A USEFUL DECISION SUPPORT MODEL FOR ETC (ELECTRONIC TOLL COLLECTION) SYSTEM SELECTION FOR CHINA'S ROAD ENVIRONMENT

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A thesis submitted to Auckland University of Technology in fulfillment of the requirements for the Degree of Doctor of Philosophy (PhD)

2021

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Declaration

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Signature of candidate

Acknowledgement

Firstly, I would like to express my sincere gratitude to my supervisor Prof. Dave Parry for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better adviser and mentor for my Ph.D study.

Besides my main supervisor, I would like to thank the rest of my thesis supervisors: Prof. Ajit Narayanan and Dr. Paul Leong, for their insightful comments and encouragement, also for high requirements which incented me to widen my research from various perspectives.

My sincere thanks also go to Prof. Haijin Chen and Prof. Weiping Jing who provided me an opportunity to join their team as intern, and who gave access to the laboratory and research facilities. Without they precious support it would not be possible to conduct this research.

Finally, I am thankful to and fortunate enough to get constant encouragement, support and guidance from all participants which helped us in successfully completing our interview work. Also, I would like to extend our sincere esteems to all staff in road administration department and laboratory for their timely support.

Abstract

The concept of decision making has emerged in many studies but is rare in ETC system selection by Road Department administrations. Existing road equipment procurement documentation shows this decision making is not structured and does not use a clear methodology. Based on China's road characteristics, this study attempted to find the decision-making factors, and integrate the decision elements into a decision model. This research demonstrates three toll road construction projects in the real world. Sensitivity analysis was used to find the influence of decision factors on optimization.

The literature review indicated ETC systems selection belongs to a multi-criteria decision-making group, who will choose a suitable system to best satisfy Road Department administrations. This decision making should have three basic elements in accordance with the multi-criteria characteristics: 1. Requirements of Road Department administrations; 2. The performance of the ETC system; 3. Criteria for measuring system performance under the requirements.

In the process of decision-making model development, both quantitative and qualitative approaches have been used as information collection, to collect useful information of the decision elements. Objective methods are used for performance evaluation and criteria weighting. Finally, the decision-making model was designed for constraint and optimization.

The main contribution of this study is to prove the decision-making activities of decision makers, including data collection, decision goal setting and performance evaluation, which can be classified, summarized and modelled, and that the overall decision-making model established in this research can be fully utilized in this field, within theoretical consistency and the universality of road application. The conclusion of this study is that decision making is a necessary activity for road department administrations to choose an ETC system under China's road environment and road policies.

The second contribution of this study is to establish a method and theory framework for building decision models in this field. This is accomplished by collecting the elements of decision making, obtaining the requirements of Road Department administrations, and

establishing performance evaluation. The demonstration work proved that under the current road environment and policies in China, different road projects have produced consistent decision-making results, which indicated that the decision outcome is suited to running in China’s road environment.

Table of Contents

List of Tables

List of Figures

LIST OF ABBREVIATIONS

AADT: Annual average daily traffic volume.

AHP: The Analytic Hierarchy Process Method.

AVI: Automated vehicle identification.

Criteria: Rules for evaluating the ETC performance under requirements of Road Department administrations, which also show the relationship between ETC attributes and requirements.

DSRC: Dedicated Short-Range Communications.

ETC: Electronic toll collection.

ETC attributes: the parameters of an ETC system.

ETC technical expert: Participants of expert-based interviews who have experience in designing and testing ETC equipment.

Expert meeting: Taken by road department administrations, carried out for decision making in road equipment procurement.

Expert-based interviews: Questionnaires were designed in this research and were used to collect decision information including ETC attributes, requirements and criteria.

Government transportation department expert: Participants of expert-based interviews who have knowledge on road polices.

OBU: Vehicle on-board unit.

Performance evaluation: The activity of transforming ETC attributes into performance values per criterion, to meet the requirements of road department administrations.

Requirements: Requirements proposed by road department administrations in the decision-making process. It represents what the road department administration wants from the decision-making activities.

RFID: Radio frequency identification.

RSI: ETC Roadside unit.

Road environment: Road environment is traffic conditions in this study, which generally include the environment determined by the regions such as traffic volume and weather conditions.

Road Department administration: Road Department administrations have the ownership and the authority to manage the road. In road equipment procurement (including the ETC system), they proposed requirements, and take expert meetings to made decisions. They are decision makers for ETC systems selection.

Road policy: Road policies are proposed by the government. They include road setting, traffic rules, and equipment usage standards. These policies are unified to ensure compatibility of the whole country transportation system.

Toll road manager: People participating in expert-based interviews who have experience in managing ETC equipment and monitoring the road environment.

CHAPTER ONE: INTRODUCTION

1 Overview

In China's highway toll collection systems, the development of an electronic toll collection (ETC) system based on radio frequency identification (RFID) technology is becoming more and more rapid. Although many manufacturers have provided the corresponding ETC products to cater for road use, some ETC products cannot satisfy the expectations of the Road Department administrations under the constraints of China's road environment and the government’s policies. Manufacturers are trying to sell their ETC products with more information on RFID technical parameters and more training to strengthen the determination of Road Department administrations. This has not been done in past studies to develop a unified decision-making method, to assist the Road Department administrations to select these ETC products. This introductory chapter describes the background of this research including research questions, research objectives, scope of study, proposed decision-making approach, general research method and contributions.

A brief outline is provided as follows:

- Review the concept of the RFID technology, ETC systems and decision support methods (section 1.1).
- Discuss the research issue along with the background of the research and a summary of the problems of research (sections 1.2 and 1.3).
- Specify the research question and objective of the study (section 1.4).
- Propose a general conceptual framework based on the decision support process (section 1.5).
- Focus on the scope and significance of different fields of the study (section 1.6).
- Provide in brief the research design and analysis (section 1.7).
- Focus on some areas of contributions to the body of knowledge and practice (section 1.8).

- Provide an outline of this thesis (section 1.9).

1.1 Decision for ETC selection

This thesis discusses the concept of decision making in the process of ETC selection by Road Department administrations and proposes an operational definition of the decision making of Road Department administrations. Simon (1959) synthesized the components of decision making from the perspective of structure, to identify three main components: factors, decision-making methods and decision-making process. Factors are the driving force, resources, reference and foundation of decision making. The decision-making process is based on the decision maker selecting suitable decision methods under the influence of existing factors.

In ETC literature, factors that determined the selection of Road Department administrations generally referred to the RFID technical parameters of ETC products. This also means that the Road Department administrations need to invite related technicians to introduce the details of RFID technology. More specifically, Road Department administrations regard the parameters of these ETC products as "key factors in planning for decision-making road related facilities" (Du & Chen, 2011).

On the other hand, psychology emphasized that decision making is a cognitive process. After this process, decision makers can decide actions in various options based on personal beliefs or reasoning about all factors, or decide the opinions that individuals want to express. Each decision process aims at producing final decisions and final selections (Edwards, 1954). The form of these choices can be a kind of action or selection. Before making decisions, decision makers often face different uncertainties about decision activities and consequences. Decision makers need to weigh the pros, cons and risks of various options to achieve optimal decision results. A decision can be defined as a psychological process (also known as a cognitive process) in the selection of several schemes. Different views have different interpretations of human decision-making behaviour. Psychological views and personal decisions come from individual needs, preferences, and perceptions. The cognitive behaviour point of view is that the decision-making process is regarded because of interaction with the outside environment. Each decision process finally has a choice: this choice can be a behaviour, it can also be an opinion (Kirkwood, 1997).

Therefore, this brief review shows that decision making is a multidimensional concept that can be studied from different perspectives (Eisenhardt & Zbaracki, 1992). This study explores these dimensional perspectives of Road Department administrations on all the factors related to RFID technology. The conceptual definition of decision making in this study is that Road Department administrations are committed to research and mastery and are willing to constantly improve their cognition of ETC products to satisfy road application and product selection.

1.2 Background of the study

Technical literature was full of introductions to related RFID applications, and explanations of ETC systems, or a conceptual and empirical work on the wide range of decision-making behaviour activities. A systematic study of the academic literature shows that there was little concern about decision making in ETC selection, which was a significant imbalance. Road Department administrations are the main decision makers in road device selection (involved ETC products). They are very eager to establish a wide and common decision-making method to solve the problem of ETC selection.

It is important to consider the decision of Road Department administrations from two aspects. First, from the perspective of Road Department administrations, cost considerations and convenience determined the original intention of the promotion of the ETC system. Second, from the perspective of ETC manufacturers, it is necessary to convince Road Department administrations to provide related cost calculations and reliability analysis to prove the effectiveness of their promotion. Many researchers believe that "ETC manufacturers provided a lot of feasibility reports, induce and persuade Road Department administrations to recognize the cost and reliability of products, and handle their decisions"(Du & Chen, 2011).

Recent studies and highway test reports show that the performance of ETC systems is affected by the technical factors of RFID. These factors include working frequency, reading distance, speed, installation method and antenna angle. However, no attempt was made to verify the relevance of these factors. Some of the literature determines the driving force of the ETC system promotion. It is found that cost is one of the important factors that affect the promotion of ETC. Other research, including the test report of the Research Institute of the Highway Ministry of Transport, indicate that the RFID technical parameters determine the stability of the ETC system. Some researchers also believe that these technical parameters are associated with cost factors to determine the final decision of Road Department administrations. In previous work of this study, an extensive search of the literature showed many factors are affecting the ETC system. However, in 15 factors which involved 30 publications, only the cost factor had been biggest concern, and the other factors are rarely concerned with in their studies. Although those researchers found some support for the factors, they do not seem to have reached a consensus on the factor relevance.

Although the RFID technical parameter as a factor affecting the ETC system has prompted the Road Department administration's decision-making direction, it does not necessarily constitute the leading cause of the decision. Many other incentives can be deduced from the relevant theories of the decision-making field. The cognition of decision-making methods and how to choose these methods should also be included in the research.

In summary, the literature review shows that there is no systematic attempt to analyze decision-making on ETC selection. There is a limited number of studies in this field and related fields, and there is no unified conclusion of the decision-making methods of Road Department administrations. The following subsection presents the motivation of this study.

1.3 Motivation and problem statement

Early and recent academic studies have recognized the impact of RFID technical parameters on the entire RFID system. However, the ETC system, which is used as a traffic application, was introduced to China only about one decade ago. In the specific road environment, the influence of RFID technical parameters has changed accordingly. Fortunately, after more than 10 years of application and many test reports, Road Department administration surveys and academic literature continues to emerge, which provides a theoretical basis for Road Department administrations to choose a suitable ETC system. Previous work of this study found that many literatures focused on the impact of a single factor on ETC, and the relationship and interactions among these factors were rarely considered. This imperfect study ignores the decision-making process of Road Department administrations and does not have the ability to provide reliable decision making for Road Department administrations. At the same time, the existing literature rarely focuses on the selection and development of decision-making methods. Because of these imperfect factors, it is difficult to propose systematic decision-making methods to solve common problems.

At present, many studies provide decision methods and a theoretical basis, but still have the following problems:

1) Many studies only focus on the test of ETC equipment and the evaluation of experimental results but lack decision-making methods. Typical studies, such as the "National Highway and Other Networking Trial Summary" (2014), put forward reliability evaluation after testing several ETC systems, including system compatibility, tag design and signal transmission. The factors affecting the performance of ETC systems are described in detail. These factors provide a powerful reference for the decision-making behaviour of Road Department administrations. In addition to this study, other studies also include an ETC system deployment plan, a feedback summary from drivers across the country, a feasibility report of road construction, etc., which directly and indirectly provide factors that are affecting road owner decision making. However, the scope and types of this information involve many aspects but few are specific decision-making methods, which can easily bring confusion to Road Department administrations and make decisions difficult.

2) Many studies provided decision-making methods and theories, but most focus on cost-benefit analysis. Only a few studies focus on other factors, such as reliability analysis. Typical studies, such as Xiong (2008), design two decision-making methods. The basic cost-benefit method is used to calculate the proportion of ETC system in highway revenue. Another method is to determine the relationship between decision-making factors by AHP and generate relative weights. Using cost-benefit analysis, a variety of decision-making factors were found through the ETC charging process, which becomes the "most effective" decision making method for Road Department administrations based on benefit calculation. In addition to this study, we searched for relevant information, and consulted 367 articles about ETC system design and decision-making methods development. Among them, 55% focused on cost-benefit algorithms and 28% used AHP to set the weight of decision-making factors. That means, it is hard to find literature on the decision making of ETC system selection.

3) Some studies provide comprehensive research based on road planning, sort out and summarize the overall technique information including the ETC system from various aspects. However, these studies usually focus on road planning and cover a wide range of information, including a study of manual toll collection systems, which makes it difficult to independently obtain information about ETC systems. Typical studies, such as Wang (2017), have designed a model to evaluate the capacity of ETC lanes and MTC lanes. Through software simulation, the model can effectively configure ETC lanes and MTC lanes at toll stations and bring convenience to traffic management. Other studies, such as Yang and Zhou (2018), analyzed individual factors of traffic lane allocation from the cost-benefit perspective. However, although these studies are very helpful to our research, they did not analyze the ETC system indices and the relevant factors involved in decision making separately, which cannot effectively provide clear guidance for the selection of an ETC system.

In addition to the lack of relevant research, the existing decision-making process reflects the unstructured decision-making behaviour of the Road Department administrators, which increases the difficulty of selecting ETC products. Even though some studies described the process of road equipment selection, the characteristics of decision making were rarely analyzed. A typical research article "Research on procurement management for expressway construction project of Shandong highway administration" (Shi, 2016) described the decision-making process of Road Department administrators in selecting road equipment, which includes ETC equipment. However, this research article does not clarify the decision-making method and the influence of RFID technology factors.

This research looks at using multi-methods for decision making for ETC selections with many RFID technical factors, many different combined objectives and many Road Department administration requirement achievements. We can put those approaches together to create a structured decision-making method much like a master key is made to open different types of gates. The current literature does not, in general, address this decision-making approach for ETC selection and I believe it is a valid gap to be investigated.

