionnaire data is used for calculation. (Equations 16 to 20).

- Composite matter-element of social-environmental impact

$$R_1 = \begin{bmatrix} C_{11} & x_{11} \\ C_{12} & x_{12} \\ C_{13} & x_{13} \\ C_{14} & x_{14} \\ C_{15} & x_{15} \end{bmatrix} = \begin{bmatrix} C_{11} & 28 \\ C_{12} & 90 \\ C_{13} & 32 \\ C_{14} & 65 \\ C_{15} & 25 \end{bmatrix} \tag{16}$$

- Composite matter-element of ecological environment impact

$$R_2 = \begin{bmatrix} C_{21} & x_{21} \\ C_{22} & x_{22} \\ C_{23} & x_{23} \end{bmatrix} = \begin{bmatrix} C_{21} & 70 \\ C_{22} & 68 \\ C_{23} & 45 \end{bmatrix} \tag{17}$$

- Composite matter-element of atmospheric environment impact

$$R_3 = \begin{bmatrix} C_{31} & x_{31} \\ C_{32} & x_{32} \\ C_{33} & x_{33} \end{bmatrix} = \begin{bmatrix} C_{31} & 72 \\ C_{32} & 68 \\ C_{33} & 86 \end{bmatrix} \tag{18}$$

- Composite matter-element of acoustic environment impact

$$R_4 = \begin{bmatrix} C_{41} & x_{41} \\ C_{42} & x_{42} \end{bmatrix} = \begin{bmatrix} C_{41} & 75 \\ C_{42} & 84 \end{bmatrix} \tag{19}$$

- Composite matter-element of water environment impact

$$R_5 = \begin{bmatrix} C_{51} & x_{51} \\ C_{52} & x_{52} \\ C_{53} & x_{53} \end{bmatrix} = \begin{bmatrix} C_{51} & 68 \\ C_{52} & 64 \\ C_{53} & 70 \end{bmatrix} \tag{20}$$

The next step is the establishment of fuzzy composite matter-element for the environmental impact. In the Geely road construction project, the evaluation index membership function is constructed by establishing descending half of trapezium function. A fuzzy membership matrix was constructed by substituting the expert's assignment of the secondary index into Equations 8 and 9, then calculating the evaluation index's membership to the corresponding level.

Taking the community and economic activity C_{11} as an example, the enquired experts assign a value of 28, which is between 40 and 20, and the membership degrees of the five evaluation levels are the following: $r_{111} = 0$, $r_{211} = 0$, $r_{311} = 0$, $r_{411} = \frac{28-20}{40-20} = 0.4$, $r_{511} = \frac{40-28}{40-20} = 0.6$. Similarly, all evaluation indicators' membership was calculated to the evaluation level to establish the corresponding fuzzy composite matter-element (Equation 21 to 25).

- Fuzzy composite matter-element of social-environmental impact

$$R_{515} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{11} & 0 & 0 & 0 & 0.4 & 0.6 \\ C_{12} & 0.5 & 0.5 & 0 & 0 & 0 \\ C_{13} & 0 & 0 & 0 & 0.6 & 0.4 \\ C_{14} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{15} & 0 & 0 & 0 & 0.25 & 0.75 \end{bmatrix} \tag{21}$$

- Fuzzy composite matter-element of ecological environmental impact

$$R_{523} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{21} & 0 & 0.5 & 0.5 & 0 & 0 \\ C_{22} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{23} & 0 & 0 & 0.25 & 0.75 & 0 \end{bmatrix} \tag{22}$$

- Fuzzy composite matter-element of atmospheric environmental impact

$$R_{533} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{31} & 0 & 0.6 & 0.4 & 0 & 0 \\ C_{32} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{33} & 0.3 & 0.7 & 0 & 0 & 0 \end{bmatrix} \tag{23}$$

- Fuzzy composite matter-element of acoustic environmental impact

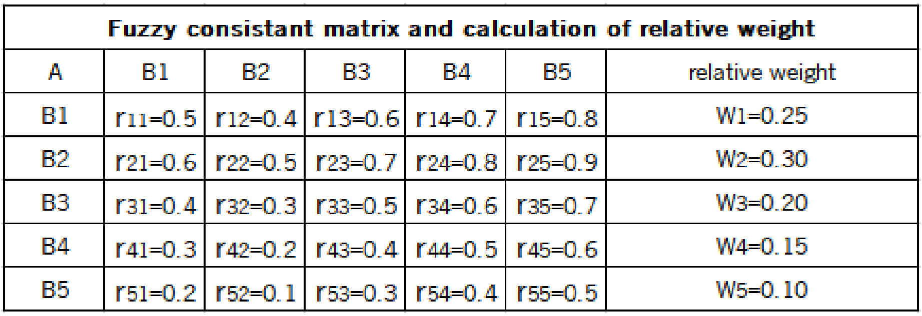
$$R_{542} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{41} & 0 & 0.75 & 0.25 & 0 & 0 \\ C_{42} & 0.2 & 0.8 & 0 & 0 & 0 \end{array}\right] \tag{24}$$

- Fuzzy composite matter-element of water environmental impact

$$R_{553} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{51} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{52} & 0 & 0.2 & 0.8 & 0 & 0 \\ C_{53} & 0 & 0.5 & 0.5 & 0 & 0 \end{array}\right] \tag{25}$$

The next step was the establishment of weight composite matter-element for the environmental impact. According to the data of the expert consultation questionnaire (the degree of importance between the indicators), combined with the quantity scale table in fuzzy analytic hierarchy process (FAHP), it was possible to calculate the membership of the comparison of the two elements, construct a fuzzy consistent matrix and calculate the relative weight of each indicator according to Equation 3. The weight determination by FAHP is presented in Table 11.

Table 11 - The fuzzy consistent matrix and calculation of relative weight for the primary indicators



Fuzzy consistant matrix and calculation of relative weight						
A	B1	B2	B3	B4	B5	relative weight
B1	r11=0.5	r12=0.4	r13=0.6	r14=0.7	r15=0.8	W1=0.25
B2	r21=0.6	r22=0.5	r23=0.7	r24=0.8	r25=0.9	W2=0.30
B3	r31=0.4	r32=0.3	r33=0.5	r34=0.6	r35=0.7	W3=0.20
B4	r41=0.3	r42=0.2	r43=0.4	r44=0.5	r45=0.6	W4=0.15
B5	r51=0.2	r52=0.1	r53=0.3	r54=0.4	r55=0.5	W5=0.10

The assignment and calculation explanation of the values shown in Table 11 is the following: $r_{11} = 0.5$ demonstrates that B_1 and B_1 are equally important; $r_{12} = 0.4$ represents B_1 is slightly less important than B_2; $r_{13} = 0.6$ represents B_1 is slightly more important than B_3. The additional memberships are assigned in the same way. According to Equation 3, to calculate w_1, $i = 1$, $n = 5$, $a = \frac{n-1}{2} = 2$, so

$w_1 = \frac{1}{5} - \frac{1}{4} + \frac{1}{10} \times (0.5 + 0.4 + 0.6 + 0.7 + 0.8) = 0.25$. The other weights are calculated in the same way, resulting in the values presented in Figure 10.

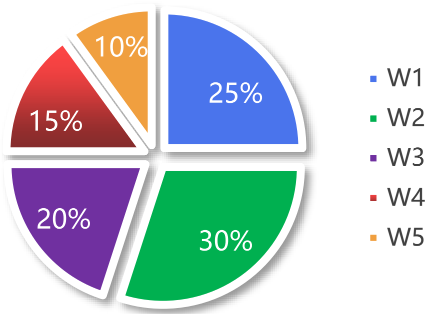
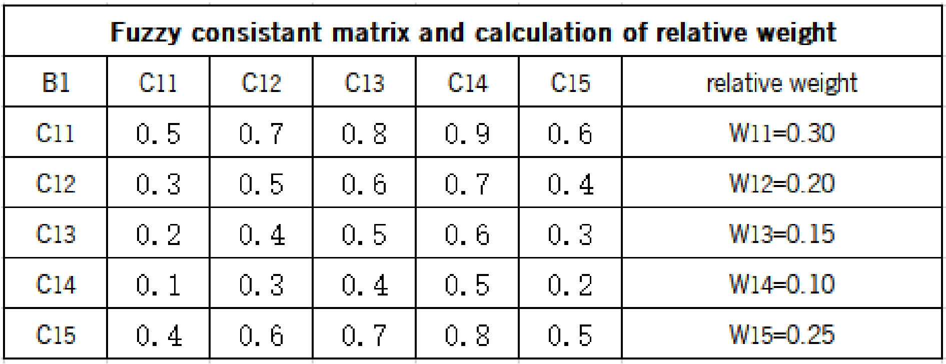


Figure 10 - Pie chart of relative weight for the primary indicators

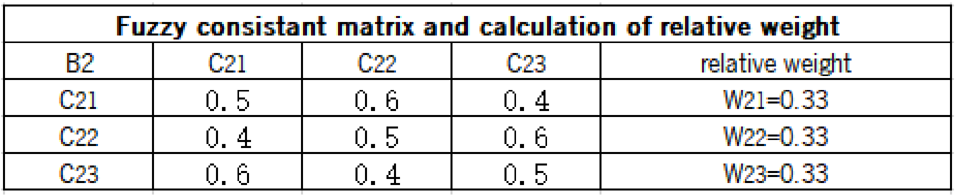
The calculation of membership and weight of secondary indicators, presented in Tables 12 to 16, was carried out the same way as the primary indicators calculation method.

Table 12 - Fuzzy consistent matrix and calculation of relative weight for indicators of B1



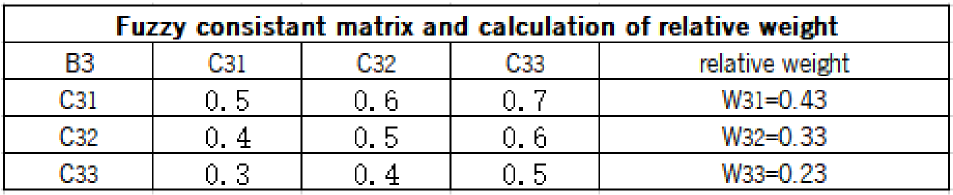
Fuzzy consistant matrix and calculation of relative weight						
B1	C11	C12	C13	C14	C15	relative weight
C11	0.5	0.7	0.8	0.9	0.6	W11=0.30
C12	0.3	0.5	0.6	0.7	0.4	W12=0.20
C13	0.2	0.4	0.5	0.6	0.3	W13=0.15
C14	0.1	0.3	0.4	0.5	0.2	W14=0.10
C15	0.4	0.6	0.7	0.8	0.5	W15=0.25

Table 13 - Fuzzy consistent matrix and calculation of relative weight for indicators of B2



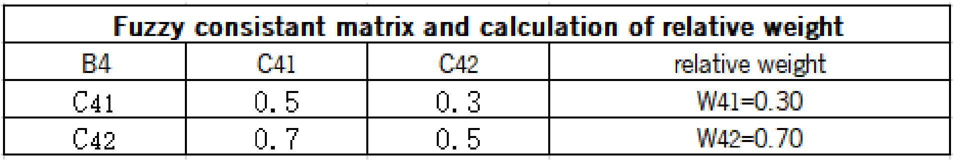
Fuzzy consistant matrix and calculation of relative weight				
B2	C21	C22	C23	relative weight
C21	0.5	0.6	0.4	W21=0.33
C22	0.4	0.5	0.6	W22=0.33
C23	0.6	0.4	0.5	W23=0.33

Table 14 - Fuzzy consistent matrix and calculation of relative weight for indicators of B3



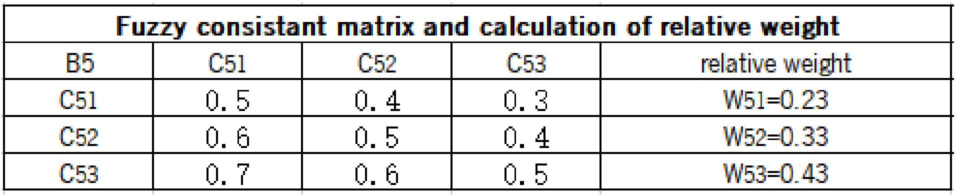
Fuzzy consistant matrix and calculation of relative weight				
B3	C31	C32	C33	relative weight
C31	0.5	0.6	0.7	W31=0.43
C32	0.4	0.5	0.6	W32=0.33
C33	0.3	0.4	0.5	W33=0.23

Table 15 - Fuzzy consistent matrix and calculation of relative weight for indicators of B4



Fuzzy consistant matrix and calculation of relative weight			
B4	C41	C42	relative weight
C41	0.5	0.3	W41=0.30
C42	0.7	0.5	W42=0.70

Table 16 - Fuzzy consistent matrix and calculation of relative weight for indicators of B5



Fuzzy consistant matrix and calculation of relative weight				
B5	C51	C52	C53	relative weight
C51	0.5	0.4	0.3	W51=0.23
C52	0.6	0.5	0.4	W52=0.33
C53	0.7	0.6	0.5	W53=0.43

The weights determined by the fuzzy analytic hierarchy process (FAHP) constitute the weight composite matter-element of indicators at all levels (Equations 26 to 31).