1.4 Research objective

Given the background of this research and overview of the problem statement, it seems that a study of the decision-making factors, the decision-making process and the decision-making methods of the Road Department administrations is urgently needed. Therefore, the main problems to be solved in this study are as follows:

What factors have an effect on the choice of ETC systems? How do they affect ETC systems?

How can we create a DSS model to establish the relationship between those factors, and address Road Department administrations' requirements?

How can we assess the proposed decision support system and determine whether the results of its implementation meet the decision-maker's expectations?

To answer the above research questions, the purpose of this study is as follows:

- Create a decision support model for ETC systems selection.
- Demonstrate this model and implement a new system for meeting the requirements of Road Department administrations.
- Evaluate the sensitiveness of this tool.

1.5 Proposed theoretical framework

From the previous discussion, we can clearly infer the factors that should be considered in ETC equipment selection: decision-making factors, method of selection and requirements of Road Department administrations. These factors not only directly affect decision-making behaviour, but also may interact with each other. Therefore, the decision-making process framework proposed in Figure 1.1 describes a rough relationship.

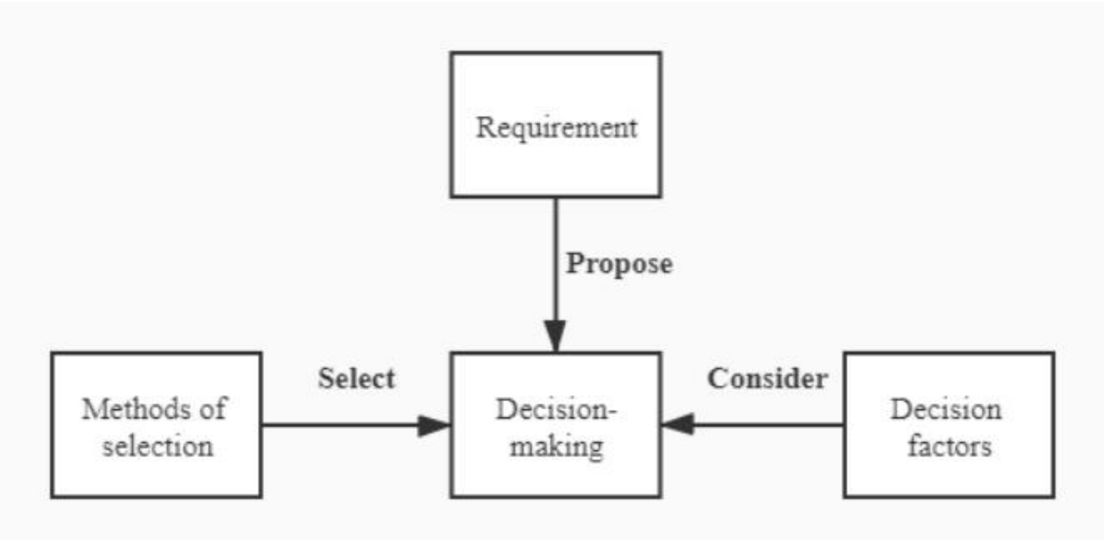

Figure 1.1 Initial theoretical framework

The initial theoretical framework in the above figure shows a rough relationship of those factors. That is requirements are proposed by Road Department administrations as goals of decision-making. In the process of decision making, suitable methods are selected and decision factors considered to finally issue the decision outcome.

A comprehensive review of related concepts and theoretical literature indicates that a compete conceptual model and a common decision-making framework need to be established to verify the role of various RFID technical parameters and ETC configuration schemes in the decision-making process. Therefore, the proposed initial conceptual discussion contributed to the development of the compete theoretical framework in Chapter 2. The next section describes the scope of this research.

1.6 Scope of the study

This study discusses basic elements associated with ETC selection (Chapter 2), to investigate in-depth the related parameters of RFID and the decision-making methods for optimizing ETC selection, and provide a reliable decision tool for Road Department administrations, especially in the Chinese traffic environment. The scope of the study covers the following aspects:

1. This study focuses on the construction of a decision model, that is, the determination of decision factors and uses of decision methods. ETC systems, as the selected object, provide RFID parameters for decision makers. In essence, this study is devoted to the establishment of a decision model.

2. As the object to be decided, ETC is widely used in technology. The model created in this study focuses on China's road environment, and under the road policies based in China, so only an ETC System based on RFID technology can be selected by this decision model. This means that other ETC technologies are not suitable for this study.

3. The ETC equipment mentioned in this study only operated under RFID technology, and the RFID components in this equipment are the core objects of decision making, including readers and tags. Other unrelated components were not suitable for this study. For example, for ETC tags, we only considered RFID components for selection, other

components such as human interface components were not in the research scope.

4. ETC equipment mentioned in this study is only applicable to the road environment, and other environments are not applicable to this study. For example, we did not consider ETC uses under water transportation.

5. Because the application environment of this study was based on the road environment in China, which involved the ownership and use right of relevant infrastructure, the decision-making process of selecting ETC equipment depends on the local legal characteristics. In China, the most of Road Department administrations belong to the government, and road directors are very concerned about the compatibility of equipment with China's ETC standards when they are making decisions.

6. The performance of the target ETC systems were generated by the decision model reflected in multiple evaluation criteria. These measures only considered the application of ETC in the current road environment, and any information irrelevant to the application of ETC systems were not within the scope of this study. For example, the profits of a specific highway included the ETC aspects and the labour aspects. We only calculated the profits which were generated by ETC equipment and ignored the profits from the human systems.

7. This research focused on the factors that decision makers can control. For example, Road Department administrations can select ETC equipment to achieve their expectations, but they cannot control the road environment and road polices that were determined by the government.

1.7 Research methods and analysis

To effectively conduct the research investigation and test the theoretical framework, both quantitative and qualitative approaches have been used as information collection (section 3.1). In brief, to collect useful information of decision elements (requirements, criteria and performance), 28 participants were invited to join this research. Initially, a semi-structured questionnaire was designed and tested for the correctness of the questions in a pilot study. Structured questions with semantic method were designed for later interviews, to quantify answers from participants.

Furthermore, the analysis methods tend to be objective methods, including performance evaluation (section 4.4) and criterion weight. Among them, the cost-benefit evaluation method was used in ETC system profits evaluation (O'Sullivan, 2003); Traffic management methods were used to evaluate ETC traffic capability (Lai, 2018); The reliability evaluation method was used to find what attributes were influencing ETC's reliability (Gu, 2018); Safety analysis was used to determine which safety design was compatible in national highway systems (Li, 2013); The battery energy consumption calculation method was used to evaluate tag life (Liu & Ba, 2016). Those performance evaluations were normalized as unique value types (section 3.2.3), and criteria were weighted by the entropy method to obtain a decision-making model objectively (section 3.2.2).

1.8 Major area of contribution

I searched a lot of research materials from academic research databases, including both English databases (Google academic, IEEE, ACM, etc.) and Chinese academic databases (cnki, wanfang, etc). I believe that my research will contribute to the selection of ETC systems based on RFID technology, under the road environment and policies of China. The main areas of contribution are:

- From a theoretical perspective, I explored decision-making elements to better understand the decision-making behaviour of Road Department administrations, which helped expand the principles of decision-making behaviour and introduce an understanding of ETC system selection. Road Department administrations, as decision makers, are responsible for ETC equipment selection. There are three types of factors that influence decision-making: ETC attributes, road environments and road policies. There are five performance evaluations at the related requirements of Road Department administrations: profit calculation, traffic management evaluation, reliability evaluation, compatibility evaluation and tag life evaluation. Five performance evaluations generating the outputs have been used to define the characteristics of criteria. Among them, constraint criteria were used to limit the selection scope and are first evaluated by decision makers. Other criteria were used to weight for optimization.

- Practical implications mainly came from the process of decision-model creation, demonstration and sensitivity analysis, that is how I followed the decision-making approach which was developed in section 3.2.3. By following this approach, selected technologies and methods (were described in Chapter 3) were used in decision-model creation. These methods are normalized performance values, a 6-point semantics method for ranking, and an entropy method for criteria weighting.

- Finally, although this research adapted some structural measures and developed some new theories, it took appropriate methods to demonstrate sensitive analysis, to prove that the decision models are generally useful and sensitive. Chapter 6 discusses further details of these contributions.

1.9 Thesis organization

The conclusion of the study is that the broad sense of decision-making leads to the focus of the research questions. This problem recognition follows a decision-making approach that creates a common decision model with the support of theories and literature to verify experience and conceptual validation. The paper is divided into six chapters as follows:

The first chapter: Introduction, discussed the concept, research background and problems, research questions, research objectives, research scope, initial theoretical framework, research methods and expected contributions.

The second chapter: A literature review mainly focused on four main aspects: consolidation theory review, generally focusing on different types of factors that affect decision making, the mainstream decision-making methods. This chapter also discusses the literature of decision making related to many different opinions, rather than simply describing the background of the Road Department administrations and ETC systems.

The third chapter: The content of this chapter is established based on a decision-making approach to create a common decision-making model, using both qualitative and quantitative information to explore the process of ongoing decision-making behaviour. This chapter further proposes expert-based interviews to obtain the ideas of participants.

And these interviews also included the basic principles involved in the research process, including the overall and sample, analysis units, selection of participants, research tools, structure measurement, selection and analysis methods of survey data.

The fourth chapter: The design of the decision model mainly shows the process of instantiate of the decision-making approach in Chapter 3. This chapter includes the use of Road Department administrations' requirements, ETC attributes and criteria, to design the performance evaluation. The RFID technical parameters and the configuration of the performance evaluation are used to find their relationship under each requirement. The whole design process is finally combined into a common decision-support model, which presents real world decision-making activities.

The fifth chapter includes two parts: the demonstration work and sensitivity test. In the process of measurement demonstration, three typical cases are extracted from the sample to be evaluated, and the results are combined to discuss the common nature. I demonstrate the consistency between data and theory by comparing the results of demonstration with the test of decision support system and comparing with the expectations of Road Department administrations. The sensitivity analysis provides the relationship between decision criteria and thresholds.

The sixth chapter is the summary and inspiration of this study. To consolidate the answers to the research problems and objectives, this chapter combines the overall results of the study, which is of great significance to researchers and practitioners. The detailed contribution to the theory and the impact of knowledge is also discussed. According to the presented research results and background, the future research direction is put forward to avoid limitations.

In summary, the study of this chapter provided the background and overview of the paper. The background information clearly defined the research gaps in the literature. The importance of the study was noted by the problems, objectives and legitimacy of the study. This chapter also outlined the research scope, including the research framework, methods and contributions. In the framework of this paper, the next chapter gives a comprehensive discussion on the relevant theories contained in the detailed review of documents from the perspective of decision makers.

CHAPTER TWO: BACKGROUND AND LITERATURE REVIEW

2 Overview

This chapter describes background of the ETC system in China and constructs a compete decision-making theoretical framework for ETC selection by reviewing literature.

A brief outline is provided as follows:

- Describes the background of ETC systems (section 2.1).
- States the decision-making process of ETC selection and decision makers (section 2.2).
- Reviews the literature related to decision making and finds out the factors that affect decision making (section 2.3).
- Defines different decision support methods and related weight setting methods (section 2.4).
- The compete decision-making theoretical framework is used to summarize the concepts involved in this study (section 2.5).

2.1 Background to ETC

In China, most ETC systems use RFID (radio frequency identification) technology (China ITS, 2015). RFID technology is the wireless use of coupling (using magnetic fields or electromagnetic fields) to transfer data for the purposes of automatically identifying and tracking tags attached to objects (Dobkin, 2012). RFID is an important technology for automatic identification systems and can be an effective way to solve the problem of information collection (Khali, Araar, & Abdulla, 2014).

2.1.1 Structure of an RFID system

An RFID system is comprised of electronic tags, readers, and RFID application platforms (Srikant & Mahapatra, 2010). Tags are attached to the objects and tracked/identified by readers. Application platforms are usually considered as an external component of RFID systems and are composed of databases and software. In some complex applications, those platforms can be operated by users at application terminals. The RFID system structure is presented in the following diagram (Want, 2006).

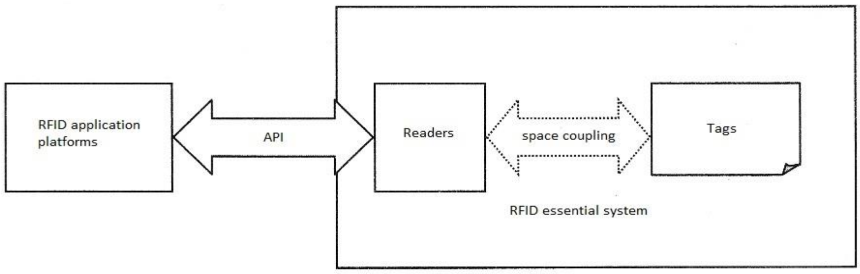

Figure 2.1.1 The RFID system structure

2.1.1.1 Tags

RFID systems use tags to identify objects. Tags can be active, battery-assisted passive, or passive. Active tags have an on-board battery and send out ID signals periodically. Battery-assisted passive tags have a small battery and are activated by orders from readers. Passive tags are inexpensive as they have no battery at all.

Tags can be classified as read-only and read/write. The read-only tag has a unique ID number that is used to record it in a database. The read/write tag can be written with some information from customers.

The tags include two important components: an integrated circuit for data storing, and another integrated circuit with an antenna to process the radio frequency signal from a reader (Dobkin, 2012).

2.1.1.2 Readers

As with tags, readers can be classified as active or passive. Passive readers are designed to receive signals from active tags. Active readers can receive and send signals to both passive and active tags.

2.1.1.3 Frequency

According to their working frequency, RFID systems can be classified as LF, HF, UHF, or microwave systems. The details of the working frequencies are presented in the following table.