- The weight composite matter-element of the secondary indicators of the social environment

$$R_{W_{1k}} = \begin{bmatrix} & C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \\ W_{1k} & 0.30 & 0.20 & 0.15 & 0.10 & 0.25 \end{bmatrix} \tag{26}$$

- The weight composite matter-element of the secondary indicators of ecological environment

$$R_{W_{2k}} = \begin{bmatrix} & C_{21} & C_{22} & C_{23} \\ W_{2k} & 0.33 & 0.33 & 0.33 \end{bmatrix} \tag{27}$$

- The weight composite matter-element of the secondary indicators of atmospheric environment

$$R_{W_{3k}} = \begin{bmatrix} & C_{31} & C_{32} & C_{33} \\ W_{3k} & 0.43 & 0.33 & 0.23 \end{bmatrix} \tag{28}$$

- The weight composite matter-element of the secondary indicators of the acoustic environment

$$R_{W_{4k}} = \begin{bmatrix} & C_{41} & C_{42} \\ W_{2k} & 0.30 & 0.70 \end{bmatrix} \tag{29}$$

- The weight composite matter-element of the secondary indicators of water environment

$$R_{W_{5k}} = \left[\begin{array}{cccc} & C_{51} & C_{52} & C_{53} \\ W_{5k} & 0.23 & 0.33 & 0.43 \end{array}\right] \tag{30}$$

- The weight composite matter-element of the primary indicators of Geely Road construction project

$$R_{W_i} = \left[\begin{array}{cccccc} & B_1 & B_2 & B_3 & B_4 & B_5 \\ W_i & 0.25 & 0.30 & 0.20 & 0.15 & 0.10 \end{array}\right] \tag{31}$$

The next step was the establishment of centralized fuzzy composite matter-element (Equations 32 to 36). The centralized fuzzy composite matter-element was calculated and established based on Equation 3.

- Centralized fuzzy composite matter-element of social-environmental impact

$$R_1 = R_{W_1} \times R_{515} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.1000 & 0.1250 & 0.0750 & 0.2725 & 0.4275 \end{bmatrix} \tag{32}$$

- Centralized fuzzy composite matter-element of ecological environmental impact

$$R_2 = R_{W_2} \times R_{523} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.2970 & 0.4455 & 0.2475 & 0 \end{bmatrix} \tag{33}$$

- Centralized fuzzy composite matter-element of atmospheric environmental impact

$$R_3 = R_{W_3} \times R_{533} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.0690 & 0.5510 & 0.3700 & 0 & 0 \end{bmatrix} \tag{34}$$

- Centralized fuzzy composite matter-element of acoustic environmental impact

$$R_4 = R_{W_4} \times R_{542} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.1400 & 0.7850 & 0.0750 & 0 & 0 \end{bmatrix} \tag{35}$$

- Centralized fuzzy composite matter-element of water environmental impact

$$R_5 = R_{W_5} \times R_{553} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.3730 & 0.6170 & 0 & 0 \end{bmatrix} \tag{36}$$

The fuzzy composite matter-elements of the social environment, ecological environment, atmospheric environment, acoustic environment and water environment can form a centralized fuzzy composite matter-element for EIA of Geely road construction project (Equation 37).

$$R_b = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} = \left[\begin{array}{ccccc} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.1000 & 0.1250 & 0.0750 & 0.2725 & 0.4275 \\ 0 & 0.2970 & 0.4455 & 0.2475 & 0 \\ 0.0690 & 0.5510 & 0.3700 & 0 & 0 \\ 0.1400 & 0.7850 & 0.0750 & 0 & 0 \\ 0 & 0.3730 & 0.6170 & 0 & 0 \end{array}\right] \tag{37}$$

Next, the comprehensive assessment for environmental impact matrix (Equation 38) was calculated by Equation 11.

$$R_x = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ x_1 & 0.025 & 0.031 & 0.188 & 0.068 & 0.107 \\ x_2 & 0 & 0.089 & 0.134 & 0.074 & 0 \\ x_3 & 0.014 & 0.110 & 0.074 & 0 & 0 \\ x_4 & 0.021 & 0.118 & 0.113 & 0 & 0 \\ x_5 & 0 & 0.373 & 0.062 & 0 & 0 \end{array}\right] \tag{38}$$

The next phase is to calculate and establish the environment impact assessment fuzzy composite matter-element (Equation 39) for the road construction project from Equations 12 and 13.

$$R_d = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_1 & 0.012 & 0.077 & 0.060 & 0.028 & 0.021 \\ d_2 & 0.025 & 0.118 & 0.134 & 0.074 & 0.107 \\ d_3 & 0 & 0.031 & 0.113 & 0 & 0 \end{array}\right] \tag{39}$$

The comprehensive fuzzy composite matter-elements for environmental impact assessment of the road construction project (Equation 40) are calculated and established from Equations 14 and 15.

$$R_D = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_j & 0.012 & 0.075 & 0.068 & 0.034 & 0.043 \end{bmatrix} \tag{40}$$

It can be seen from the results of the comprehensive evaluation that $d_{max} = d_2$, and the status of the evaluation level M_2 corresponding to d_2 shows that road construction harms the environment, but the impact is small. By adopting effective pollution prevention and environmental protection measures, the environment's negative impact can be controlled and reduced, so the project's analysis from the environmental protection perspective is feasible.

3.3. Application of model after using impact reduction methods in different site conditions

For the application of the model after using impact reduction methods in different site conditions, the primary considerations are the following: new projects, reconstruction projects (reconstruction of existing roads), urban roads, rural roads, and road construction projects with large differences in geological conditions (such as mountain roads).

3.3.1. Urban road (Binjiang road – reconstruction project of an urban road)

Binjiang road (Figure 11) is located in the urban area of Nanchong City, next to the Jialing River. From Jialing District in the south to Shunqing District in the north, it has a total length of 12 kilometres and is the backbone of the urban road network. Before the reconstruction of the two-way four-lane road was set up. A fence was used to separate the motorways from the non-motorized lanes. The roads were separated by ordinary asphalt concrete pavements and organized drainage pipes. Because this road is located in the central area and is the city's main road, the traffic volume is enormous. According to the 2012 traffic statistics, the daily traffic volume exceeds 30,000 vehicles. The traffic congestion during the peak period is severe. The road environment has seriously affected the city's healthy development (i.e., harsh noise and air pollution; water resources are not effectively used and saved). To ease urban traffic congestion, enhance road capacity, optimize road functions (e.g., permeation, noise reduction), improve the urban municipal road infrastructure, and increase the landscape's aesthetics, the government carried out a large-scale reconstruction of Binjiang Road. After the road's reconstruction, the width is 50 meters, with a central green belt of 7 meters and eight lanes in both directions. The design speed is 60 kilometres per hour. The outermost lanes are set as bus lanes with harbour-style bus stops. There are five new parking lots with 2,000 parking spaces increase. Binjiang Road adopts noise-reducing permeable asphalt concrete pavement (OGFC) and uses an organized drainage pipe network. The road construction is combined with the riverside's green belt of Jialing River to form an excellent urban sponge.

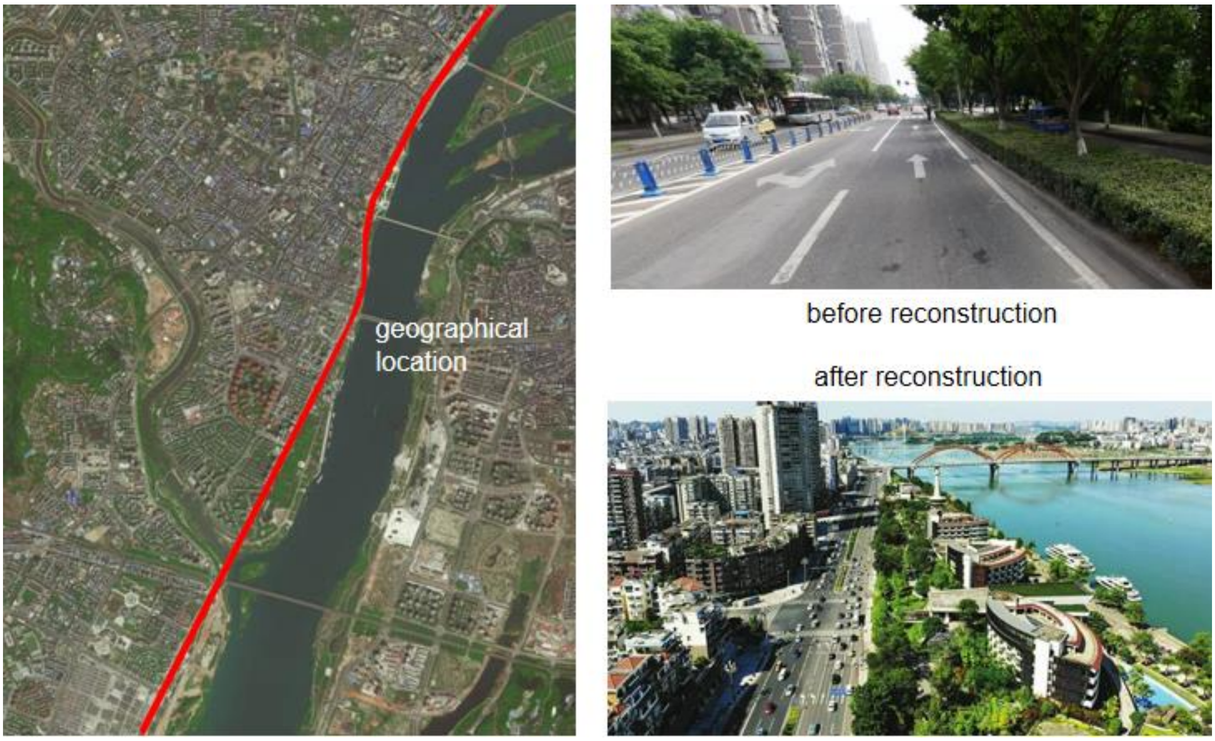


Figure 11 - Geographical location (Google Earth) and comparison of Binjiang road reconstruction

The questionnaire composition of Binjiang Road is very similar to that of Geely Road. A total of 200 questionnaires were sent out and 122 were returned, as shown in Figure 12.

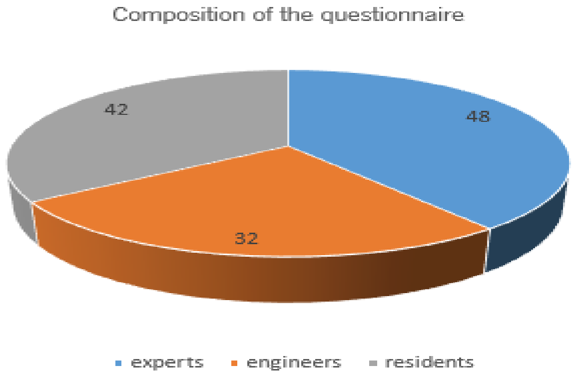


Figure 12 - Composition of questionnaire on Binjiang road

Since Binjiang road has similar environmental conditions to the case study of the road projects of Geely road, but the road is a reconstruction project, the indicator system's secondary indicators have only changed slightly. Model testing (Equations 41 to 44) is based on expert consultation and relevant environmental data, while the indicator system and relative weights are the same used in Geely road.

- Establishment composite matter-elements of environmental impact for primary indicators

$$R_1 = \begin{bmatrix} C_{11} & 25 \\ C_{12} & 50 \\ C_{13} & 30 \\ C_{14} & 62 \\ C_{15} & 25 \end{bmatrix}; \ R_2 = \begin{bmatrix} C_{21} & 65 \\ C_{22} & 62 \\ C_{23} & 30 \end{bmatrix}; \ R_3 = \begin{bmatrix} C_{31} & 72 \\ C_{32} & 68 \\ C_{33} & 86 \end{bmatrix}; \ R_4 = \begin{bmatrix} C_{41} & 80 \\ C_{42} & 80 \end{bmatrix}; \ R_5 = \begin{bmatrix} C_{51} & 65 \\ C_{52} & 62 \\ C_{53} & 66 \end{bmatrix} \quad (41)$$

- Establishment of fuzzy composite matter-element for the environmental impact

$$R_{515} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{11} & 0 & 0 & 0 & 0.25 & 0.75 \\ C_{12} & 0 & 0 & 0.5 & 0.5 & 0 \\ C_{13} & 0 & 0 & 0 & 0.5 & 0.5 \\ C_{14} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{15} & 0 & 0 & 0 & 0.25 & 0.75 \end{bmatrix}; \ R_{523} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{21} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{22} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{23} & 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix};$$

$$R_{533} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{31} & 0 & 0.6 & 0.4 & 0 & 0 \\ C_{32} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{33} & 0.3 & 0.7 & 0 & 0 & 0 \end{bmatrix}; \ R_{542} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{41} & 0 & 1 & 0 & 0 & 0 \\ C_{42} & 0 & 1 & 0 & 0 & 0 \end{bmatrix}; \quad (42)$$

$$R_{553} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{51} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{52} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{53} & 0 & 0.3 & 0.7 & 0 & 0 \end{bmatrix}$$

- Establishment of centralized fuzzy composite matter-element for the environmental impact

$$R_b = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} = \left[\begin{array}{ccccc} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.0100 & 0.1900 & 0.3125 & 0.4875 \\ 0 & 0.1155 & 0.5445 & 0.1650 & 0.1650 \\ 0.0690 & 0.5510 & 0.3700 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0.2195 & 0.7705 & 0 & 0 \end{array}\right] \tag{43}$$

- Comprehensive assessment for environmental impact

$$\begin{gathered} R_x = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ x_1 & 0 & 0.003 & 0.475 & 0.078 & 0.122 \\ x_2 & 0 & 0.035 & 0.163 & 0.050 & 0.050 \\ x_3 & 0.069 & 0.110 & 0.074 & 0 & 0 \\ x_4 & 0 & 0.150 & 0 & 0 & 0 \\ x_5 & 0 & 0.220 & 0.771 & 0 & 0 \end{array}\right]; \\ R_d = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_1 & 0.028 & 0.064 & 0.072 & 0.026 & 0.034 \\ d_2 & 0.014 & 0.150 & 0.163 & 0.078 & 0.122 \\ d_3 & 0 & 0.003 & 0 & 0 & 0 \end{array}\right]; \\ R_D = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_j & 0.006 & 0.072 & 0.079 & 0.035 & 0.052 \end{array}\right] \end{gathered} \tag{44}$$

The results of the comprehensive evaluation show that $d_{max} = d_3$, and the status of the evaluation level M_3 corresponding to d_3 reveals that this road construction has almost no impact on the environment.

3.3.2. Rural road (Huatong road: an existing road)

Huatong road (Figure 13) starts from Xihua Avenue in Shunqing District in the south and reaches Tongren Village in the north. It runs countercurrent along the Xihe River, with a total length of 18.5 kilometres, a width of 7.5 meters with two lanes in both directions. It uses ordinary asphalt concrete pavement and has unorganized drainage. The design speed is 30 kilometres per hour. Huatong Road connects Huafeng Town, Xinfu Village and Tongren Village. Along the way, there are Chinese medicinal material bases, sericulture bases, pear orchards, maple leaf forests, and tourist landscapes such as Sifangzhai, Qipingzhai, Xihe Tourist Corridor and Xishan Scenic Area. Before the road construction, residents along the way can only detour in and out of the urban area. After the road is completed, the travel time would be shortened from 50 minutes to about 20 minutes. It dramatically facilitates residents' travel along the route and promotes rural tourism and economic development.

Huatong Road is a rural road that passes through many villages and residential areas along the way. The terrain is generally flat, vegetation is rich, wildlife is scarce, and there are no tunnels and large-scale bridges along the way. Other conditions such as geology and climate are similar to those of urban area.

Figure 13 - Geographical location (Google Earth) and detail of Huatong road

Since Huatong road goes into the rural areas from the edge of the urban area, the environmental impact on road construction has some differences from urban areas, mainly related to the ecological environment. Thus, the indicator system needed to be adjusted (Table 17).

Table 17 - The indicator system of environmental impact of Huatong road construction project

target layer	primary indicators	secondary indicators
The indicator system of environmental impact assessment of urban roads construction project	social environment (B1)	impacts on communities and their economic activity (C11)
		impacts arising from land acquisition and resettlement (C12)
		impacts on employment (C13)
		impacts on road safety (C14)
		impacts on transportation (C15)
	ecological environment (B2)	impacts on vegetation (C21)
		impacts on soil erosion (C22)
		impacts on aesthetics and landscape (C23)
		impacts on wild animals (C24)
	atmospheric environment (B3)	impacts on NO2 (C31)
		impacts on CO (C32)
		impacts on TSP (C33)
	acoustic environment (B4)	noise during road construction (C41)
		noise during road operation (C42)
	water environment (B5)	impacts on BOD (C51)
		impacts on PH (C52)
		impacts from petroleum substances (C53)

Equations 45 to 48 present the model testing for Huatong road based on expert consultation and relevant environmental data.

The composition of Huatong Road's questionnaire is shown in Figure 14.

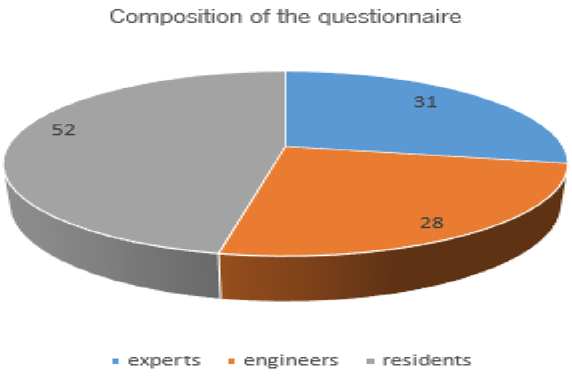


Figure 14 - Composition of questionnaire on Binjiang road

- Establishment composite matter-elements of environmental impact for primary indicators

$$R_1=\begin{bmatrix}C_{11} & 25\\ C_{12} & 65\\ C_{13} & 30\\ C_{14} & 62\\ C_{15} & 20\end{bmatrix};\ R_2=\begin{bmatrix}C_{21} & 70\\ C_{22} & 66\\ C_{23} & 45\\ C_{24} & 70\end{bmatrix};\ R_3=\begin{bmatrix}C_{31} & 65\\ C_{32} & 62\\ C_{33} & 68\end{bmatrix};\ R_4=\begin{bmatrix}C_{41} & 68\\ C_{42} & 70\end{bmatrix};\ R_5=\begin{bmatrix}C_{51} & 63\\ C_{52} & 62\\ C_{53} & 64\end{bmatrix} \quad (45)$$

- Establishment of fuzzy composite matter-element for the environmental impact

$$R_{515}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{11} & 0 & 0 & 0 & 0.25 & 0.75 \\ C_{12} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{13} & 0 & 0 & 0 & 0.5 & 0.5 \\ C_{14} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{15} & 0 & 0 & 0 & 0 & 1 \end{bmatrix};\ R_{524}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{21} & 0 & 0.5 & 0.5 & 0 & 0 \\ C_{22} & 0 & 0.3 & 0.7 & 0 & 0 \\ C_{23} & 0 & 0 & 0.25 & 0.75 & 0 \\ C_{24} & 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix};$$

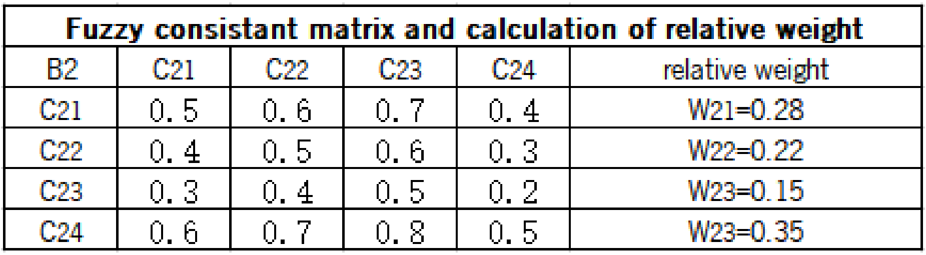
$$R_{533}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{31} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{32} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{33} & 0 & 0.4 & 0.6 & 0 & 0 \end{bmatrix};\ R_{542}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{41} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{42} & 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}; \tag{46}$$

$$R_{553}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{51} & 0 & 0.15 & 0.85 & 0 & 0 \\ C_{52} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{53} & 0 & 0.2 & 0.8 & 0 & 0 \end{bmatrix}$$

- Establishment of weight composite matter-element for the environmental impact

Because Huatong road adjusted the secondary indicators in the indicator system's ecological environment, it is necessary to recalculate its relative weights, presented in Table 18. The relative weights of the primary indicators and the remaining secondary indicators refer to the case study's weight data.

Table 18 - Fuzzy consistent matrix and calculation of relative weight for indicators of Huatong road construction project



Fuzzy consistant matrix and calculation of relative weight					
B2	C21	C22	C23	C24	relative weight
C21	0. 5	0. 6	0. 7	0. 4	W21=0.28
C22	0. 4	0. 5	0. 6	0. 3	W22=0.22
C23	0. 3	0. 4	0. 5	0. 2	W23=0.15
C24	0. 6	0. 7	0. 8	0. 5	W23=0.35

- Establishment of centralized fuzzy composite matter-element for the environmental impact

$$R_b = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.0600 & 0.2400 & 0.1500 & 0.5500 \\ 0 & 0.3810 & 0.5065 & 0.1125 & 0 \\ 0 & 0.2325 & 0.7575 & 0 & 0 \\ 0 & 0.4700 & 0.5300 & 0 & 0 \\ 0 & 0.1535 & 0.8365 & 0 & 0 \end{bmatrix} \tag{47}$$

- Comprehensive assessment for environmental impact

$$R_x = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ x_1 & 0 & 0.002 & 0.060 & 0.038 & 0.138 \\ x_2 & 0 & 0.114 & 0.152 & 0.034 & 0 \\ x_3 & 0 & 0.047 & 0.152 & 0 & 0 \\ x_4 & 0 & 0.075 & 0.080 & 0 & 0 \\ x_5 & 0 & 0.015 & 0.084 & 0 & 0 \end{array}\right];$$

$$R_d = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_1 & 0 & 0.050 & 0.105 & 0.014 & 0.028 \\ d_2 & 0 & 0.114 & 0.152 & 0.038 & 0.138 \\ d_3 & 0 & 0.002 & 0.060 & 0 & 0 \end{array}\right]; \tag{48}$$

$$R_D = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_j & 0 & 0.055 & 0.106 & 0.017 & 0.055 \end{array}\right]$$

From the results of the comprehensive evaluation previously presented it can be seen that $d_{max} = d_3$, and the status of the evaluation level M_3 corresponding to d_3 show that this road construction has almost no impact on the environment.

3.3.3. Mountain road (S304 - Jincheng Section: an existing road)

Jincheng Town is located in the northeast of Nanchong City. Most of the territory is in the low mountains and valleys. The ground elevation is generally 520 to 650 meters above sea level, and the highest point is 744 meters above sea level. The town has a total population of 178,080 people and is rich in oil and gas resources. S304 is a provincial road with a secondary road with a width of 8.5 meters and two-lane in both directions. The road first used cement concrete pavement. After decades of operation, the pavement presented extensive damage.

The government has widened the road width and changed the original cement concrete pavement into a modified asphalt concrete pavement to meet the demand for roads in the new era without implementing organized drainage. As the Jincheng town is located at the top of the small valley, it has brought great difficulties in constructing the road.

Many heavy vehicles and curves on the mountain road led to frequent traffic accidents and natural disasters, and the road S304 in Jincheng section (Figure 15) are often renovated and maintained to minimize those problems.

Figure 15 - Geographical location (Google Earth) and detail of S304 - Jincheng Section

Equations 49 to 52 present the model testing based on expert consultation and relevant environmental data for this new location at S304 - Jincheng Section. The indicator system and relative weight are consistent with those of Huatong road.