Table 2.1.1 Working frequencies

	Frequency	Distance	Costs
LF	125 - 134 KHz	Few cm	Low
HF	13.56 MHz	1m	Low
UHF	900MHz	~ 3m	Moderate
Microwave	2.4 GHz or 5.8 GHz	10m	High

2.1.2 The ETC system

Electronic toll collection (ETC) is a wireless system to automatically collect the usage fee or toll charged to vehicles using toll roads, HOV lanes, toll bridges, and toll tunnels. Since recent decades, the electronic tolling landscape has evolved significantly in every region of the world. From technology changes in the Asia-Pacific, to environmental mandates in Europe and the initiation of Road Usage Charging in North America, ETC systems updated for every year and expanded. Alongside national activity, toll network interoperability continues to advance in India, Colombia, China and Philippines. The European EETS market has also evolved with recent legislative amendments coming into force no later than October 2021. All the while, advances in technology and lower prices – especially in RFID – are enabling the growth of ETC to more and more markets at more ambitious scales (Jackson, 2021).

Nowadays, different countries and regions adopt ETC systems of different technologies according to their road environment and road policies. These ETC uses include barcode-based ETC, RFID-based ETC, ANPR ETC, VPS ETC, and active infrared system (Milenkovi,2018). For example, In New Zealand, the ETC system uses sophisticated cameras and sensors to capture an image vehicle's registration plate and assigns the correct toll (NZ Transport, 2022). However, this study focuses on the ETC selection in Chinese road environment, which is mainly based on the following reasons.

1. Most of the ETC applications in the world adopt RFID technology (Wang, 2015), and the ETC System Based on China's road environment also adopts this technology, which means the research based on China's road environment is technically universal.

2. China has the longest highway mileage in the world (China ITS, 2015), which means the ETC selection based on China's road environment can provide massive data support for this research.

3. The rapid growth of China's infrastructure (China ITS, 2015) has provided a better environment for further research. At write up this thesis, the mileage of China's highway has increased by more than 1000 kilometers per year. This means that many ETC equipment have been purchased by road department administration. At the same time, existing highways also need to expand ETC toll lanes. This provides a continuous impetus for the further research.

4. Although the road environment and road policies of countries around the world are different, the selection of ETC system has the same objective. Any suitable ETC systems have characteristics of 1) Prevents traffic jams. 2) Reduces pollution in the toll station area. 3) Increases profits by increasing the traffic flow and 4) Saves labor costs that are a fundamental aspect of traditional toll collection systems (Du & Chen, 2011). No matter changing technology adoption and road environment, ETC selection conforms to the decision-making framework in section 2.5.

Therefore, research on RFID-based ETC selection activities in China's road environment has applicability and scalability.

2.1.3 RFID-based ETC

RFID-based ETC systems are RFID systems aimed to eliminate delays caused by manned toll booths by collecting tolls electronically (China ITS, 2015).

In those ETC systems, each vehicle is equipped with an on-board unit (OBU), which integrates all functions of tags. The signals from the OBUs are sent to toll stations equipped with a Roadside Unit (RSU), which has the full functions of a reader. These signals are then relayed to a central computer which calculates the fee to be paid. As ETC systems in China use RFID technology for signal transmission, ETC manufacturers integrate RFID tags into OBUs and RFID readers into RSUs. At the beginning of this PhD. research, ETC systems had been widely used around China (Du & Chen, 2011).

2.1.3.1 OBU structure

As the carrier of the ETC tag, a OBU (on-board vehicle unit) is usually designed as a small device, its size usually does not exceed 100 x 60 x 10 mm (Zhang, 2017). The structure of an OBU is shown in the following figure.

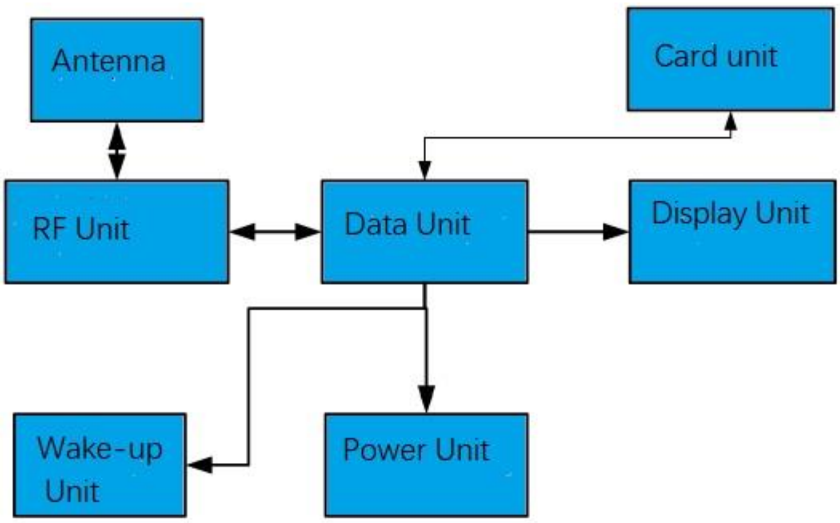

Figure 2.1.3.1 OBU structure

From above diagram, a typical OBU device should include the following components:

- Antenna: used to transmit signals between the OBU and RSU.
- RF (Radio frequency) unit: used to receive and identify the RF signal from the antenna.
- Data unit: used to receive the signal from RF unit and convert it into data.

- Power unit: the power supply system. When signal transmission occurs by the OBU and RS, this system will be activated and support the operation of the OBU. The rest of the time, this system will switch to sleep mode to save energy.
- Wake-up unit: used to wake up the OBU from sleep mode.
- Card unit: This is designed to connect the bank card with the data unit and used to charge the fees from the user's account.
- Display unit: used to display the user's account balance.

The OBU uses the RF unit and antenna to transaction data with the ETC reader (RSU). In this study, we believed the antenna, power unit, wake-up unit and RF unit are important components of ETC tags and explore the impact of their characteristics on Road Department administrators' decision making. The rest of the components, limited by the research scope (section 1.6), including a payment interface (card unit and display unit) are not involved in this research work.

2.1.4 ETC systems in China

ETC systems bring many benefits to road management in China (Wang, 2015). The greatest advantage of ETC systems is automatic vehicle identification. This means the road users need not waste time making payments before the toll station, and vehicles can pass smoothly through the toll gate. This can prevent traffic jams and increase the flow of traffic, thus increasing profits for road owners. Meanwhile, the automatic vehicle identification can avoid many of the costs of traditional systems. A lot of the costs associated with labour are saved which results in more profits for road owners. However, in the report "ETC application in China" (Wang, 2015), it is mentioned that many Road Department administrations complain about 1) the cost of tags, 2) the difficulty selecting tags, and 3) unreasonable traffic resource allocation.

2.1.4.1 The cost of tags

In China, highways belong to the government, which includes costs of ETC systems on the roads (Intellectual research consulting group, 2016). At present, the cost of OBUs is mostly borne by the OBU sales, which means that costs will ultimately be subsidized by the government or deducted from future profits (Wu, Sun & Zhang, 2017). This means the Road Department administrators must consider the cost of tags when selecting ETC systems.

2.1.4.2 Difficulty selecting tags

When the Road Department administrations are faced with different OBU design schemes, there is a contradiction between the requirements of low cost and high stability, which leads to difficulty in selection.

Most of the passive tags are designed to keep costs low. They usually do not include on-board batteries as their power is derived from the signal transmitted by readers. This means they are small, have a simple chip design, are easier to produce and are inexpensive to maintain. On the other hand, the signals derived from the power of readers are usually weak; they have a short reading distance and weak crypto-graphical protection. Unlike passive tags, active tags have an on-board battery. When accurately configured, they solve all the issues that are problematic for passive tags. However, their weaknesses are the advantages of passive tags. Therefore, the power supply of tags is usually a characteristic considered by Road Department administrations when deciding which ETC system to purchase. If the Road Department administrations lack an understanding of the characteristics of their road environments, it could result in unnecessary costs under low stability requirements, or the tag may not satisfy the high stability requirements of the road environment. (Wang, 2015).

2.1.4.3 Ineffective traffic resource allocation.

Ineffective traffic resource allocations limit the development of ETC systems. In China, both traditional toll collection systems and ETC systems are usually set up on the same highway. This means that the traffic flow determines the number of ETC lanes. When a highway is first operational, a smaller number of ETC vehicles lead to fewer ETC lanes because Road Department administrations allocate more traffic resources to the traditional toll collection system which has more road users. This situation causes the ETC systems to not generate the expected revenue and to ETC Lane congestion. On the contrary, if the number of ETC lanes exceeds the expectation, it will lead to the unnecessary construction cost of ETC lanes and congestion of non-ETC lanes. Mostly, traffic congestion will increase the cost of road management, which will affect the promotion of the ETC system (Uniconic, 2013).

2.2 Characteristics of ETC selection

Another purpose of review work is to extend a compete decision-making framework from the initial decision process (section 1.5). Initially a review of relevant theories to support this development is to find:

1.The object of decision making.

2.Decision-making behaviour.

3.Decision maker.

4.The characteristics of decision-making behaviour.

The following sub-sections discuss these works.

2.2.1 The object of decision-making

The purpose of decision-making is to select the appropriate ETC systems. In recent decades, ETC systems have been adopted by department administrations as normal road equipment for vehicle identification and toll collection in China (Bhuptani & Moradpour, 2005), and most of them are used to manage the collection of tolls without human intervention by using radio frequency signals to identify vehicles that are installed with tags when they drive into the detection area of readers (Mutigwe & Aghdasi, 2012). In China, most toll roads use a DSRC (Dedicated Short-Range Communications) mechanism, which is based on radio frequency identification RFID technology (Jiancheng, Lili, & Bo, 2010). The most important advantages of RFID use are the ability to identify tags quickly and automatically without requiring physical contact, and the ability to work in high movement environments. Other benefits include: 1) fast data transfer and identification; 2) high storage capacity, long usage, and wide applications; 3) dynamic modification of the tag's information; 4) improved security and service; 5) dynamic communication; and 6) identifying/tracking tags in extreme environments (AIDC, 2015).

The above review indicated ETC systems in selection have following characteristics:

1.Use RFID technology.

2.Are used for toll collection in road transportation.

3. In the actual road equipment procurement, ETC systems are usually selected together with other road equipment (Mutigwe & Aghdasi, 2012). Due to the limitations of this research scope (section 1.6), this study only discusses the selection of ETC systems

as well as the influence of other road equipment on ETC selection.

2.2.2 Decision-making behaviour: road equipment procurement

The decision-making behaviour of selecting an ETC system occurs in the procurement of road equipment. Shi (2016) described the process of procurement in Road Department administrations. He pointed out that Road Department administrations should follow the process below when purchasing road equipment (including ETC systems):

1. Road Department administrations put forward the purchase application and the equipment performance requirements based on their road environment to the equipment manufacturers.

2. The equipment manufacturers review those requirements and provide ETC equipment information.

3. Road Department administrations take an expert meeting. Those experts first review the ETC equipment's attributes, road environment and road policies, then evaluate candidate products by various criteria, to find a suitable ETC system that satisfies the requirements of the Road Department administrations. Shi (2016) indicated that inviting participation of experts with different work characteristics helps to obtain balanced recommendations and facilitates a fair procurement process. ETC selection under different opinions and criteria attracts attention from Road Department administrations.

4. Road Department administrations determine the procurement and sign the procurement contract.

The above review indicated the decision-making behaviour of ETC system selection has following characteristics:

1.Requirements are proposed by Road Department administrations in the decision-making process. These requirements represent what the Road Department administrations want from the decision-making activities. They can be either unique or multiple.

2.Decision-making behaviour needs to consider three factors: ETC attributes, road environment and road policies. ETC attributes are the parameters of an ETC system. Road environment is the traffic conditions in this study, which generally include the environment determined by the regions such as traffic volume and weather conditions. Road policies are proposed by the government. They are road settings, traffic rules and equipment technical standards. These policies are unified to ensure compatibility of the whole country transportation system.

3. Road Department administrations take expert-meetings to carry out decision-making. In expert-meetings, criteria are rules for evaluating the ETC performance under the requirements, which also show the relationship between ETC attributes and a requirement.

2.2.3 Decision makers.

Road Department administrations are decision makers in ETC selection. According to the “property law of China” (2007), the ownership of infrastructure belongs to the government. Meanwhile, local transportation departments and road administration are responsible for road management. In this study, the Road Department administration is a type of organization which includes the local transportation department and road administration, and is responsible for road equipment procurement (Shi, 2016).

2.2.4 Compatibility to road policies

In China, Road Department administrations are required to have an ETC systems network, and tags should be compatible with all systems. This requirement is derived from the report ETC application in China (China ITS, 2015), which was released by the Ministry of Transportation. The main content of this report is focused on improving the compatibility of existing ETC systems in order to make collecting tolls more convenient and efficient for road users. It requires ETC systems to have the ability to detect vehicles that come from other regions. In networked ETC systems, when drivers are driving across regions, vehicles will not be required to switch tags.

Although the Chinese Central Government issues a unified ETC standard for ETC use, this does not mean that the standard is mandatory. There are some regions that have adopted their own ETC standards. This leads to their ETC systems not being compatible with central government ETC systems completely. The report ETC application in China (China ITS, 2015) stated that the "ETC systems networking" will be standardized in five years in order to bring convenience and efficiency to road users. At the time of writing, vehicles in China are still required to install a tag for each of the local ETC systems when road users are driving across. However, it should be emphasized this situation is improving rapidly.

2.2.5 Multi-objective decision making

ETC selection has the characteristics of multi-objective decision-making, which is embodied in the following aspects:

1. The Road Department administration puts forward requirements in accordance with the road environment and road policies, which are often multiple and independent. This means decision making must achieve multiple goals.

2. Decision making needs to evaluate the ETC systems' performance under multiple criteria. This makes the decision criteria diverse.