Due to the remoteness of S304-Jincheng Section and scattered personnel, the questionnaire survey is very difficult. In the same way, 200 questionnaires were sent out, but only 103 copies were returned and available. The composition of the questionnaire is very different from that of urban roads. See Figure 16 for details.

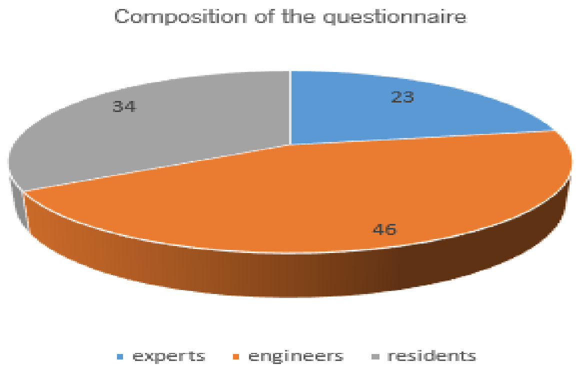


Figure 16 - Composition of questionnaire on S304 - Jincheng Section

- Establishment composite matter-elements of environmental impact for primary indicators

$$R_1 = \begin{bmatrix} C_{11} & 25 \\ C_{12} & 65 \\ C_{13} & 30 \\ C_{14} & 75 \\ C_{15} & 20 \end{bmatrix};\ R_2 = \begin{bmatrix} C_{21} & 75 \\ C_{22} & 80 \\ C_{23} & 45 \\ C_{24} & 75 \end{bmatrix};\ R_3 = \begin{bmatrix} C_{31} & 65 \\ C_{32} & 62 \\ C_{33} & 68 \end{bmatrix};\ R_4 = \begin{bmatrix} C_{41} & 68 \\ C_{42} & 70 \end{bmatrix};\ R_5 = \begin{bmatrix} C_{51} & 63 \\ C_{52} & 62 \\ C_{53} & 64 \end{bmatrix} \quad (49)$$

- Establishment of fuzzy composite matter-element for the environmental impact

$$R_{515} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{11} & 0 & 0 & 0 & 0.25 & 0.75 \\ C_{12} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{13} & 0 & 0 & 0 & 0.5 & 0.5 \\ C_{14} & 0 & 0.75 & 0.25 & 0 & 0 \\ C_{15} & 0 & 0 & 0 & 0 & 1 \end{array}\right];\ R_{524} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{21} & 0 & 0.75 & 0.25 & 0 & 0 \\ C_{22} & 0 & 1 & 0 & 0 & 0 \\ C_{23} & 0 & 0 & 0.25 & 0.75 & 0 \\ C_{24} & 0 & 0.75 & 0.25 & 0 & 0 \end{array}\right]; \quad (50)$$

$$R_{533} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{31} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{32} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{33} & 0 & 0.4 & 0.6 & 0 & 0 \end{array}\right];\ R_{542} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{41} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{42} & 0 & 0.5 & 0.5 & 0 & 0 \end{array}\right];$$

$$R_{553} = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{51} & 0 & 0.15 & 0.85 & 0 & 0 \\ C_{52} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{53} & 0 & 0.2 & 0.8 & 0 & 0 \end{array}\right]$$

- Establishment of centralized fuzzy composite matter-element for the environmental impact

$$R_b = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} = \left[\begin{array}{ccccc} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.1250 & 0.1750 & 0.1500 & 0.5500 \\ 0 & 0.6925 & 0.1950 & 0.1125 & 0 \\ 0 & 0.2325 & 0.7575 & 0 & 0 \\ 0 & 0.4700 & 0.5300 & 0 & 0 \\ 0 & 0.1535 & 0.8365 & 0 & 0 \end{array}\right] \tag{51}$$

- Comprehensive assessment for environmental impact

$$R_x = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ x_1 & 0 & 0.031 & 0.044 & 0.038 & 0.138 \\ x_2 & 0 & 0.208 & 0.059 & 0.034 & 0 \\ x_3 & 0 & 0.047 & 0.152 & 0 & 0 \\ x_4 & 0 & 0.075 & 0.080 & 0 & 0 \\ x_5 & 0 & 0.015 & 0.084 & 0 & 0 \end{array}\right];$$

$$R_d = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_1 & 0 & 0.074 & 0.083 & 0.014 & 0.028 \\ d_2 & 0 & 0.208 & 0.152 & 0.038 & 0.138 \\ d_3 & 0 & 0.002 & 0.044 & 0 & 0 \end{array}\right]; \tag{52}$$

$$R_D = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_j & 0 & 0.099 & 0.093 & 0.017 & 0.055 \end{array}\right]$$

It can be seen from the results of the comprehensive evaluation that $d_{max} = d_2$, and the status of the evaluation level M_2 corresponding to d_2 shows that this road construction harms the environment, but the impact is small.

3.3.4. Ring Expressway (G4201: an existing road)

Nanchong Ring Expressway (Figure 17) is 42 kilometres long, 24.5 meters wide, four lanes in both directions, and uses SMA concrete pavement due to its high rutting resistance, good temperature stability, good crack resistance and durability, which can well meet the traffic demand and driving safety. The design speed of the expressway is 80 kilometres per hour.

The Ring Expressway locates around the urban-rural junction and surrounds the main urban area. It has the dual attributes of the expressway and municipal roads. The road mainly runs through hilly areas, passes through a few mountains and river canyons, and sets a few tunnels and bridges along the way. The intersections of roads and densely populated areas are set up with noise barriers and protective forest barriers to reduce noise and ensure safety. More slope protection and planting vegetation are installed in mountainous areas to maintain water and soil balance and prevent disasters.

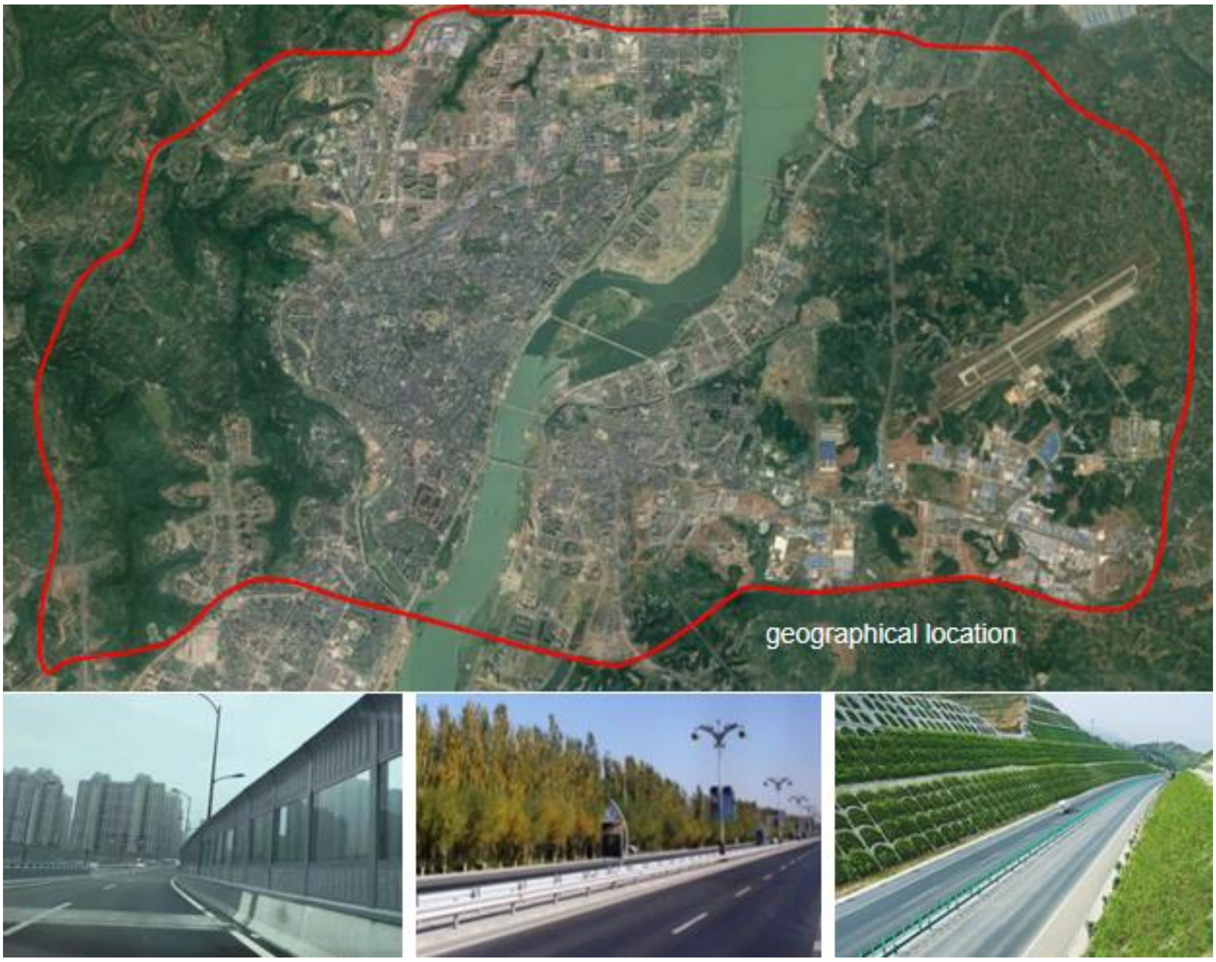


Figure 17 - Geographical location (Google Earth) and detail of Ring Expressway

200 questionnaires were sent out and returned 114 copies. The composition of the questionnaire is shown in Figure 18.

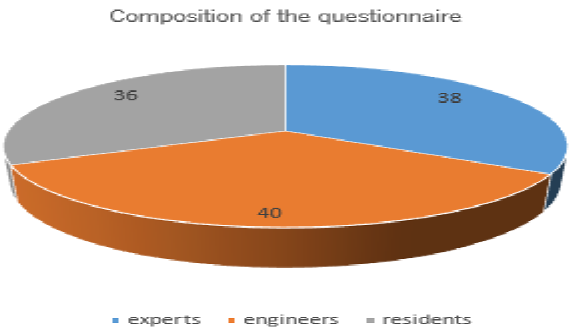


Figure 18 - Composition of questionnaire on Ring Expressway

Equations 53 to 56 present the model testing based on expert consultation and relevant environmental data. The indicator system and relative weight are consistent with those of Huatong road.

- Establishment composite matter-elements of environmental impact for primary indicators

$$R_1 = \begin{bmatrix} C_{11} & 25 \\ C_{12} & 82 \\ C_{13} & 30 \\ C_{14} & 62 \\ C_{15} & 20 \end{bmatrix}; R_2 = \begin{bmatrix} C_{21} & 75 \\ C_{22} & 65 \\ C_{23} & 45 \\ C_{24} & 70 \end{bmatrix}; R_3 = \begin{bmatrix} C_{31} & 65 \\ C_{32} & 62 \\ C_{33} & 68 \end{bmatrix}; R_4 = \begin{bmatrix} C_{41} & 68 \\ C_{42} & 70 \end{bmatrix}; R_5 = \begin{bmatrix} C_{51} & 63 \\ C_{52} & 62 \\ C_{53} & 64 \end{bmatrix} \tag{53}$$

- Establishment of fuzzy composite matter-element for the environmental impact

$$R_{515} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{11} & 0 & 0 & 0 & 0.25 & 0.75 \\ C_{12} & 0.1 & 0.9 & 0 & 0 & 0 \\ C_{13} & 0 & 0 & 0 & 0.5 & 0.5 \\ C_{14} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{15} & 0 & 0 & 0 & 0 & 1 \end{bmatrix}; R_{524} = \begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{21} & 0 & 0.75 & 0.25 & 0 & 0 \\ C_{22} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{23} & 0 & 0 & 0.25 & 0.75 & 0 \\ C_{24} & 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}; \tag{54}$$

$$R_{533}=\left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{31} & 0 & 0.25 & 0.75 & 0 & 0 \\ C_{32} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{33} & 0 & 0.4 & 0.6 & 0 & 0 \end{array}\right];\ R_{542}=\left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{41} & 0 & 0.4 & 0.6 & 0 & 0 \\ C_{42} & 0 & 0.5 & 0.5 & 0 & 0 \end{array}\right];$$

$$R_{553}=\left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ C_{51} & 0 & 0.15 & 0.85 & 0 & 0 \\ C_{52} & 0 & 0.1 & 0.9 & 0 & 0 \\ C_{53} & 0 & 0.2 & 0.8 & 0 & 0 \end{array}\right]$$

- Establishment of centralized fuzzy composite matter-element for the environmental impact

$$R_b=\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix}=\left[\begin{array}{ccccc} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.0200 & 0.1900 & 0.0900 & 0.1500 & 0.5500 \\ 0 & 0.4400 & 0.4475 & 0.1125 & 0 \\ 0 & 0.2325 & 0.7575 & 0 & 0 \\ 0 & 0.4700 & 0.5300 & 0 & 0 \\ 0 & 0.1535 & 0.8365 & 0 & 0 \end{array}\right] \tag{55}$$

- Comprehensive assessment for environmental impact

$$R_x=\left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ x_1 & 0.005 & 0.048 & 0.023 & 0.038 & 0.138 \\ x_2 & 0 & 0.132 & 0.134 & 0.034 & 0 \\ x_3 & 0 & 0.047 & 0.152 & 0 & 0 \\ x_4 & 0 & 0.075 & 0.080 & 0 & 0 \\ x_5 & 0 & 0.015 & 0.084 & 0 & 0 \end{array}\right]; \tag{56}$$

$$R_d=\left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_1 & 0.001 & 0.062 & 0.094 & 0.014 & 0.028 \\ d_2 & 0.005 & 0.132 & 0.152 & 0.038 & 0.138 \\ d_3 & 0 & 0.015 & 0.023 & 0 & 0 \end{array}\right];$$

$$R_D = \left[\begin{array}{cccccc} & M_1 & M_2 & M_3 & M_4 & M_5 \\ d_j & 0.002 & 0.070 & 0.089 & 0.017 & 0.055 \end{array}\right]$$

From the results of the comprehensive evaluation, it can be seen that $d_{max} = d_3$. The status of the evaluation level M_3 corresponding to d_3 shows that this road construction has almost no impact on the environment.

4. RESULTS ANALYSIS

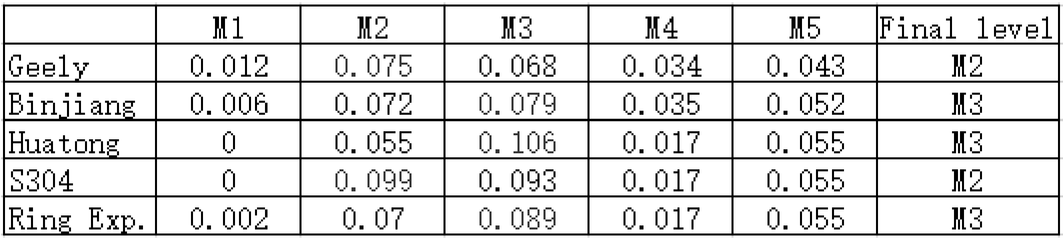
4.1. Environmental impact of urban roads construction

The environmental impact of urban roads construction mainly includes the positive impacts, the negative impacts and no impact. According to the partition of assessing level (Table 8), the impact was divided into five levels. M_1 represents that road construction harms the surrounding environment, and the impact is great. M_2 represents that road construction harms the surrounding environment, and the impact is small. M_3 represents that road construction has almost no impact on the surrounding environment. M_4 represents that road construction has a positive impact on the surrounding environment, and the impact is small. M_5 represents that road construction has a positive impact on the surrounding environment, and the impact is great.

4.1.1. Overall impact

From the five urban roads studied (Table 19), it is possible to analyze and find that the environmental impact of urban roads construction is generally negative, but the impact is minimal (M_2). Although the comprehensive evaluation of the environmental impact of urban roads construction shows that it has no impact on the environment and is at M_3 level, its value is infinitely close to M_2, which means that even small errors in the road construction process will cause a negative environmental impact.

Table 19 - The overall environmental impact level of urban roads construction



	M1	M2	M3	M4	M5	Final level
Geely	0.012	0.075	0.068	0.034	0.043	M2
Binjiang	0.006	0.072	0.079	0.035	0.052	M3
Huatong	0	0.055	0.106	0.017	0.055	M3
S304	0	0.099	0.093	0.017	0.055	M2
Ring Exp.	0.002	0.07	0.089	0.017	0.055	M3

4.1.2. Positive impacts

Urban roads link urban residents in commercial areas, public places, residential areas, and other urban functional places. They determine the convenience and efficiency of people's work, study, and life, and are also an essential channel for township residents to connect to other urban areas. The construction of urban roads has dramatically improved the urban transportation network. It is the primary condition for ensuring transportation for economic development, the basis for satisfying residents' travel, and the key to improving resource utilisation efficiency. Simultaneously, urban road construction will increase a large number of employment opportunities and ensure social stability. Therefore, urban road construction's positive impact is mainly reflected in the social environment's impact (Figure 19).

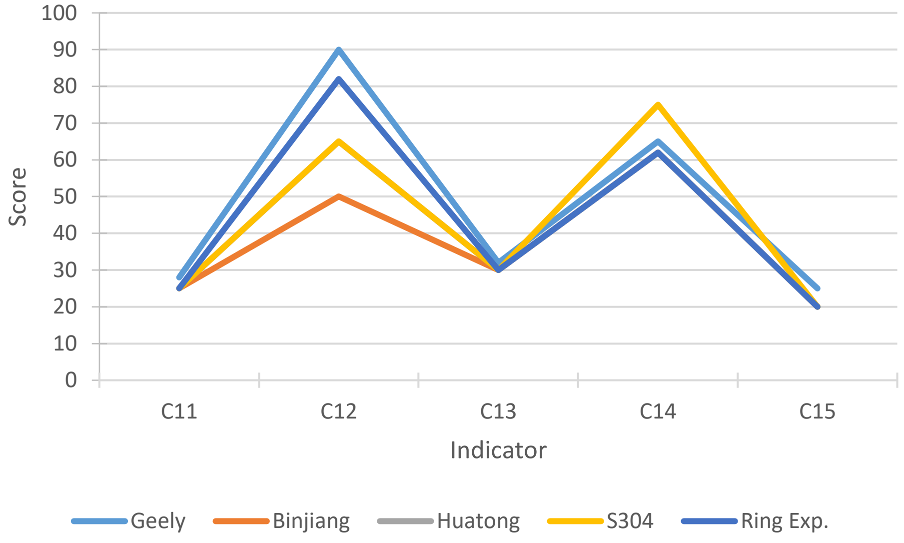


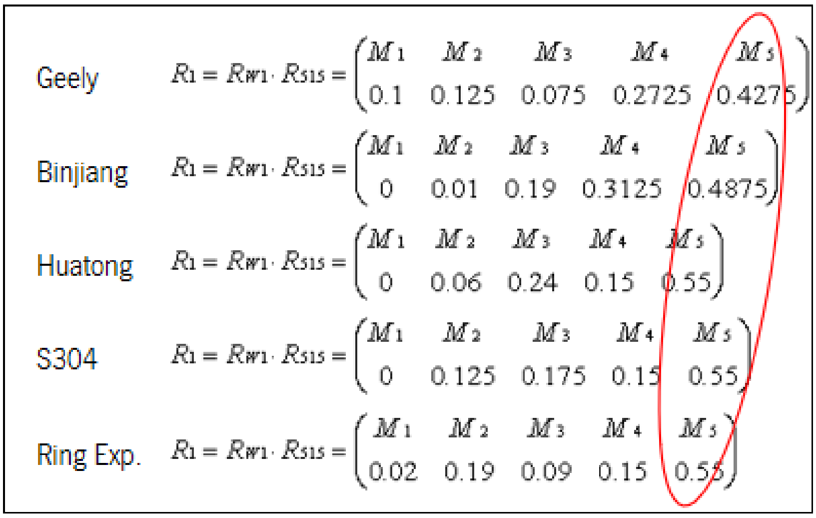
Figure 9 - Secondary index score of social-environmental impact

From the secondary index score of the social-environmental impact, it can be concluded that:

i) The positive environmental impact of urban roads construction is mainly reflected in the impacts on communities and their economic activities (C_{11}), impacts on employment (C_{13}), and impacts on transportation (C_{15}), especially in residents 'activities and transportation. The negative impacts mainly include impacts arising from land acquisition and resettlement (C_{12}) and impacts on road safety (C_{14}), and their impacts on different roads vary wildly, mainly because the road environment is different and the positive measures taken are also inconsistent ;

ii) According to the curve drawn by the scores, the secondary urban indicators of the five urban roads studied on the social environment have the same trend, just the scores are different, indicating that the road construction has a consistent impact on the social environmental factors and trends, but the degree of influence is different.

iii) Observing Figure 20, it can be seen that the most comprehensive impact level of the five urban roads construction on the social environment is in M_5. The status of the evaluation level M_5 in road construction shows that its positive impact is more significant on the surrounding environment.



Geely $R_1 = R_{W1} \cdot R_{515} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.1 & 0.125 & 0.075 & 0.2725 & 0.4275 \end{pmatrix}$

Binjiang $R_1 = R_{W1} \cdot R_{515} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.01 & 0.19 & 0.3125 & 0.4875 \end{pmatrix}$

Huatong $R_1 = R_{W1} \cdot R_{515} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.06 & 0.24 & 0.15 & 0.55 \end{pmatrix}$

S304 $R_1 = R_{W1} \cdot R_{515} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0 & 0.125 & 0.175 & 0.15 & 0.55 \end{pmatrix}$

Ring Exp. $R_1 = R_{W1} \cdot R_{515} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 & M_5 \\ 0.02 & 0.19 & 0.09 & 0.15 & 0.55 \end{pmatrix}$

Figure 10 - Comprehensive impact of the social environment

It shows that although road construction has some negative impacts on some secondary indicators of social environmental impact, overall road construction has a tremendous positive impact on the social environment. It also reflexes the significance of urban roads construction.

4.1.3. Negative impacts

Judging from the indicators of the environmental impact assessment system of the five urban roads construction studied, the negative environmental impacts of urban roads construction are far-reaching, involving all the primary environmental indicators (Figure 21) and most of the secondary environment indicators (Figure 22), except the positive impact factors in the social-environmental indicators.