3. Decision making produces the final optimal scheme.

Therefore, we selected the decision-making methods with multi-objective characteristics as a reference to develop the decision-making model.

2.3 Factors on decision making

In section 2.2.2, we indicated three factors are considered in ETC selection: ETC attributes, road environments and road policies. The following literature review work explores these factors.

2.3.1 ETC attributes

ETC attributes are important parameters to show the performance of ETC equipment, which are provided by the equipment manufacturers and appear in equipment manuals. These parameters are not only related to RFID technology, but also reflect the information of non-RFID technology (such as cost). This review is from the industry report (China ITS, 2015) to summarize the ETC attributes and to help develop a complete conceptual model for decision making.

2.3.1.1 Costs of ETC systems

Costs play an important role in product selection for purchasers of ETC systems. For this research, the cost was composed of tags and readers. For readers, the cost is mainly for an antenna, internal circuitry, and the power supply. The design of tags must include an antenna, materials and possibly an additional power supply. Also, the built-in chip costs need to be calculated if the application requires them. As per the statement in section

2.1.3.1, Road Department administrations select ETC systems and install RSUs. They pay for the OBUs which are made available to drivers for free. Drivers pay to fit the OBUs and use their bank cards in the OBU to pay for tolls.

In addition, Road Department administrations consider the needs of drivers. Ackerman and Heinzerling (2002) indicated that the traditional system for collecting tolls directly from drivers caused inconveniences of increased travel time, increased fuel consumption, and increased pollution in the toll collection area. The introduction of ETC systems would solve these complaints and, in theory, drivers would be more likely to use that roadway.

Implicit problems, including systems management, are also considered by Road Department administrations. System delays may result in lower efficiency which may reduce the traffic flow in a specific time period. This will reduce the Road Department administration's income; it also will lead to traffic congestion in front of the toll station.

2.3.1.2 Range of detection

Range of detection is an important parameter of ETC systems.

The paper “ETC Application in China” (China ITS, 2015) listed situations for range of detection. These two ranges of detection are illustrated in the following figures.

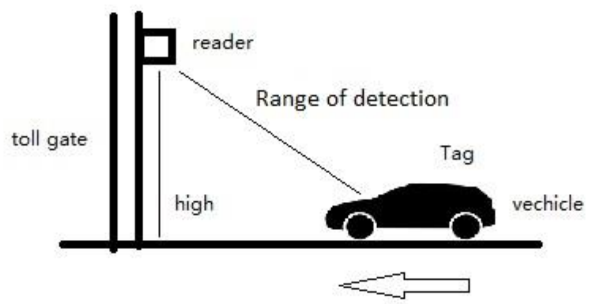

Figure 2.3.1a Reading distance of road based ETC system

The paper “ETC Application Reports from Five Cities” (Baike, 2013) defined the range of detection as the distance between tags and readers. It also indicated that range is an important parameter in most ETC systems.

From Wu, T.-Y., et al.’s (2012) research, highways are divided into several traffic lanes in a traditional toll station. Those lanes are designed to be different widths to accommodate different types of vehicles. In an ETC system, it is the range of detection that determines how wide the lanes can be. From the Road Department administrations' perspective, this range coverage determines the capability of traffic lanes. The following picture shows the range of detection of a single traffic lane.

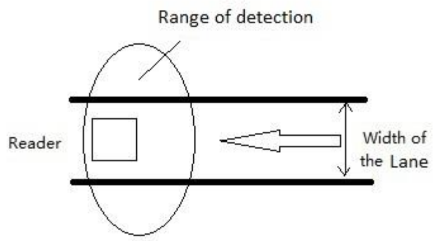

Figure 2.3.1b The coverage of signal on single ETC lane

Zhang (2017) mentioned the number of readers used in an ETC system helps determine the cost of that system. The authors indicated that a traffic lane must be covered by enough readers to ensure every vehicle can be detected by ETC systems. A reader with a small range will require the use of many readers, and that will increase costs. There is another option for Road Department administrations – to choose a long-range system. The following figure shows the range coverage of detection on multiple traffic lanes. This option shows the possible low costs for readers.

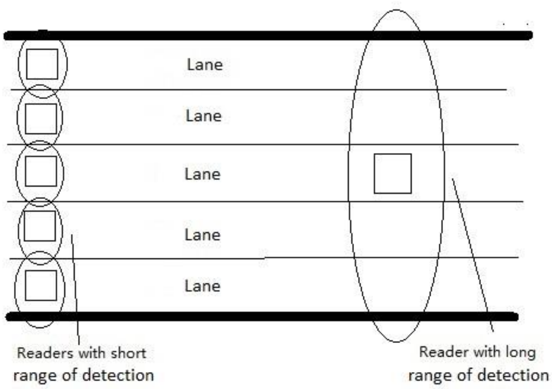

Figure 2.3.1c The coverage of signal on many ETC traffic lanes

Another industry report, ETC system testing summary of the National Highway Network (Ministry of transportation, 2014), shows that the range of detection also determines how high the toll gate can be. Usually, readers are installed on the top of the toll gate, but some OBU locations are set on the bottom of the vehicle. The long range means many types of vehicles can pass through the toll lane successfully.

2.3.1.3 Speed

The speed of vehicles is another important parameter in an ETC system.

The industry report "ETC system testing summary of the National Highway Network" (Ministry of transportation, 2014) shows that many manufacturers claim their systems can still accurately read the on-board tags when vehicles are moving at high speed. However, the paper "ETC Application in China" (China ITS, 2015) indicated the reliability of ETC systems can be negatively affected by vehicles moving at high speed. Researchers Khali, Araar, and Abdulla (2014) believed that speed is the most important factor in determining an effective ETC system because the system's anti-collision, anti-interference features will be changed in a situation with fast movement. Thus, Zhang, et al. (2010) believed that improving the reliability, scheduling, and efficiency of large-scale transportation are the most challenging factors for RFID applications in a high-speed environment. Based on that proposal, Pérez, et al. (2010) provided a method which can make the ETC system run efficiently even when vehicles suddenly change their speed.

Another situation was mentioned in the industry report "ETC system testing summary of the National Highway Network" (Ministry of transportation, 2014). This report showed that many ETC toll stations require vehicles to reduce their speed when they pass through a toll gate. This is mainly to prevent interference from the following vehicle. The figure below illustrates following-vehicle interference in a high-speed environment.

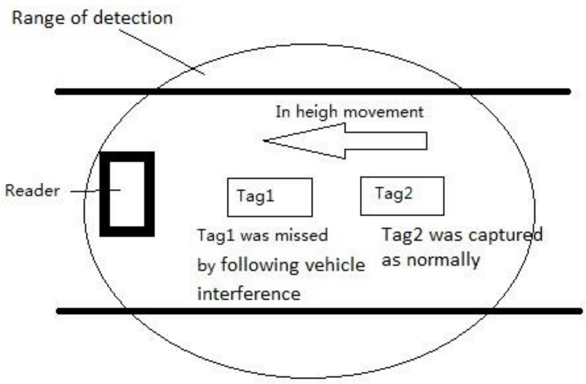

Figure 2.3.1d Following vehicle interference.

Lim, et al.'s (2002) research described that following vehicle interference is when readers first detect the following vehicle and will ignore the toll collection from first vehicles in a high movement environment. In this case, the speed limitation of ETC systems is usually lower than the speed cap of tags that were provided by the manufacturers.

2.3.1.4 Atmospheric changes

The paper "ETC Application in China" (China ITS, 2015) stated that atmospheric changes can affect how tags are detected by ETC systems. The review found that atmospheric changes include changes of humidity and temperature.

Saarinen, Frisk, and Ukkonen (2012) found that tags had different failure times, modes, and mechanisms when there were humidity changes. When the humidity value changed rapidly, the system produced more errors. One year later (2013), the same researchers ran a tags experiment in a humidity-cycling environment, where the humidity varied from 85%RH (Relative Humidity) to 10%RH and the temperature ranged from 85°C to 25°C. Through this experiment, they found the mechanism failed when the weather changed.

Research paper "ETC Application in China" (China ITS, 2015) suggested that when extreme climate conditions can be affect ETC systems' performance, the highway should be closed as in the case of low visibility conditions. The extensive test report "ETC System Testing Summary of the National Highway Network" (Ministry of transportation, 2014) showed most ETC systems tests factored in weather conditions such as sunny, foggy and rainy.

2.3.1.5. Frequency selection

Frequency selection is also considered a parameter driving ETC selection. At present, there are still some regions that are using their own ETC systems, for instance, 5.8GHz frequency is popular in highway uses, 2.45GHz frequency is popular in river-based transportation. In addition, 433MHz and 915MHz tags are attractive to many customers as they generate lower costs when in use.

The research paper 'The comparison of ETC between 5.8GHz and 915MHz" (Uniconic, 2013) suggested that tags using the 5.8GHz working frequency have more advantages than the 915MHz working frequency.

Uniconic (2013) believed that 5.8GHz tags have high transmission capability. The data transmission rate of a 5.8GHz system is 500Kbps of write and 250Kbps of read. Such transmission speeds mean they can complete the payment process correctly and can be of use in other ITS industries in the future. The data transfer rate of a 915MHz system is 0.3kbps of write and 6kbps of read. That means it will take 12ms to read 8 bytes of data from a single tag and 25ms to write 1 byte of data. As 915MHz ETC systems have limited writing ability, this will cause many errors in the writing process; the customers can only use its reading function too. This limitation is a huge obstacle to the application of 915MHz systems in a similar environment.

Wang, et al. (2009) indicated that 5.8GHz systems have a long transmission distance. In most ETC systems, the communication time and distance between readers and tags are very important. In some situations, systems that have a long communication distance and a short time for signal transmission will be the first choice of customers. This is because the two-way communication distance of 5.8GHz systems is guaranteed to be at least 10 meters according to DSRC protocols. The reverse scattering principle means downlink and uplink communication will not be interfered with by other tags, so tags can be read reliably at a specific distance.

"ETC Application in China" (China ITS, 2015) pointed out that 5.8GHz systems are safer. For 915MHz systems, because of the low working frequency, the data transmission rate is relatively low, and thus microwave communication between tags and readers is easily tapped. 5.8GHz systems are the opposite; they completely avoid the disadvantages of 915MHz systems.

However, another industry report of the advantages of RFID in transportation and logistics (Motorola, 2014) was more inclined towards the 915MHz system, which has the fundamental advantage of lower costs. This report considered that 915MHz systems are more suitable for single uses.

Similarly, the paper "ETC System Testing Summary of the National Highway Network" (2014) indicated 2.45G is considered by some Road Department administrations to have good signal penetration. With a 2.45GHz working frequency, it is easy to maintain good stability of signals even in an extreme external environment.

2.3.2 Road environment

Road environment refers to all external influences on a road, including road conditions, road facilities, terrain, and other traffic activities. According to section 1.6, this study only focused on the road information that affects the selection of ETC systems by the Road Department administration. This information affects the performance of ETC equipment on the road.

1.Traffic volume

Traffic volume refers to the number of vehicles joining traffic through a certain location or section of the road within a period (Li, 2019). Participants' vehicles include motor vehicles, non-motor vehicles and pedestrians, this means traffic volume can be divided into different types of vehicle traffic. However, in the absence of special instructions, traffic volume only refers to motor vehicle traffic volume and the number of vehicles that drive through in both directions within a period. It is not only an index for calculating the actual capacity of a road section, but is also the main basis for road classification and determination of road grade. In the practical application of traffic flow, its representation methods include average traffic volume, peak hourly traffic volume and design hourly traffic volume (Jiancheng, 2010). Traffic volume can also be used to calculate the road revenue, that is, in this research, it can be used to predict the revenue generated by ETC systems (Li, 2019).

Traffic investigation, analysis and traffic prediction are the basis for the present situation evaluation and comprehensive analysis of highway construction projects in the stage of feasibility analysis. They are also the main basis for determining the construction scale, technical level, road facilities, profit evaluation and geometric alignment design of highway construction projects (Li, 2019). The level of traffic investigation, analysis and traffic volume prediction, especially the quality and reliability of the prediction, will directly affect the decision making of the project and the economic rationality of engineering and technical design. Traffic volume varies with time and space. This change with spatial location is called spatial distribution, which generally refers to the situation that changes with the difference of region, route, direction, lane and so on, at the same time or under similar conditions.

The average traffic volume of these cases, is named the annual average daily traffic volume (AADT), which is the total traffic volume in a year and is divided by the total number of days in a year; AADT is the basis for roads planning, facilities selection and determining road level. It certainly can be used for ETC selection. Other commonly used average traffic volumes can be converted into annual average daily traffic volume (Lim, 2002).

2. Toll rate

The toll rate is used to reflect the cost of a region or type of vehicle on the highway. It is mainly determined by 1. The total investment of highway; 2. Forecast traffic flow; 3.Other economic factors. This affects ETC selection, as the type of road environment and toll rate is used to analyse the possible revenue by Road Department administrations (Li, 2019).

3.Open and closed toll systems

There are two toll road systems: open toll road systems (with a main toll station) and closed toll road systems (with an access toll station) (Li, 2019).

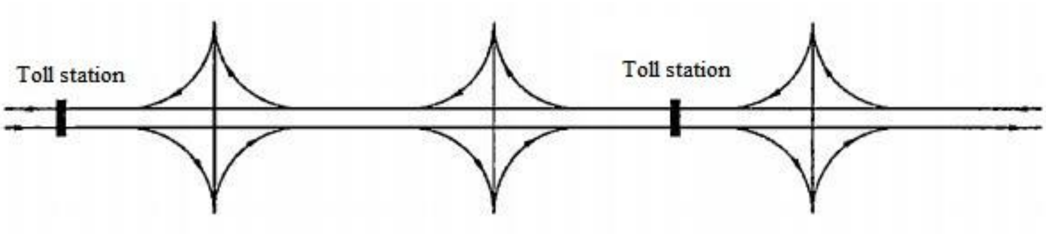

Figure 2.4.2 Top views of open toll station system

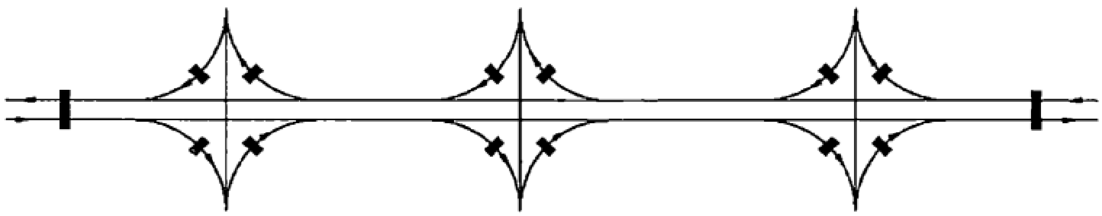

Figure 2.4.2a Top views of closed toll station system

In the open toll system (Figure 2.4.2), all vehicles are charged through the main toll stations which are built along the highway. Although this system can reduce the infrastructure cost because of no need to build toll stations at highway exits, it can lead to traffic congestion. And this system can also cause the escaping of tolls (Li, 2019).

In the closed toll system (Figure 2.4.2a), vehicles are charged when they enter the highway. Toll stations are usually built at the entrance and exit of highway, and when vehicles pass through, they are counted into the toll system (Li, 2019).

2.3.3 Road policy

A lot of information on road deployment and equipment use has been used as general data for Road Department administrations across China to address the requirement for road compatibility of transportation equipment (section 2.2.4).

Among road policies, the most mentioned is the width of traffic lanes (Wang, 2017). Although in China, road setting needs to be tailored to local conditions, the restriction of road polices ensures the universality of road construction and reduces costs. In this study, according to the width of the traffic lanes and the coverage of the ETC readers' signal, the number of ETC lanes can be determined (section 2.3.1.2:Range of detection). This is very important in cost-benefit analysis. At the same time, the width of traffic lanes is also a necessary parameter in the verification of traffic volume at toll stations (section 2.2.2) because it can be found from the calculation that the width of traffic lanes also determines the capacity of toll stations. In addition, the width of the isolation zone of a highway between traffic lanes needs to be applied to the calculation.

Cost of tags should be included in the total costs. In China, the cost of the OBU is a form of government subsidy paid for drivers(section 2.3.1.1). As government has ownership of highways, the total cost of ETC tags is included in the total costs of the ETC system. From the perspective of Road Department administrations, this involves how much of the infrastructure cost is the spend on ETC tags, which requires statistics of the proportion of the project's road mileage to the total mileage of the project area. Meanwhile, as a developing country, China's private vehicle ownership increases by a certain percentage every year (Shang, Han & Guan, 2019). These data play an important role in helping to calculate the cost of ETC tags.

Other equipment information are involved in road policies. For example, tag power consumption, frequency restriction and other technique information.

2.3.4 Characteristics of decision factors

The literature review summarized that the ETC attributes, road environment and road policies have the following characteristics:

1. ETC attributes come from the RFID parameters and the cost of the equipment. This information is provided by equipment manufacturers for selection by the Road Department administration (Section 2.2.2). This means that the information belongs to the object of decision-making behaviour (Section 2.2.1).

2. Road environment refers to the unique environment of the road under the jurisdiction of the Road Department administration. This information affects the performance of ETC equipment according to the local road conditions (such as traffic volume), thus affecting the decision making. The road environment may also be changed by the local traffic conditions.

3. Road policy refers to the compatibility of traffic management and road equipment operation (Section 2.2.4). The decision making of Road Department administrations is subject to these policies, but cannot change this information.

2.4 Decision-making method

This part comes from the literature review to discuss the possible methods used by Road Department administrations in ETC selection. The review work compared with major decision-making methods supports the relevant theoretical findings of this development.

2.4.1 Major decision methods

Major methods include complete enumeration approach, computational procedures, cost benefit analysis, multiple criteria decision making, AHP (The Analytic Hierarchy Process Method) and hybrid method. Review work shows these methods are helpful to the development of decision models. This is mainly reflected in:

1. Cost benefit analysis suitable for the cost calculation of ETC systems.

2. Enumeration methods and computational procedures suitable for listing feasible schemes and testing ETC system performance.

3. Multi-criteria, AHP and hybrid methods are beneficial to the design decision model. This is because they have more than two decision-making objectives, and need a

variety of criteria to evaluate and optimize the decision of the scheme. These characteristics are similar to the decision-making behaviour mentioned in section 2.2.5.

1.Complete Enumeration Approach

An enumeration is a complete, ordered listing of all the items in a collection (Ray, 1984). In the design of the decision support system, the enumeration method is used to collect and evaluate all feasible schemes, which are then used to produce the optimal results (Adelman, 1992). In some industrial applications, a limitation of the enumeration method is that it is difficult to list all feasible schemes and that will result in large deviations between results and expectations (Charnes, 1978). This method is effective when it is predicted that there are few feasible schemes (Charnes, 1978).

2.Computational procedure

The computational procedure usually uses a series of algorithms to describe the characteristics of a specific problem and can call upon the stored information to obtain the desired results (Shohet, 2004). The direct search algorithm is a typical method when decision makers transfer the requirements into the proposed decision model. This method was first introduced by Hooke and Jeeves in 1961; other algorithms such as tabu, genetic and golden-section soon followed. It can perform a "logical search" (Power, 2015), and then solve the problem using a logical statement. Russell and Taylor believed that a direct search algorithm can be applied in the situation of a scheduling problem, but also can assist users to find solutions in other areas.

3.Cost benefit analysis

The cost benefit analysis method has been introduced into decision support system development and effective evaluation can result in meaningful suggestions for this important area of finance (Ackerman, 2002). Two theories are involved in this method: comparing costs and decision making in evaluating benefits. The methods of cost benefit can be utilized for financial support in certain applications; however, it is difficult to quantify the benefit of a specific DSS. For a host organization, qualitatify will be a huge benefit for the systems' development (Pearce, 2006). Although there are only a few methods for defining the benefits of cost benefit methods, some intangible benefits will be considered in the analysis, and those benefits should be researched separately. In the cost benefit method, the discount rate should be discussed for directly reflecting the intangible benefits (Quah, 2007).

4.Multiple-Criteria Decision Making

Multi-criteria decision making (MCDM) refers to the decision making in a set of finite scenarios which are conflicting and inconsistent (Triantaphyllou, 2000). The mechanism of multi-criteria decision-making methods is:

1. Projects can be evaluated, sorted and selected.

2. When researching a project, each decision factor is treated as the main criterion, and the numeric value of these factors is processed and extracted in a series of methods, then giving weight to the importance of each factor.

3. Matrices can be used to process evaluation data and organize matrix information in a variety of ways. Decision-making meetings also can be organized to quickly reflect the opinions of decision-makers, resulting in a consistent outcome.

MCDM can be divided into two categories: multi-attribute decision making (MADM) and multi-objective decision making (MODM). Among them, multi-attribute decision making, also known as multi-objective decision making with limited scenarios, refers to the decision-making problem of choosing the best alternative or ranking the scenarios when analysing multiple attributes. Multi-objective decision making refers to the decision that needs to analysis two or more objectives (requirements) simultaneously, and the best decision needs to satisfy the factors that are related and restricted to each other (Liu, 2007).

The multi-criteria method can be expressed in an equation as follows.

$$C(C_1, C_2 \dots C_n) = \sum_i^n W_i \times V_i(C_i) \quad (2.4.1)$$

where, C and C_i indicate the criteria, which are rules for evaluating the performance under the objectives of decision making; W_i represents the relative importance (weights) of criterion i in all criteria; V_i represents the performance under the criteria of C_i. The equation shows that a variety of tools and methods can be applied to the multi-criteria method, including effective constants, effective models, and operation utility models. Choosing the most appropriate methods and tools depends on the specific characteristics of the research questions (Triantaphyllou, 2000). In this equation, quantitative and qualitative criteria can be used, according to weights, and will indicate the expected performance of each criterion in the decision support system. These criteria include natural units and artificial scale measurements (Liu, 2007). Other tools, including semantic divide and questionnaire survey, can also be used to assess the satisfaction of users in various aspects in the decision-making process.

5.AHP (The Analytic Hierarchy Process Method)

The Analytic Hierarchy Process (AHP) method was first proposed by Saaty (1980), which can be used to evaluate and develop a decision support model. The AHP method constructs any complex problem with multi-criteria, multi-evaluators, and multi-periods into a hierarchical model. Elements located at the high level belong to general problems, such as the goal of a decision project, while the lower level elements are expressed in detail, such as the specific selection criteria. At each level, each pair of elements is compared to determine the relative importance of the completion of the high-level goals. By using this method, the properties of alternatives can be evaluated or achieve the total objective (Saaty, 1980).

The AHP is also one of the multi-criteria decision methods. Meanwhile, some of the differences are also highlighted, which contains the advantages of AHP application. First, the analytic hierarchy process can solve the problem systematically, and be able to provide the depth of the problem; it can evaluate the task that has been completed at a high level and determine the difference between results and expectations. Second, this method can be used to represent different views and different dimensions to evaluate the proposed DSS in different levels of models and different criteria. Here, uncertainty and risk can be involved in the scope of the model size (Kahraman, 2003). The third advantage is mainly embodied in the evaluation of the value of the DSS. This method is proposed to introduce users to comparing the pair elements, rather than forcing them to arrange weights directly (Saaty, 1980). Fourth, the analytic hierarchy process has the consistency of inspection; if the judgement of the decision maker is not consistent throughout the whole process, the decision maker can re-evaluate the process. According to Saaty (1980), the developer of the AHP method, a consistency ratio of 10% or less is considered acceptable. When the degree of consistency is poor, it is necessary to get more information about the comparisons of the selection criteria involved. Such action typically calls for the collection of data from another round of judgments. Fifth, the analytic hierarchy process can evaluate the stability and flexibility of the model. Because the single element of the model does not affect the whole system, it becomes stable (Boender, 1989). Base on this principle, different objectives and programmes can be easily introduced into this model (Pohekar, 2004). The last advantage is that the method provides a friendly assessment of the environment and is beneficial to the decision-making process in panel discussions.

There are four steps to building an AHP model:

1. The AHP focuses on decomposing a complex problem into the appropriate levels, which include criteria and sub criteria, objectives and sub-objectives, as well as alternatives. A typical hierarchical model structure is shown in the following figure. In this figure, each layer has m criteria and n alternatives. After the establishment of a hierarchical structure of a specific problem, pairwise comparisons are used to create the criteria for measurement priorities and the decision alternatives. The pairwise comparisons include two methods: 1) to distinguish the importance between two current criteria or options at the higher level, and 2) to describe how to achieve these goals.

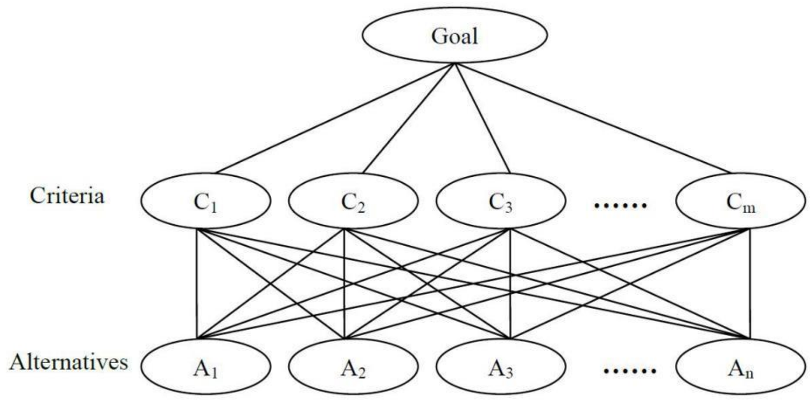

Figure 2.4.1 Pairwise companions (Saaty,1980)

3.Use preference tables to rank importance. Saaty (1980) defined a potential model, which included a scale of preferences from 1-9; 1 being a weak preference and 9 being a strong preference, for example, when a decision-maker was requested to decide on a preference between two criteria (e.g., C1 and C2), if they have a strong preference for C1 (9), then according to the preference table below, the preference of C2 should be marked as less than 9. Also, the decision maker needs to distinguish between their preference for each of two alternatives in the same table. It should be emphasized that preference judgment is subjective, and different decision makers may have inconsistent preference ratings.

Table 2.4.1 Preference table (Saaty,1980)

Verbal Judgment of Preference	Numerical Rating
Extremely preferred	9
Very strongly to extremely	8
Very strongly preferred	7
Strong to very strongly	6

Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally to preferred	1

The m criteria pairwise comparisons are introduced in a (m*m) matrix. Similarly, the comparison of each criteria has (n*n) alternatives that also can be presented by a pairwise comparison matrix. Here, A is defined as a (n*n) comparison matrix with n objects.

$$A = \left[A_{ij}\right] \tag{2.4.1b}$$

The comparison should be satisfied by:

$$a_{ji} = \frac{1}{a_{ij}} \tag{2.4.1c}$$

The normalized relative priorities $R_i(i = 1 \ldots n)$ will generate the method as:

$$A \times R = \rho_{max} \times R \tag{2.4.1d}$$

where R is right vector and ρ_{max} is the corresponding value, the priorities should achieve the conditions by following:

$$\sum_{i=1}^{n} R_i = 1 \tag{2.4.1e}$$

where W_j is the weight of criterion C_j, and the corresponding priority of alternative A_i is R_j^i, the total priority of alternative A_i can be defined as P_i, and that equation can be represented as below:

$$P_i = \sum_{j=1}^{m} R_i^j \, W^i \tag{2.4.1f}$$

Saaty (1980) also defined the consistency index (CI), which is used to measure the inconsistency that may occur in pairwise values, although Saaty's pairwise comparison matrix is always used in DSS design. The equation of the consistency index is presented as follows:

$$CI = \frac{(\rho_{max} - n)}{(n-1)} \tag{2.4.1g}$$

For each matrix, Saaty (1980) introduced a random value, called the random index (RI), and provided a resulting list of matrix sizes. For consistency ratio, the equation can be represented as:

$$CR = \frac{CI}{RI} \tag{2.4.1h}$$

Furthermore, the average random index for various matrix sizes is calculated in following table:

Table 2.4.1a Average random index (Saaty,1980)

Matrix Size (n)	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4. To evaluate the consistency. Saaty (1980) stated that the consistency ratio should be less than 0.10. If that ratio is acceptable, the decision process can be accepted. Otherwise, the decision maker should reconsider and revise the pairwise comparison until it satisfies this consistency evaluation.