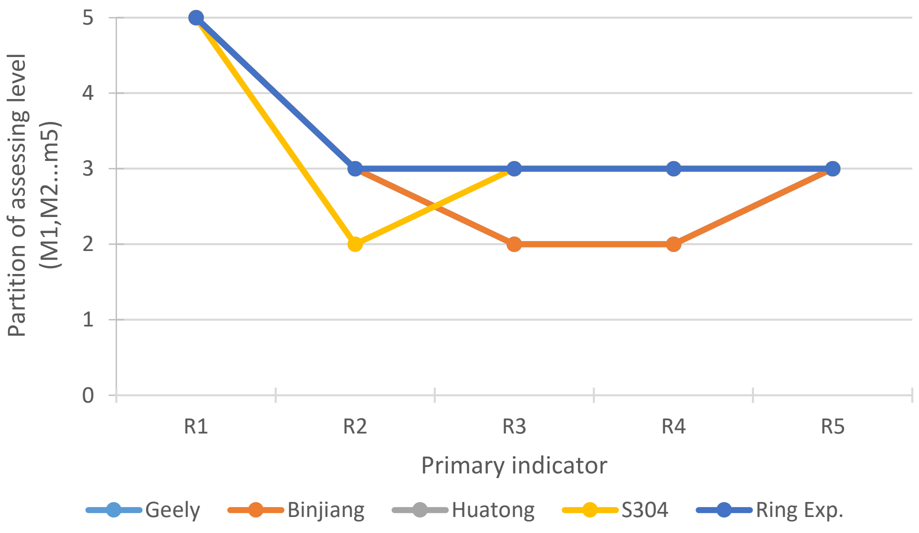


Figure 21 - Environmental impact assessment of the primary indicators

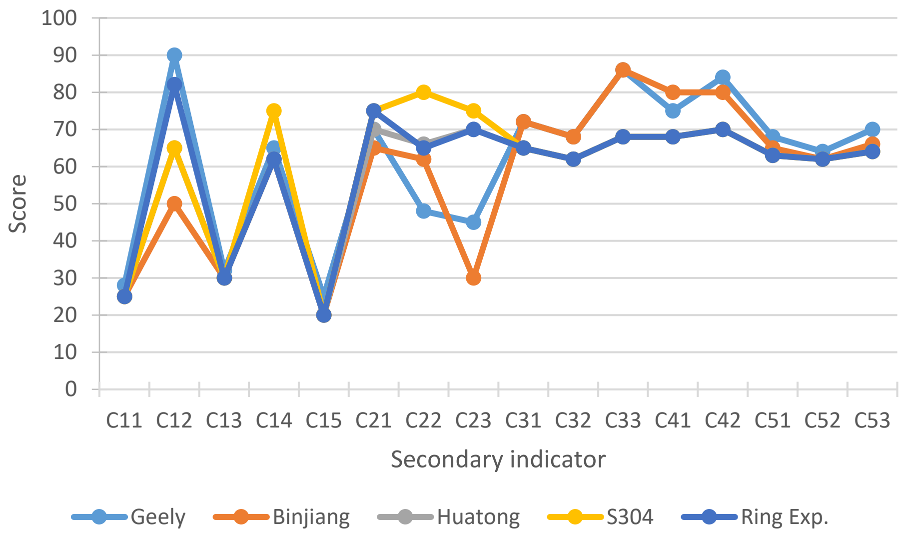


Figure 22 - Score of the EIA secondary indicators

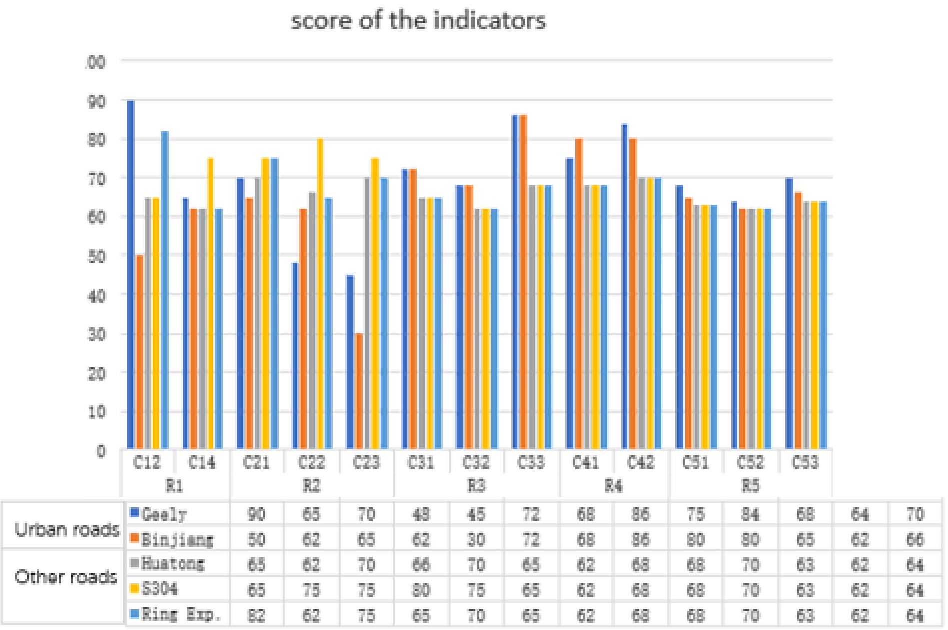
This observation is also the main reason leading to the negative impact of road construction on the comprehensive environmental assessment, which requires adequate road construction measures to eliminate or reduce the negative impact on the environment and meet environmental assessment requirements.

4.2. Environmental impact of roads construction in different urban conditions

Road construction with different conditions (e.g., geographic location, geology, hydrology, climate) has very different environmental impacts. The five roads studied in this work were divided into four categories according to the geographical conditions, including urban roads, suburban roads, rural roads, and mountain roads. The road's positive impact is always reflected in the social environment's impact, such as improving transportation efficiency, increasing employment opportunities, and promoting economic development. The influence trend of almost all roads is similar, but the degree is different. Therefore, the negative environmental impacts of road construction will be discussed in more detail.

4.2.1. Urban roads

As the densest and most important part of the road network, urban roads construction has a significant impact on the environment. Geely Road is a newly built urban road that mainly radiates transportation in the industrial park, while Binjiang Road is a rebuilt urban trunk road and the backbone of urban transportation. Nevertheless, the EIA of all roads studied is first compared in Figure 23.



		C12	C14	C21	C22	C23	C31	C32	C33	C41	C42	C51	C52	C53
Urban roads	■ Geely	90	65	70	48	45	72	68	86	75	84	68	64	70
	■ Binjiang	50	62	65	62	30	72	68	86	80	80	65	62	66
Other roads	■ Huatong	65	62	70	66	70	65	62	68	68	70	63	62	64
	■ S304	65	75	75	80	75	65	62	68	68	70	63	62	64
	■ Ring Exp.	82	62	75	65	70	65	62	68	68	70	63	62	64

Figure 11 - Comparison of urban roads and roads in other conditions

The following conclusions were drawn by comparing the construction impacts on the environment of all roads evaluated:

i) Urban road planning is essential to meet most people's needs, connecting as many public places as possible. Road paths' requirements will inevitably bring about large-scale demolition and resettlement and will cause significant social impact. Dense urban population and a large amount of traffic flow in road operations, and road safety, will also become a social concern.

ii) The urban ecological environment is an artificial ecological environment and a non-self-sufficient ecological environment that requires many resources. The construction of urban roads will occupy many land resources and occupy the living space of vegetation.

iii) From the perspective of urban atmospheric environment, road operation, and a large amount of motor vehicle exhaust have become the primary source of urban air pollution, which seriously threatens human health. Road dust is also one of the factors of air pollution near the sides of roads. Compared with road construction under other conditions, the atmospheric pollution caused by urban road construction is more severe due to lack of sufficient space for dilution and lack of absorption and transformation of vegetation.

iv) The urban traffic system is the primary pollution of the urban acoustic environment, especially during peak traffic, when the peak traffic area's noise exceeds 80 decibels. Urban road construction requires a tight construction period, a high degree of mechanization, multiple construction sections simultaneously, because urban traffic flow is more affected during construction than in other roads' conditions. By comparison, it is found that the noise pollution of urban road construction and operation phases is much greater than other conditions of roads.

v) The hardening of urban roads prevents soil erosion and loss, but intensifies water resources loss, especially during the rainy season, and road path flow will cause significant pollution to urban water resources.

Then, the comparison was restricted to two urban roads. As Geely road and Binjiang road are urban roads, road construction's environmental impact is more or less the same (Figure 24).

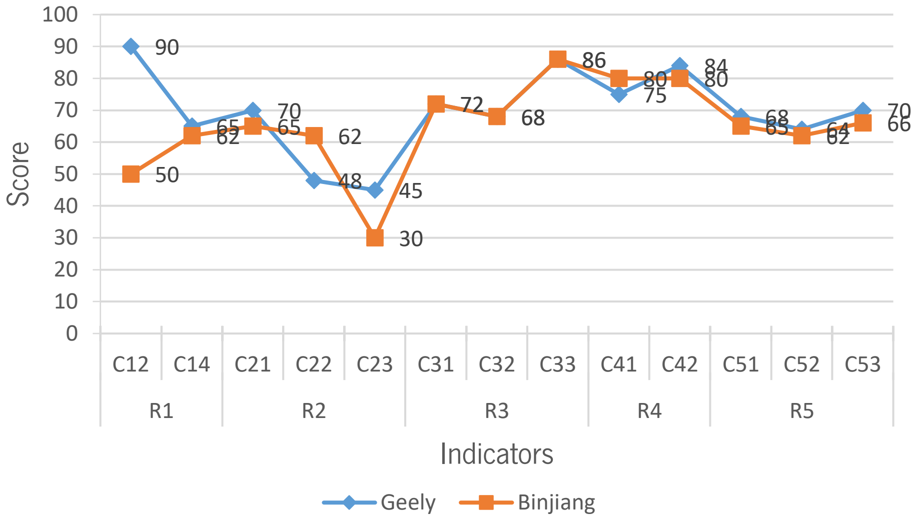


Figure 12 - Comparison of new urban road and an urban road reconstruction

However, there are still some differences between the two urban roads evaluated, mainly because one is a newly constructed urban road, and the other is a rebuilt urban road:

i) Road reconstruction is based on the original road, re-planning the original road construction, so it will not occupy much land, and does not involve demolition and resettlement. Due to road reconstruction, traffic congestion will be caused, which is temporarily not conducive to travel. New roads need to occupy many land resources, involving the demolition and resettlement of residents along the road, impacting society.

ii) From the ecological environment perspective, land use by new urban roads will destroy vegetation, more or less, and the reconstruction roads are built based on the original urban roads, with less vegetation damage. The urban new roads and reconstruction roads will use organized drainage and have little impact on soil erosion. According to the grade and status of urban roads, road aesthetics and landscapes are somewhat different. Binjiang Road, which is an urban distributor road, have a better assessment of aesthetics and landscapes.

iii) As an area with an enormous traffic flow and the highest population density, urban roads are the most sensitive to atmospheric and acoustic pollution. Both the atmosphere and noise generated during construction or operation have a more significant impact on the environment than road construction under other conditions.

iv) Urban roads usually use organized drainage systems, and many new sponge systems have been built. Most pavements use asphalt concrete pavements with better drainage, so their negative impact on the water environment is reduced.

4.2.2. Rural roads

Rural roads are an essential channel connecting cities to the countryside. As an essential part of the road network, it is an excellent convenience to develop the rural economy and people's travel. However, rural roads' construction also brings a series of environmental problems, as shown in Figure 25 for a rural road built in Huatong.

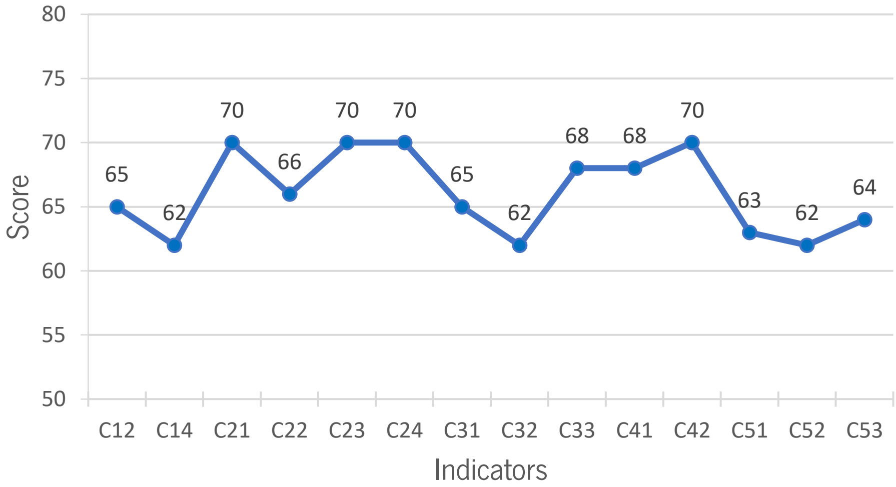


Figure 13 - Environmental impact assessment scores for indicators of Huatong rural road construction

Therefore, it is of great significance to discuss the environmental impact on rural road construction:

i) From the overall view of the environmental impact score of rural road construction, the environmental impact of rural road construction is at the M_2 level, that is, road construction harms the environment, but the impact is small.

ii) During the rural road planning, the road route should avoid new tunnels and bridges as much as possible, and demolish few houses to reduce capital investment. Rural road construction is accompanied by more land encroachment and severe vegetation damage. Since road planning mostly uses unorganized drainage, soil erosion is relatively severe. There are few aesthetic and landscape planning along the road, and road construction destroys the original ecological aesthetics. Road construction affects the living space and environment of wild animals along the way. Compared with urban roads' construction, rural roads' construction has caused more significant damage to the ecological environment.

iii) Due to the vast rural area, lush vegetation, small traffic flow, and scattered population, the sensitivity of villages to air and noise pollution is significantly reduced compared to cities, so the impact of road construction on the atmospheric and acoustic environment is relatively small.

iv) Rural roads use an unorganized drainage system, and rainwater penetrates groundwater or nearby rivers through the soil near the roadside. Most of the roads are graded using ordinary asphalt concrete with lower grades and have no drainage and noise reduction functions. Therefore, rural road construction will have a small negative impact on the water environment along the road.

4.2.3. Mountain roads

Mountain roads and country roads are similar, and there are many similarities in their environmental impact. The main difference is related to geological conditions (Figure 26).