6. Hybrid decision methods

Hybrid methods refers to multiple decision-making methods that are used in complex decision-making environments (Ribeiro, Moreira, van den broek, & Pimentel, 2011), which can eliminate the limitations of a single decision-making method. In the past five years, hybrid methods have been applied to solve many multi-objective issues. The approaches of hybrid methods were designed for specific fields with multi-objectives but were not universal. The existing research shows the combined method can be applied in their fields and can address the issues of a single method. However, there is no common framework to be developed to answer (Kar, 2015). To satisfy complex decision environments and decision objectives, neural network algorithms are usually used in this decision method to deal with the following problems:

1. The relationship between single methods which are used to design the proposed hybrid method.

2. Reasons for single method selection in specific field uses which are not mentioned by the previews section.

3.The relationship between sub goals in multi-objective optimization.

2.4.2 Comparing possible approaches

There are three possible decision-making methods: ones that have multi-objective features, ones that are multi-criteria, and ones that are AHP and hybrid methods. Their characteristics are presented in the following table.

Table 2.4.2 Characteristics of possible decision-making methods

	Objectives	Criteria/methods	Relationship between criteria/methods
Multi-criteria	Multi-objective	Multi criteria	Importance ranked by weight
AHP	Multi-objective	Multi criteria	Criterion was ranked by hierarchical model
Hybrid methods	Multi-objective	Multi methods	Switch methods by using different technology, such as neural network

Other decision-making methods in section 2.4.1 are not suited for this study. The reasons are listed as follows:

1.The Road Department administration's multiple requirements determined the decision-making have multiple sub-objectives. It is not suitable for this study to calculate the optimal profit only. Therefore, the cost-benefit method is not suited to this research.

2.The road environment and road policies determine the requirements of the Road Department administrations. Therefore, it is difficult to obtain a consistent set of requirements and solutions, which means the enumeration method is not suitable for this research.

3.The sub-objectives proposed by Road Department administrations are independent and produced by parallel levels, there is no subordinate or hierarchical relationship in the sub-objectives. Therefore, the AHP method is not suitable for this study.

4.The relationship between sub-objectives proposed by Road Department administrations does not belong to the concept of neural networks; thus, the hybrid decision-making method is not suitable for this study.

2.4.3 Weighting technologies and their characteristics

Objective techniques, including objective weighting techniques, are suitable for data extraction in this study, because these methods are based on existing data. At present, subjective technology and objective technology have the following characteristics:

The subjective method (Hou, 2019) is a method to determine the attribute’s weight according to the decision-maker's (expert's) attention to each attribute. The original data is obtained by the expert's subjective judgment based on experience. The commonly used subjective methods include average method (Hou, 2019), Delphi method (Yuan, 2015), AHP method (Jayant, 2017), binomial coefficient method (Tian, 2019), ring ratio scoring method (Hou, 2019), minimum square method (Mazen, 2019), fuzzy method (Chen, 1992), etc.

The subjective method is an earlier and more mature method. The advantage of the subjective weighting method is that experts can reasonably determine the order of attribute weights according to the actual decision-making problems and experts' own knowledge, so as not to contradict the actual importance of the attributes. However, the decision making or evaluation results have strong subjective randomness and poor objectivity, which increases the burden on decision analysts and has great limitations in application.

In the objective method (Zhang, 2018), original data is formed by the existing data of each attribute in the decision-making scheme. Its basic idea is this: the attribute weight should be the measurement of the variation of each attribute in the attribute set and the influence on other attributes; the original information of weighting should be directly from the objective environment, and the process of processing information should be to deeply explore the interrelationship and influence of each attribute; and then, the attribute weight is determined according to the relationship of each attribute or the amount of information provided by each attribute. If an attribute has no difference for all decision schemes (for example, the attribute values of each decision scheme are the same), the attribute has no effect on scheme identification and sorting, and its weight should be 0; if an attribute has significant difference for attribute values of all decision schemes, such attribute will play an important role in scheme identification and sorting, and it should be given a large score weight. Therefore, the size of the attribute should be determined according to the value difference of each scheme under the attributes. The greater the difference, the greater the weight of the attribute, and vice versa.

Common objective methods include principal component analysis (Zhang, 2018), entropy method (De Boer, 2005), deviation and mean square deviation method (Wang, 1999), multi-objective programming method (Weng, 2019), etc. Among them, the entropy method is widely used. The data used in this method is decision matrix, and the determined attribute weight reflects the dispersion degree of attribute value.

Review work shows 1. The objective method is mainly based on the original data to extract values, not easily affected by emotion from interviews; 2. In the case of sufficient theoretical information, the use of mathematical results can reduce the cost of interviews.

2.5 The competing theoretical framework

This research adopts the concept of multi-criteria decision making to explain the decision-making behaviour of highways departments (Section 2.4.3). According to the concept of multi-criteria decision making proposed by Triantaphyllou (2000), and the multi-criteria equation 2.4.1， the compete decision-making framework of this research should include the following elements:

1. Requirements of Road Department administrations.

2. At the expert-meetings held by the Road Department administrations, the experts proposed the criteria for evaluating the performance of ETC equipment under the requirements of the Road Department administration.

3.The performance of ETC systems was evaluated by experts at the expert-meeting.

4. The satisfaction of Road Department administrations are used to present if the ETC system satisfies the requirements.

Among them, the satisfaction can be calculated by the following equation, which was referred from equation 2.4.1.

$$S = \sum_{i=1}^{n} W_i \times P_i(C_i) \qquad (2.5.2)$$

From above equation, S indicates the satisfaction of the Road Department administration with an ETC system. The integer i is any number from 1 to n. It means n criteria are used to evaluate the performance of ETC in decision-making behaviour, and i is the sequence number of a criterion. Ci represents one of all criteria in the decision making. Pi represents the ETC system performance evaluated under the criterion Ci. Wi represents the weight of criterion Ci.

When more than one ETC system is evaluated by the Road Department administration, the system with the highest satisfaction will be selected. The following improved equation can be used to describe this behaviour.

$$Max(S_j) = Max\left(\sum_{i=1}^{n} W_i \times P_{ij}(C_i)\right) \qquad (2.5.3)$$

From above equation, the integer j is any number from 1 to m. It presents m (total number) ETC systems were provided by manufacturers, and j is the sequence number of a system.

This study presented an initial model in section 1.6 to demonstrate the ETC selection process. However, by consolidating the conceptualized ETC selection and decision-making process in the literature review, more insight can be gained. Therefore, this study incorporates these concepts into the compete model (see Figure 2.5) to explore the roles of requirement, performance, criteria, and satisfaction in decision making. The proposed compete model follows the characteristics of the multi-criteria decision-making method. To avoid duplication, I have only listed four elements (requirements, performance, criteria, and satisfaction).

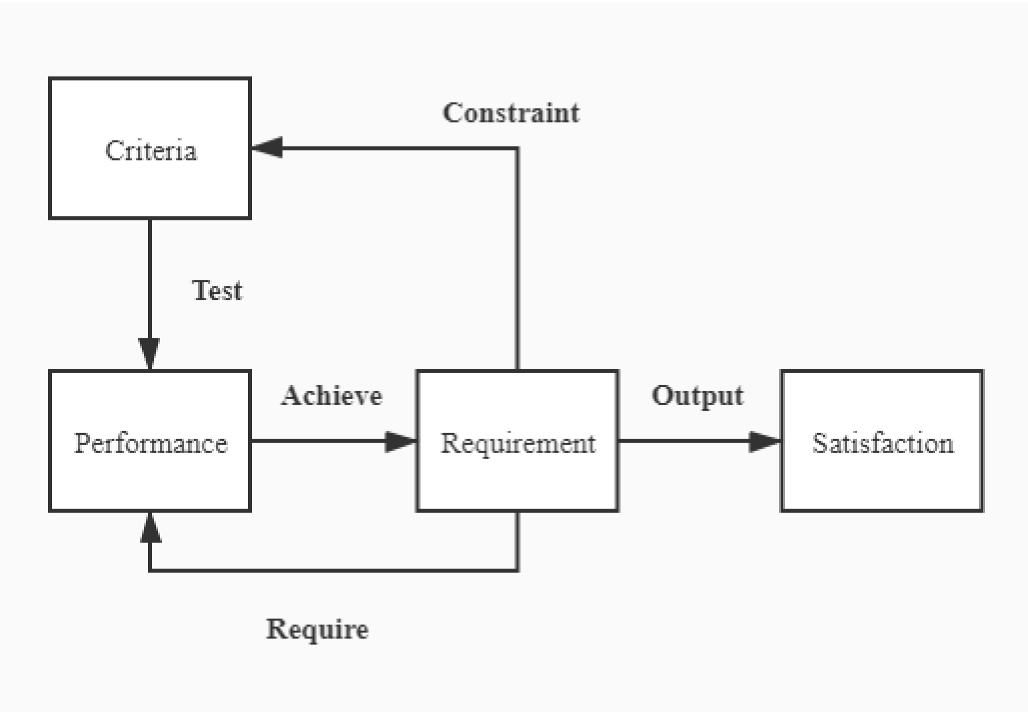

Figure 2.5 Proposed compete framework

Figure 2.5 shows the relationship of four elements in decision making:

- Require: requirements proposed by Road Department administration, as decision goals to obtain suitable ETC systems.
- Test: criteria proposed by experts in expert-base meetings, as the testable expression to evaluate the ETC system performance under requirement.
- Achieve: ETC systems performance are evaluated under each criterion, and the

evaluation results are used to measure if decision making has achieved the requirements of Road Department administrations.

- Output: satisfaction is output data from the performance evaluation, to outranking the ETC systems in selection.
- Constraint: requirements limit the scope of decision making, to ensure that criteria do not overflow this range.

2.6 The decision support system for ETC selection

A decision support system is an information system that supports business or organizational decision-making activities (Desanctis & Gallupe,1987). In ETC selection, the decision model developed by this research strived to replace the existing unstructured decision with structured decision. Based on the types of decision problems and the contents of this study, the decision support systems for ETC selection are divided into the following three status.

1. Unstructured decision: The traditional road equipment procurement (section 2.2.2) process is complex, and its decision-making process and methods have no certainty rules to follow, nor unify decision-making rule and model to reference. The opinions of decision makers (knowledge, experience, perception, judgment, insight, personal preference and decision-making style, etc.) have a considerable impact on the decision-making effect of each decision stage.

2. Semi-structured decision: The data of traditional road equipment procurement (section 2.2.2) are uncertain or incomplete. Although there are some decision criteria and appropriate performance evaluation can be established to meet the requirements of the road administration department, the decision criteria may be changed due to the requirements of the road administration department. Therefore, if researchers only pay attention to some special requirements of the road administration department, such ETC selection behavior may become a semi-structured decision. For example: only calculate the profit of a toll road. This is the situation that this study tried to avoid.

3. Structured decision: The purpose of this study is to describe the environment and rules of the ETC selection with a certain model, generate a decision scheme in an appropriate way, and select the best satisfaction value from a variety of ETC systems

(section 2.5). Because this research is devoted to establishing such a model, it can be simulated by computer.

It can be seen that the purpose of this study is to use a model to solve the decision-making problem of ETC selection and select the optimal decision from a variety of schemes (structured decision). It can help the road administration department make decisions on the road environment with a massive ETC product information and not specified in advance. Therefore, the decision support system developed in this research has a universal architecture (Dialog-Data-Modeling, DDM), with three parts (Desanctis & Gallupe,1987).

1. The database (or knowledge base).
2. The model (the decision context and user criteria).
3. The user interface.

2.6.1 The database

The database of ETC selection mainly contains the knowledge and expertise of decision makers. This is mainly reflected in the performance analysis of ETC System based on road environment and road policies. That is, in section 2.5, the compete decision framework discussed the relationship between requirements, criteria and performance with require, test, achieve and constraint.

2.6.2 The model

Equation 2.5.2 described the decision context and decision makers' criteria. Satisfaction of ETC systems was calculated by this equation based on criteria of road department administrators are results of ETC selection activities.

2.6.3 The user interface

The user interface of decision support system was embodied in two aspects, which is used to describe the data input and output.

1. Inputs: Any factors, numbers and characteristics to analyze of ETC selection, includes ETC attributes, road environments and road policies.

2. Outputs: The maximum satisfaction was generated by equation 2.5.3, based on the decision model (section 2.6.2).

2.7 Summary

A number of conclusions can be drawn from the above discussion regarding the background of ETC systems and the characteristics of decision making to ETC selection.

First, China's ETC system adopts RFID technology. The ETC tag is installed on the vehicle, which is called an OBU; the ETC reader is installed on the toll gate, which is called an RSU. However, Road Department administrations complain current ETC uses have problems with 1) the high costs of tags, 2) difficulty selecting tags, and 3) unreasonable traffic resource allocation.

Second, the literature review revealed that the decision-making behaviour of selecting ETC systems are occurring in the procurement of road equipment. ETC attributes, road environments and road policies are important factors that affect this behaviour.

Third, there are five important decision methods useful in this research. Among them, cost-benefit analysis is suitable for the cost calculation of ETC systems; the enumeration method and computational procedure are suitable for listing feasible schemes and testing ETC system performance; the multi-criteria decision-making method is conformed to the design of the decision model.

Finally, according to the concept from review work, the compete decision-making framework of this research should include the elements of requirements, criteria, performance and satisfaction. The relationship of these elements was presented in Figure 2.5.

CHAPTER THREE: METHODOLOGY AND RESEARCH PLAN

3 Overview

The rationality of this research methodology development is provided in this chapter. The design and analysis path of this study developed specific methodological directions according to research objectives and the decision-making process framework. The theoretical framework (section 2.5) indicated four elements are involved in decision making: performance evaluation, criteria weighting, requirements definitions and satisfaction calculations. Among them, information collections that were based on expert-based interviews, were used to explore the influence of each element (performance, criteria, requirements) in decision making (section 2.5); data analysis was based on objective methods (section 2.4.4), using existing data from review work (Chapter 2) to support decision-making theories and explore the characteristics of each element.

Therefore, the objectives of this chapter are to:

- Justify the methods used in information collection (section 3.1).
- Justify the data analysis in each sub-process of the decision support framework (section 3.2).
- Justify and explore the research protocol to be used in information collection. (section 3.3).

3.1 Methodological approach

From the perspective of the Road Department administrations, expert-meetings (Chapter 2.1.2) indicated decision-making processes and decision elements (Chapter 2.6). However, this decision-making process is not structured, which includes: 1. inconsistent requirement results in different criteria and weights; 2. different criteria when requirements are consistent. The reason for this lack of structure is the impact of the road environment and road policies. Since the selection of ETC systems does not present a traditional mathematical formula, information collection is required to use semi-structured questionnaires. The issue of semi-structured technology is that more information may be generated that is ultimately inconsistent with the expectations of the interview. In this research, the interview environment can overcome this problem, because participants of interviews are often experienced in ETC selection.

Considering that ETC selection belongs to a multi-criteria decision-making group, criteria and their weights should be defined to assist making decisions among multiple ETC systems (section 2.5). Meanwhile, the characteristics of decision making (section 2.2.2) and the advantages of objective methods (section 2.4.4) require researchers to use quantitative methods to measure criteria.

This study used semi-structured technology to collect qualitative information on requirements, ETC attributes, and criteria. Weighting preference, on the other hand, requires using a quantitative method to complete the measurement. Researchers emphasized the rationality of combining both qualitative and quantitative techniques (Denzin, 1989; Strauss & Corbin, 1990). This combination is intended not only to develop or extend existing theories, but also to enrich the data from interviews and enhance quantitative output (Beedles, 2002). Therefore, this combination can overcome the limitations of the single method.

3.2 Research design

Considering different ETC systems are provided by manufactures, with their performance under different criteria, and they may have some conflicting criteria for ETC selection as well, this decision-making issue is a multi-criteria problem. The proposed multi-criteria decision support framework is a procedure to be organized as ETC selection, but important information such as requirements, ETC attributes and criteria, were collected from expert-based interviews. The following figure shows the sub-process, output, and inputs from information collections.

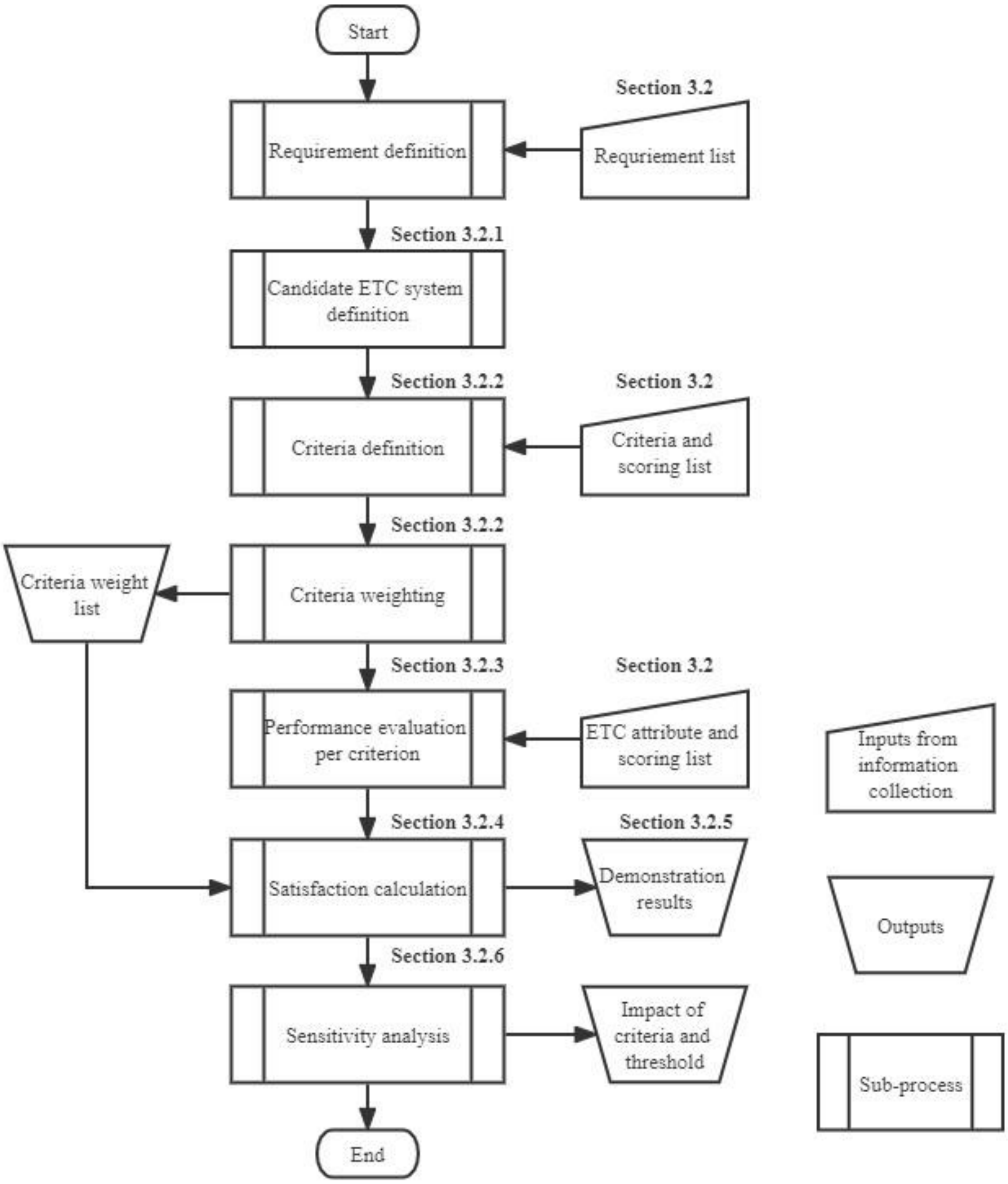

Figure 3.2 Decision-making framework

As shown in the above figure, the first step includes the requirements of the Road Department administration, which were obtained from expert-based interviews. The scope of candidate ETC systems which were given in the literature review (section 2.2.1), are more detailed in this chapter. Then, ETC attributes were used to participate in the evaluation, and quantitative techniques objectively measured experts' opinions on performance evaluation. In the interviews of this study, experts from different fields were invited to participate. This combination allowed for a sufficient diversity of opinions while still occasionally sharing a common understanding of some of the core issues (section 2.2.2). Next, criteria and their weights were defined. Quantitative methods were also used to measure ranking from experts, and the entropy method was used to obtain criteria weights. The researchers then calculated how satisfied the Road Department administration was with each ETC equipment. After presenting the experimental results, a sensitivity analysis was performed to determine the impact of the criteria and ETC attributes on decision-making.

3.2.1 Candidate ETC system definition

The candidate ETC system refers to the ETC equipment provided by the manufacturers waiting to be selected by the Road Department administration when procuring road equipment (section 2.2.2). That is, the object of the decision making (section 2.2.1). The candidate ETC system is a broad concept, which is not limited to road device procurement activities, in this research, it means all ETC devices that satisfy the requirements of Road Department administrations. This made it difficult for researchers to define the scope of the system in terms of technical parameters. Based on the review work (Chapter 2) and the scope of the study (section 1.6), the candidate ETC system defined in this research must have the following characteristics:

1. A candidate ETC system must be the object of selection, which is a road equipment with RFID technology, and is used for road toll collection (Chapter 2.2.1).

2. It composed of a reader (an antenna is used to transmit signals from tags and a reader is used to convert signals to data) and tags (including antenna, radio frequency generator, power supply system and security-related integrated circuits) (limited by the study scope in section 1.6).

3. Its performance is determined by ETC attributes (section 2.3.1) and is influenced by the road environment (section 2.3.2) and road policies (section 2.3.3).

3.2.2 Criteria definition and weighting

Review work indicated that criteria are rules for evaluating the ETC performance under requirements (section 2.2.2). Information collection provides an opportunity for the researcher to reach out to experts who have experience with ETC selection. Through the data collection agreement, I interviewed participants with expert-meeting experience to identify criteria. Extensive experience in ETC selection made the definition of the criteria conform to the requirements of this study. In addition, two techniques are used to rank criteria and determine criteria weights: 6-point semantics and entropy methods.

1. 6-point semantics

This research used 6-point semantics preference to categorize the collected information. At present, there are three types of popular preference tables: 5-point preference, 7-point preference and 9-point preference. The semantic table of this study was developed from the 5-point preference table. It divides semantic intensity into 1-5 levels, representing five different semantics from "strongly disagree" to "strongly agree". In this research, all the participants in expert-based interviews had experience in ETC equipment selection. They knew the objective of the questionnaire and could eliminate uncertain answers as much as possible. 5-point preference can distinguish the level of tendency, and is also better at avoiding the occurrence of uncertainty. Therefore, compared with the other two preference tables, the 5-point preference suits the characteristics of this research (Saaty, 1980).

Due to the different work characteristics of experts who were participating in information collection, there are different scores for each criterion. Therefore, I have used this technology to categorize intonation intensity. For the classification of criterion importance, we divided them into the following scores according to the semantics of the participants.

Rank 0: This criterion is not in my consideration, and there is no context related with my work.

Rank 1: This criterion is not important in the decision-making process.

Rank 2: This criterion is less important in the decision-making process.

Rank 3: This criterion is moderate in the decision-making process.

Rank 4: This criterion is more important in the decision-making process.

Rank 5: This criterion is very important in the decision-making process.

It should be emphasized that when a criterion scored 0, the rating was not included in the calculation. Meanwhile, when the average score was 5, the criterion was taken as a prerequisite for decision making. That is, the value under the criterion can be calculated in the satisfaction equation only after the weight was scored in the range of 1-5.

2. Using entropy methods for weighting

In this study, I used the entropy method to measure the weight of each criterion. The reason for using this method depends on the discussion of section 2.2.2. It indicated that experts from different positions bring diversity on their weighting scoring. That diversity usually attracts Road Department administrations to determine the optimal in comprehensive decisions.

Information from review work indicated that the weighting of decision criteria has the following characteristics:

1. Based on their experience, experts independently rank and determine the importance of each criterion.
2. The differences suggested by experts attracted more attention from Road Department administrations.
3. Experts who participate in the decision can provide the suggestion within the scope of their position.
4. Experts come from a wide range of positions and may have diversity in their suggestions.

Therefore, compared with other methods (mentioned in section 2.4.4), the entropy weight method was used in this study and satisfied the following conditions.

1. Suitable for expert scoring, feedback from industry-knowledgeable and experienced participants minimized the deviation caused by clear suggestions. The entropy weight method was helpful in reducing this deviation.
2. More samples bring more accurate results. The expert-based interview in this study invited 28 participants from three different positions. Diversified feedback resulted in more objective weighting.
3. Experts' different opinions may lead to different weighting. The entropy weight method was helpful to show these differences. Differentiated decision-making output facilitated the choice of Road Department administrations.

As the process of entropy calculation was complex (De Boer, 2005), we used an example to represent its features:

If a Road Department administration has many criteria to evaluate ETC systems (we set the total number of criteria as m), according to De Boer's (2005) theory, we can calculate the entropy value H_j under a specific criterion (we call this criterion j) by using following equations 3.2.2.

$$H_j = \frac{1}{ln(n)} \sum_{i=1}^{n} P_{ij}\, ln\left(P_{ij}\right) \tag{3.2.2}$$

$$P_{ij} = \frac{(1+y_{ij})}{\sum_{k=1}^{m}(1+y_{kj})} \tag{3.2.2a}$$

As the internal parameter, the possibility value of entropy changes should be calculated. In equation 3.2.2, we used P_{ij} to present that possibility of changes. Both i and j are nature numbers; We set i as a specific ETC system, and j as the criterion of the ETC system i. y_{ij} presented the ranking score (set by the semantic table) issued by experts for the criterion j.

$$W_j = \frac{(1-H_j)}{n-\sum_{j=1}^{n} H_j} \tag{3.2.2b}$$

Finally, we introduced the entropy value H_j into equation 3.2.2b, and calculated the entropy weight W_j of the criterion j.

After we calculated the weight W_j, then we introduced those weights into equation 2.5.3 (discussed in section 2.5), and generated the satisfaction value.

3. ETC attributes ranked by the semantic method

The semantic scoring method was used to measure the participation of ETC attributes in performance evaluation. Under a certain requirement of the Road Department administrations, the discussed ETC attributes with high scores will be included in the performance evaluation, and those with low scores will be excluded. It pointed out is that the mechanism of the semantic scoring method is consistent with the criteria ranking (section 3.2.2).

Rank 1: The discussed ETC attribute is not considered in this performance evaluation at all.

Rank 2: The discussed ETC attribute has only a small chance of being considered in this performance evaluation, but such participation in decision making is not universal. For example, ETC tags with anti-interference designs are often installed on vehicles transporting metal items, which does not mean that all on-board tags need to have this design. At the same time, closed anti-interference containers can be used to replace this design. This means that ETC attribute may affect decision making, but it is not absolute.