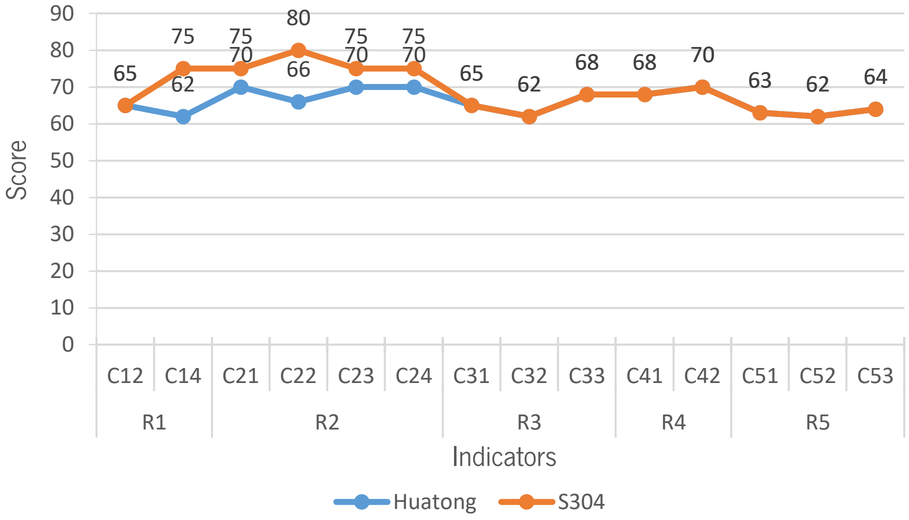


Figure 14 - Environmental impact comparison between rural and mountain roads

From the graphical comparison of the environmental impact of a mountain and rural road construction, it was possible to find:

i) The impact of the mountain road and rural road construction on the environment similar, and the main differences reflect the degree of impact on the social and ecological environment.

ii) In terms of the social environment, due to the limitation of geological conditions of mountain roads, a large number of steep slopes and bends will appear, which is where road safety accidents occur intensively.

iii) In terms of ecological environment, due to the unique geological conditions of mountain roads, geological disasters are very prone to occur during the rainy season, causing soil erosion and affecting road safety. The construction of mountain roads destroys vegetation, changes the mountains' original ecological aesthetics and landscape, and causes severe damage to the ecological environment.

4.2.4. Suburban roads

The suburbs are the fringe areas of urban areas, and they are the junction of urban areas and rural areas. They have the comprehensive characteristics of urban areas and rural areas. Suburban roads have a large geographic space, where vegetation, wildlife, landscapes, and other ecological environments may be features that positively impact road construction. They have good ability to diffuse atmospheric and noise pollution and have strong self-recovery capabilities. Therefore, suburban road construction's environmental impact is between urban and rural roads (Figure 27).

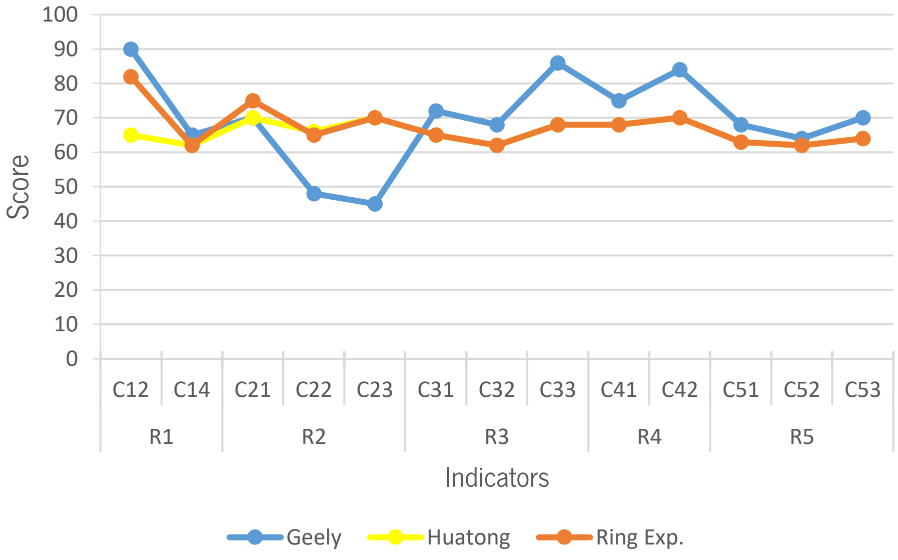


Figure 15 - Environmental impact on suburban roads

Nevertheless, the negative impact of suburban road construction on the social environment is more significant than that of urban roads, and the damage to the ecological environment is more significant than that of urban roads.

4.3. Environmental impact after using impact reduction methods

The environment is a space where humans and living beings live. According to the assessment and analysis of the impact on the environment of multiple road constructions, it can be concluded that road construction generally harms the environment. Therefore, it is necessary to carry out an environmental impact assessment of road construction and take environmental protection measures at various stages to prevent, eliminate or reduce the negative impact of road construction on the environment. It is also the best way to promote the sustainable development of road construction.

4.3.1. Open Graded Friction Courses

Open Graded Friction Course (OGFC) is an intermittent graded asphalt mixture. Its principal function is to improve the pavement's anti-skid ability. Simultaneously, OGFC has good drainage performance and reduces driving noise, and it is also called permeable pavement or low noisy pavement.

The OGFC pavement structure is shown in Figure 28. OGFC is used as the wear layer (surface layer) of asphalt concrete pavement. Its design porosity is generally greater than 18%, and it has strong structural and drainage capacity. Below the OGFC, there is a layer of impervious material. The water passing through the permeable layer flows onto the impervious layer and drains laterally through the drainage system without affecting the base layer and the foundation.

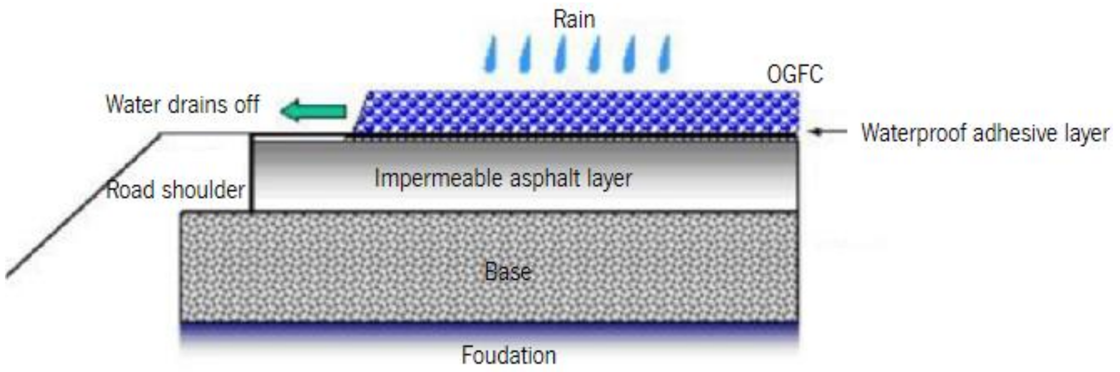
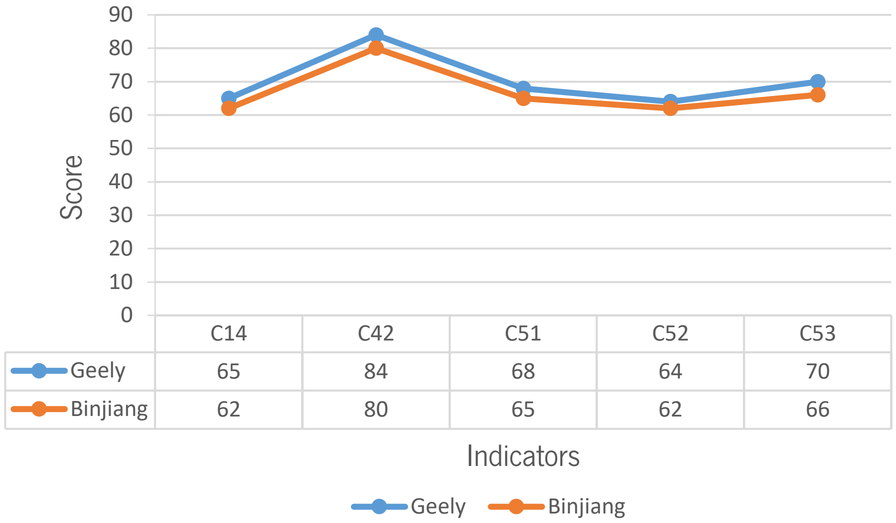


Figure 16 - The structure of Open Graded Friction Course

A comparative analysis of two urban roads using Open Graded Friction Course and Asphalt Concrete impervious pavement solutions is presented in Figure 29. Geely Road has a high demand for heavy-duty trucks on the road and has pavement with a polymer-modified asphalt concrete surface layer, while Binjiang Road is a primary distributor of the city and uses an OGFC pavement structure.



	C14	C42	C51	C52	C53
Geely	65	84	68	64	70
Binjiang	62	80	65	62	66

Figure 17 - Environmental impact of Open Graded Friction Course and Asphalt Concrete pavement

The following conclusions were obtained from environmental impact assessment of those two solutions:

i) The environmental impact of Binjiang Road, using an OGFC pavement, is slightly superior to that of Geely Road, using ordinary polymer-modified asphalt pavement.

ii) In terms of the social environment, OGFC pavement can improve road safety. Because OGFC adopts a large pore structure and has good water permeability, it can improve the road surface's anti-slip ability in rainy days, ensure good contact between tires and the ground, improve the visibility of road surfaces in rainy days and night, and ensure driving safety.

iii) In terms of the acoustic environment, due to the developed pore space of the OGFC pavement, it acts as a porous sound-absorbing material. Simultaneously, the noise generated by air's compression at the bottom of the tire is suppressed by the pore structure's dissipation and plays a role in reducing road noise. Through a large number of experiments and measurement statistics, it is found that it generally can be reduced by 3 decibels. Due to eliminating the water body's noise explosion on rainy days, the noise reduction effect is more prominent, reaching 8 dB.

iv) In terms of water environment, OGFC's super-permeable capacity cooperates with the urban drainage system and sponges, which significantly protects the city's water resources, reduces road runoff, and reduces the pollution of the road construction to the water environment.

OGFC pavement is a kind of high-porosity noise-reducing and permeable pavement. It is an excellent ecological and environmentally-friendly pavement. It can be widely used on urban expressways, urban distributors, and pavements with better environmental conditions. It is suitable for urban road asphalt concrete pavement in rainy areas. However, it is not suitable for road sections with low road environment, more dust and impurities, and low speed and heavy loads.

4.3.2. Sponge system

Sponge city, also known as a water-elastic city, follows ecological priority, combines natural ecological functions with artificial intervention functions and effectively controls rainwater runoff. This solution realizes the urban development model of natural accumulation, a natural penetration, and natural purification conducive to repairing urban aquatic ecology, conserve water resources, enhance urban flood control capabilities, improve the quality of new urbanization, and promote the harmonious development of human and nature.

Urban "sponge" (Figure 30) includes rivers, lakes, ponds and other water systems, as well as urban supporting facilities such as green spaces, gardens, and permeable pavements.

Figure 18 - Sponge system of Binjiang road

The extensive application of the "sponge city" materials shows excellent water penetration, pressure resistance, wear resistance, anti-skid properties, environmental protection, sound absorption and noise reduction. The solution is beautiful and colourful, comfortable, easy to maintain, and effectively alleviates the urban heat island effect so that urban roads no longer generate heat.

In the new era, the sponge city is an innovative idea that promotes green buildings, low-carbon cities, and smart cities' formation. It is an organic combination of modern green new technologies and social, environmental, humanistic and other factors under the new era's characteristics.

As a main urban distributor, Binjiang road has constructed the urban sponge system for ecological and environmental protection. The sponge system mainly includes OGFC permeable pavement, a central landscape isolation zone, sidewalk permeable bricks, green belts on both sides, an artificial lake, Jialing River and an urban rainwater pipe network.

Rainwater and road runoff pass through permeable roads, landscape, green belts, rivers, lakes and other seepage water and water collection systems to accumulate, infiltrate, purify, and enter the urban rainwater pipe network.

From the assessment of the environmental impact of Binjiang road, the road reconstruction combined with a sponge system saves water resources and reduces pollution of the water environment. The sponge system reduces the water on the road pavement and enhances the road surface's anti-skid ability, thereby enhancing road safety. The construction of the central isolation belt and the green belts on both sides enhances the water collection capacity, enriches the urban landscape aesthetics, ensures road safety, and reduces air pollution. The large pores of the permeable pavement and landscape vegetation have strong sound absorption and noise reduction effects, reducing noise pollution.

Generally speaking, urban sponge systems' construction positively impacts the social environment, ecological environment, atmospheric environment, acoustic environment and water environment, and is of great significance to implement sustainable urban development.

4.3.3. Road shelter forest and slope protection

Road shelter-belts (Figure 31) are forest belts planted on both sides of the road. The primary purpose is to ensure road safety, reduce soil erosion, increase landscape aesthetics, purify the air, and reduce noise.

Figure 19 - Road shelter forest and slope protection

Slope protection, also presented in Figure 31, refers to the road safety problem caused by the collapse caused by soil erosion due to rain.

By analyzing the application of road shelter forests and slope protection in the environmental impact assessment of road construction (Figure 32), several conclusions were found and presented in the following paragraphs.

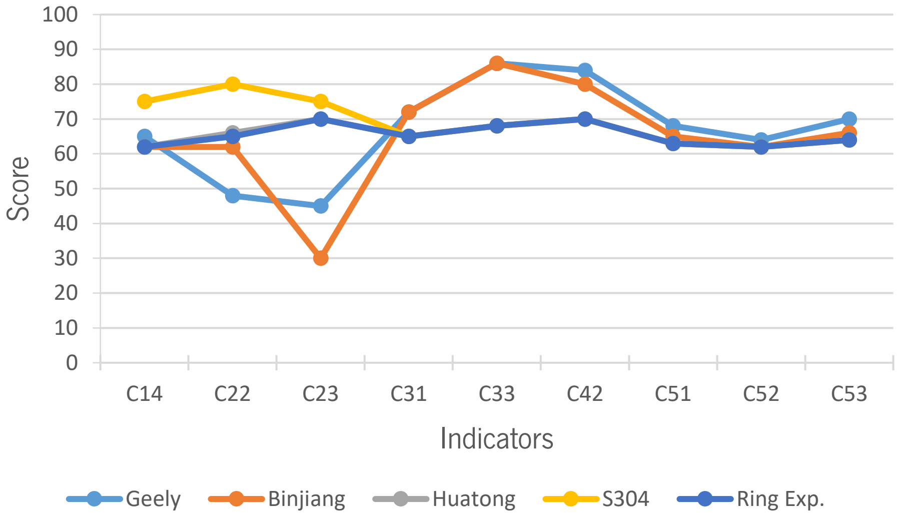


Figure 20 - Road shelter forest and slope protection in environmental protection

Road construction destroys the vegetation and soil structure along the way, causing soil erosion and landslides, which has a severe impact on road safety and ecological environment, especially in rural areas, mountains and suburbs. However, the application of protective forests and slope protection has reduced the damage caused by road construction to the environment and played a particular role in repairing the environment's persecution.

The construction of protective forests is a small restoration of damaged vegetation, which has a good effect on maintaining water and soil balance. The protective forests on both sides of the road provide an excellent guarantee for road traffic safety and improve the landscape aesthetics along the way, partially compensating the damage caused by road construction to the natural ecological landscape. The leafy protection forest also has a good effect on dust and noise reduction. At the same time, the shelter forest also has a significant improvement effect on the water environment.

The slope protection is mainly useful in the mountainous area. Due to the road construction, the mountain has to be destroyed, and the original soil and mountain structure are changed. It is easy to cause landslides during the rainy season, block traffic and affect road safety. The construction of slope protection improves the soil's stability, and the lawn implantation recovers the damaged ecological environment.

4.3.4. Dust removal and monitoring system

Road dust and automobile exhaust are the primary sources of air pollution in urban road construction. Road dust runs through the road construction stage and road operation stage. During the road construction period, the material storage site, mixing station, material transportation, and paving are primary pollution sources. During the road operation period, the driving vehicles will also cause a lot of dust pollution and endanger citizens' health.

Dust removal facility (Figure 33) uses spray water mist and water bubbles to prevent dust from spreading, to achieve effective measures to reduce particle matter (PM2.5, PM10) and total suspended particles (TSP). At the same time, the fence is also a meaningful way to block dust and noise.

The urban road environmental monitoring system (Figure 33) can measure real-time PM2.5, PM10, TSP, noise, temperature, wind speed, wind direction and other parameters, and transmit them to the background management system on time to provide a basis for the decision-makers. The monitoring system can be configured with automatic spray or linkage with water bubble equipment. When the suspended matter in the air reaches a certain level, the equipment is automatically turned on, which will take into account the functions of energy-saving and environmental protection.

Figure 21 - Dust removal and monitoring system

Analyzed from the roads studied' evaluation results in the Huatong road, S304 road and Expressway, which have similar road environments, the three roads' evaluation results are also consistent (Figure 34).

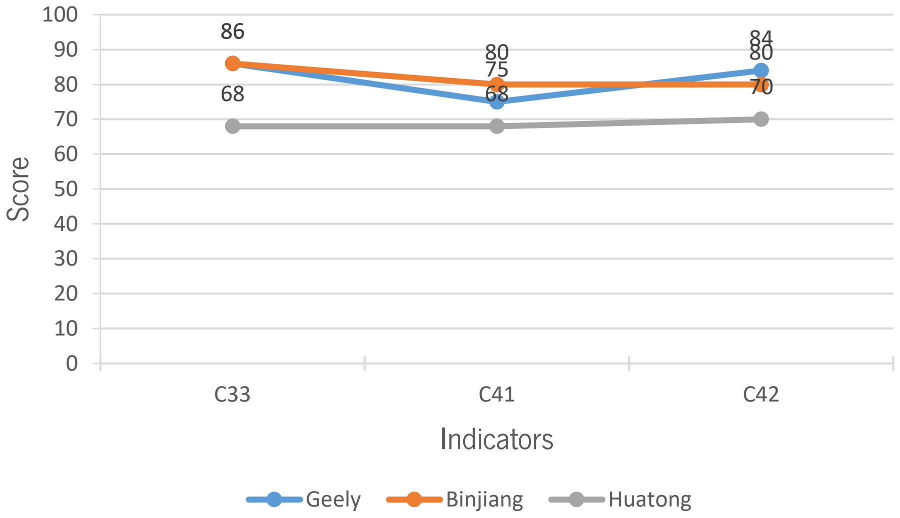


Figure 22 – Effect of applying dust removal and monitoring system in environmental protection

Since urban roads are relatively sensitive to atmospheric and acoustic environments, many dust removal and noise reduction measures have been taken during road construction and operation, and a large number of environmental monitoring systems have been set up. It reduces the negative impact on the environment of road construction and plays a specific role in environmental protection. However, through the comparison of urban roads (Geely Road and Binjiang Road) with rural and mountain roads, it is found that the negative impact of urban road construction on the urban atmospheric and acoustic environment is still far more significant than the impact on rural and suburban areas.

With the promotion of green roads, low-carbon roads and sustainable road construction, there are more and more environmental protection measures for road construction. Other environmental protection measures for road construction are:

i) route planning to reduce land encroachment and house demolition;
ii) bus lanes and harbour platforms to ensure road safety;
iii) construction of selected equipment to reduce noise and atmospheric pollution.

5. CONCLUSIONS AND PROSPECTS

5.1. Conclusions

The comprehensive evaluation of road construction's environmental impact is a complicated systematic project, which involves social, economic, ecological, and other factors. It is still in the development stage. There are many dependent and independent variables in the environmental impact assessment of road construction, being difficult to draw accurate conclusions only from their qualitative and quantitative analysis. Therefore, the fuzzy matter-element comprehensive evaluation method uses a fuzzy theory combined with matter-element analysis for a more comprehensive analysis to assess the impact of road construction on the environment, make the assessment structure more accurate and reasonable, which is of significant importance for the sustainable development of road construction.

This thesis analyzes the current situation of urban road construction environmental impact assessment in China and internationally through literature review, and expounds the necessity of establishing a comprehensive evaluation system of urban road construction environmental impact. A relatively complete evaluation system of environmental indicators for urban road construction was established by screening various environmental assessment indicators and comparing weighting and environmental assessment methods. Fuzzy hierarchy weighting method, fuzzy matter-element comprehensive evaluation method, and fuzzy objects were constructed for that evaluation system. The meta-model and its application in different road environments and environmental protection measures have verified its rationality, comprehensiveness and applicability.

The main conclusions drawn from this work are related to these five points, which are then discussed in more detail:

i) establishment of environmental assessment index system;
ii) determination of weight by fuzzy analytic hierarchy process;
iii) definition of a fuzzy matter-element comprehensive evaluation method and model;
iv) application of fuzzy matter-element model;
v) environmental impact assessment of multiple road construction projects with different conditions.

The selection of environmental impact assessment factors is essential in the environmental impact assessment of road construction. The evaluation factors selected only based on careful consideration of the social development, environmental characteristics, and environmental behaviour of pollutants, and the coordinated actions of pollutants are comprehensive and reasonable. In this work, the collation of general environmental impact factors, combined with the index system thinking and principles, established a comprehensive evaluation index system for road construction environmental impact. The index system can be adjusted appropriately according to the geographical, geological, climate, hydrological, and other specific road construction projects' environmental conditions.

A core issue of environmental impact assessment of road construction is the weighting of evaluation factors because the weights will have a decisive impact on the evaluation results. This work analyzes the methods of determining various weights in the current environmental impact assessment of road construction, points out their shortcomings, combines fuzzy theory with AHP, and proposes a new weighting method, fuzzy AHP. This method introduces the fuzzy consistent matrix into the analytic hierarchy process, and uses the fuzzy consistent matrix to reflect the uncertainty and ambiguity of expert judgment, overcomes the deficiencies of the traditional analytic hierarchy process, and improves the rationality of the weight determination. The method is applied to five roads with different conditions. The results show a reasonable and effective weighting method, which improves road construction environmental assessment's scientificity.

The fuzzy matter-element evaluation method combines fuzzy mathematics theory and matter-element analysis and is a comprehensive evaluation method. Through the comparative study of various environmental impact assessment methods, the fuzzy matter-element comprehensive evaluation method is applied to the environmental impact assessment of road construction, and a fuzzy matter-element model is established. The model obtains the evaluation results through qualitative and quantitative comprehensive analysis, which can more fully reflect the real situation of road construction projects' environmental impact and the comprehensive evaluation method's systematic and rationality.

The fuzzy matter-element comprehensive evaluation model was applied in new roads, reconstruction roads, urban roads, rural roads, mountain roads, suburban roads, and road construction projects. After using different environmental impact reduction methods, the fuzzy matter-element model's feasibility and rationality were verified.

Through the environmental impact assessment of multiple road construction projects with different conditions, it is exposed that the positive impact of road construction is mainly reflected in transportation and economic development. However, road construction harms other environments. From the overall assessment, road construction has a small negative impact on the environment. Through the application of the model, it is verified that various environmental protection measures play an essential role in preventing and reducing negative impacts in the environmental impact assessment of road construction, and are an essential measure to achieve the sustainable development of road construction.

5.2. Prospects

Road construction projects' environmental impact assessment is a muti-objective, multi-attribute complex evaluation involving knowledge in multiple subject areas. Although this thesis discusses the comprehensive evaluation method of the road construction environment, there are still many problems that need to be discussed in more depth due to the limitations of time, energy and other conditions. The prospects of this wark are the following:

i) Carry out more in-depth research on the road construction environmental impact assessment index system, to obtain a comprehensive and regional road construction environmental assessment index system, making the environmental assessment content more clear and conducive to practical operation and application.

ii) When the actual index scores and weights are determined, data are obtained through questionnaires and expert scoring. Due to the number of questionnaires and expert preferences, there will always be some deviation from the actual data. Therefore, in the subsequent research, making the research even more scientific and reliable is still an important topic.

iii) Due to the strong regional nature of road construction, there are considerable differences in different natural conditions, economic conditions, social environment, traffic conditions, among others. The existing environmental assessment lacks a unified standard. The environmental assessment of road construction is different from other environmental evaluation standards in the field are also very different, which brings many difficulties to the evaluation work. Therefore, it is also essential to develop corresponding standards to characterize road construction projects' environmental impact.

iv) The combination of fuzzy theory and matter-element analysis is still in the preliminary stage. Although applied in some fields, it needs to be verified with more practice in applying road construction environmental assessment to determine the comprehensive assessment method's science and rationality.

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