Rank 3: The discussed ETC attribute is likely to participate in the performance evaluation, the possibility of this participation depends on the road environment and policies.

Rank 4: The discussed ETC attribute is considered in this performance evaluation, but such participation may not conform to special ETC applications. For example, the normal ETC tag design does not meet the anti-interference requirements. These tags can be installed on most vehicles, but may not suit anti-interference metal transport vehicle installation.

Rank 5: The discussed ETC attribute is fully involved in this performance evaluation.

Like criteria ranking, a 0 mark of an ETC attribute means participants are not sure of the performance evaluation under this requirement. Meanwhile, only with an average score above 3 will the discussed ETC attribute be considered in performance evaluation.

3.2.3 Methods of performance evaluation

Published literature and industry reports provided methods for performance evaluation under different requirements. These methods include the following content:

1. Cost-benefit evaluation methods considering planned cost, unplanned cost and persisted cost were used in ETC system profits evaluation (O'Sullivan, 2003).

2. Traffic management methods, such as ETC equipment deployment in front of toll station, traffic flow analysis and traffic lane configuration were used to evaluate ETC traffic capability (Lai, 2018).

3. The reliability evaluation method provided a reference to indicate abilities of ETC equipment to effectively resist the external environment, to improve reliability (Gu, 2018).

4.The contents of safety protocol and anti-collision protocol in road policies indicated the conditions for ETC equipment to satisfy the compatibility requirements (Li, 2013).

5.The battery energy consumption calculation method was used to evaluate the tag life (Liu & Ba, 2016).

The above methods are used in performance evaluation to solve the following problems:

1. Objectively evaluate the performance of ETC systems under a certain criterion. For example, under the "profit" criterion, the high benefit of ETC systems will be satisfied by the Road Department administration.

2. To find the characteristics of the criteria. For example, the "profit" criterion requires that the ETC system bring considerable revenue, while the "safety" criterion requires that the ETC equipment must adopt the signal encryption protocol of ISO / IEC 18000-6c and EPC class 1 Gen 2. It can be seen that the "profit" criterion uses revenue to quantify the performance, and the "safety" criterion requires the system to meet specific conditions, and they have different characteristics.

3.2.4. Using Normalization to unify measurement

Different criteria have their own characteristics, which lead to inconsistency in the performance evaluation. For example, the result of the profit calculation is capital, while the result of the traffic management evaluation is unit time traffic volume. It is not easy to quantify two types of data into a unified standard. The solution is that I used normalization to set these values into a uniform measurable range. The normalized formula was expressed as follows (Chankong, 2008).

$$P_{ij} = \frac{x_{ij}-x_{minj}}{x_{maxj}-x_{ij}} \qquad (3.2.3)$$

In the above equation, the integer i is any number from 1 to n, which means there are n criteria are used to evaluate the performance of ETC; i is the sequence number of a criterion; the integer j is any number from 1 to m. which presents there are m (total number) ETC systems provided by manufacturers, and j is the sequence number of a system; P_{ij} is the normalized performance; x_{minj} presents the minimal performance value of ETC system under criterion j; x_{maxj} presents the maximal performance value of ETC system under criterion j.

3.2.5 Demonstration and evaluation

The demonstration work used the developed model to produce a set of new ETC systems to address Road Department administrations' requirements. In this stage, I have used three real world road projects as the experiment environment to run this decision-making model. The detailed information of the results was issued after inputting ETC attributes into this model. All demonstration work followed the below approach:

1. To create a sample database of a set of ETC systems with information of both readers and tags which are provided by manufactures.
2. List assumptions of road environment, policies and other outer data.
3. Transfer the ETC attributes as the decision input.
4. Introduce those decision inputs into the decision model with the mathematical formation as linear, equation, or decision trees.
5. Produce the Road Department administrations' satisfaction value to the proposed ETC system as decision output to address the Road Department administrations' requirements.

The evaluation work mainly presented the difference between the resulting system (with the highest satisfaction value) and the ETC system currently used. Typically, I listed the current system's parameters, and when there is no difference between that currently used and the decision output, the decision model is considered to meet the requirements of the Road Department administrations. In contrast, when the difference occurred after comparison, the model needed to be improved. The process of the evaluation work is presented below:

1. Find the ETC system that has highest satisfaction value.
2. List RFID parameters of both current ETC system and decision output.
3. Compare and find out the difference.
4. Evaluate the difference and find out the reason.

3.2.6 Sensitivity analysis

Sensitivity analysis focused on the impact of each factor in the decision output. In this study, the coordinate system is used to describe the impact that can intuitively show decision-making details. Sensitivity analysis focuses on the following works:

1. Analyze and explain the impact of the output (criteria) of performance evaluation and the satisfaction calculation of Road Department administrations.
2. Analyze and explain the impact of each threshold (discussed in section 4.4.2) on the satisfaction calculation of Road Department administrations.

3.3 Information collection

This study used expert-based interviews to collect information. The most significant advantage of expert-based methods is that experienced participants can provide representative opinions and feedback. In this study, this advantage is mainly reflected in the following aspects:

1. The expert-based participants have rich experience in ETC equipment selection and can put forward appropriate opinions and feedback.

2. They can accurately understand the questions which are issued by researchers, without semantic and conceptual ambiguity.

3. Researchers can avoid the introduction of relevant theories, to improve the efficiency of interview.

The following sections describe objectives, data collection methods and the questionnaire settings of the expert-based interviews.

3.3.1 Objectives of interviews

The purpose of the interviews was obtaining elements (requirements, criteria, performance) from the decision-making theoretical framework (see section 2.5) and was presented as input in the decision support approach (see Figure 3.1). The expert-based interview was designed and expected to achieve the following objectives:

1. Collect requirements from Road Department administrations.

2. Collect criteria from Road Department administrations' ETC selection activities and rank the importance for each criterion.

3. Collect ETC attributes that were useful in performance evaluation.

3.3.2 Determining the participants

The participants of interviews have rich knowledge of ETC selection and experience in participating in expert-meetings which were held by Road Department administrations. To collect information accurately, they should have the following abilities:

- Be able to summarize the requirements of Road Department administrations
- Be able to propose criteria to measure ETC performance and understand the importance of the criteria in decision making

- Be knowledgeable about ETC equipment and know which ETC attributes are useful for performance evaluation

3.3.3 Population and the sample of the study

Three groups of participants were invited for interviews: ETC technical experts, toll road managers, and government transportation department experts. ETC technical experts are persons with experience in designing and testing ETC equipment, have knowledge of ETC attributes and know how those attributes affect ETC system performance; toll road managers are persons with experience in managing ETC equipment and monitoring the road environment, they know how the road environment affects performance evaluation; government transportation department experts are people who understand road policies, and know how road policies constrain performance evaluation. Those participants came from the following research institutions and traffic management departments and have knowledge on ETC selections and equipment parameters:

1) Samples from ETC technical experts

The Intelligent Research Consulting Group (2016) listed both road and water transportation research institutions in China. There are more than 40 highway research institutions listed. Their works include the selection and testing of ETC equipment. By the end of data collection, I had collected answers from 17 ETC technical experts from these institutions. The reason for inviting ETC technical experts from these research institutions are:

1. These institutions are responsible for the testing of road ETC equipment and directly provide advice on the selection of local road equipment.

2. These institutions are responsible for testing product samples provided by RFID equipment manufacturers and determine whether these devices can be used for highway ETC system development.

3. These institutions do not participate in the production of RFID equipment, but have detailed information about RFID component manufacturers, and can provide detailed ETC product technical parameters (ETC attributes).

2) Samples from toll road managers

The Intelligent Research Consulting Group (2016) also pointed out, at the end of 2015, the Chinese mainland had provincial, autonomous region and municipality highway administrations. This means, to collect local road traffic information and relative ETC management data, I could find the suitable toll road managers according to the toll station lists which were provided by those highway administrations. By the end of data collection, I had collected samples from 10 toll road managers. The reason for inviting toll road managers from these provincial highway administrations was:

1. These highway administrations are responsible for the management of the local highway. They can provide information on the uses of ETC equipment and the operating status of toll stations in the area.

2. These highway administrations can provide road environmental information in the area, which includes traffic flow and the impact of ETC equipment on traffic management.

3. The information provided by these provincial highway administrations guides the planning of future highways, including the selection of road equipment such as ETC devices.

3) Sample from government transportation department experts

According to the Intellectual Research Consulting Group's (2016) statement, the ownership of China's highway determined that road policies are decided by the government. This means that road policy is consistent in China, and I believe that inviting one government transportation department expert from the transportation department to this expert-based interview was enough to ensure the integrity of this part of information collection.

3.3.4 Selection of qualified participants

This study used a variety of methods to ensure that participants were qualified.

Li (2019) pointed out that it is necessary to select knowledgeable key information stakeholders in any survey works. This means the ideal participants should have the quality of participating in ETC product design, road management and road policy implementation, and the experience of participating in the expert-meetings of road equipment selection (discussed in section 2.2.2). More specifically, as suggested by Shen (2019), the respondents were qualified from ETC research institutions and provincial administrations, who had complete knowledge and experience that they might have interest in the research. Considering these qualifications, those participants selected for this study were either technical experts of a project team or have experience of participating in the decision-making process of ETC selection.

In addition, there would not be more than one participant from each ETC-related institution, because qualified participants could provide a comprehensive opinion on behalf of the institution. At the same time, this also avoided repeatability of the collected information.

3.3.5 Protocol of expert-based interviews

The expert-based interview process follows a specific protocol and was ethics approved by AUTEC (ethics application 17/122 in Appendix 6), this protocol is shown in the following figure.

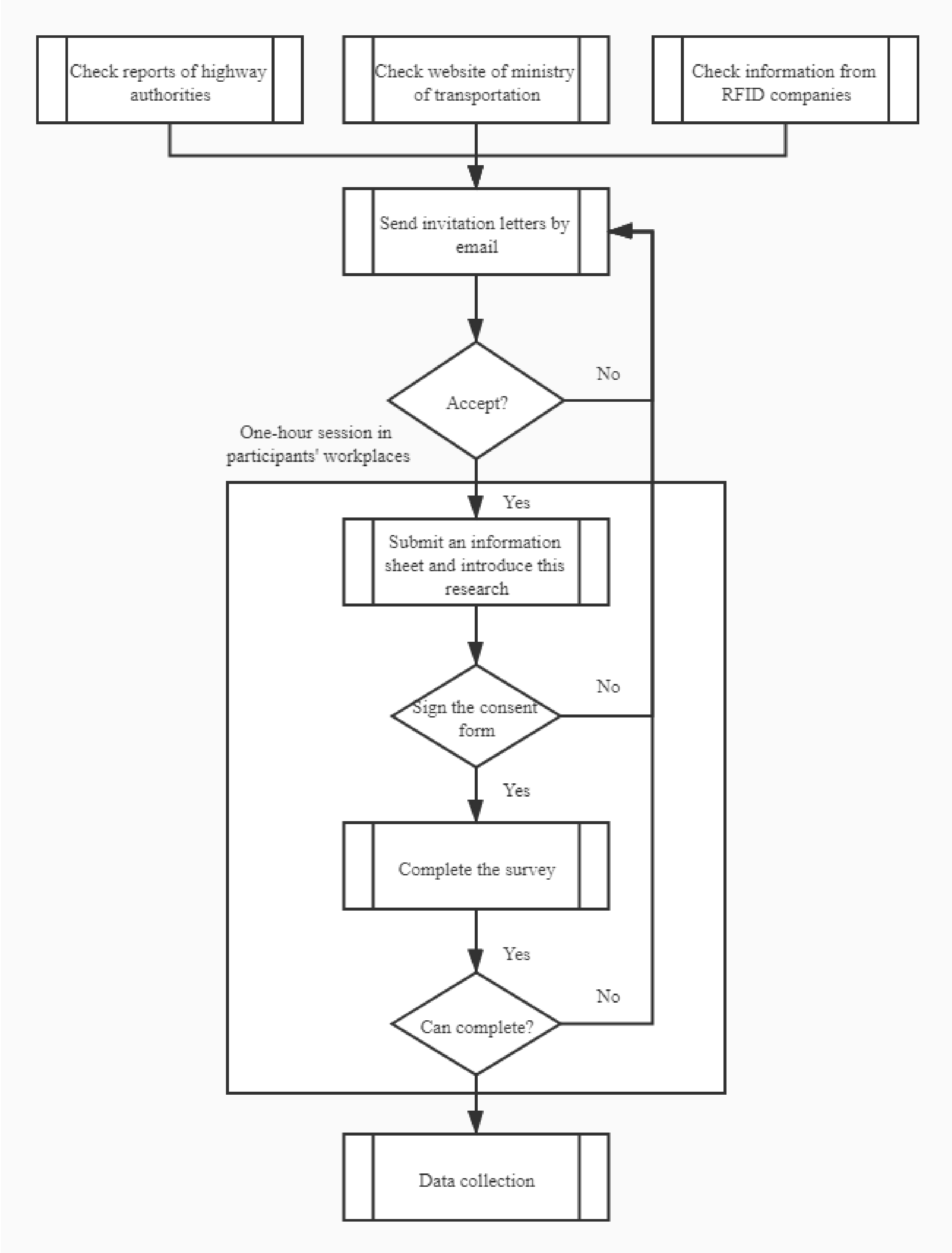

Figure 3.3.5 Protocol of expert-based interviews

The list showed participants were involved in 40 provincial research institutions, 31 highway administrations and government road management departments (discussed in section 3.3.3). I got to know these institutions and departments from reports of the national highway authority, the transportation ministry website and the directories of RFID companies, and recorded their contact information. Invitation letters (appendix 1) were then used to first contact these departments and institutions by email. Once I received responses from these institutions and departments, I recorded the information of the respondents and the interview locations (all interview locations in this study were participants' workplaces). In the process, I had read e-mails from these participants in detail and made sure that the information they provided was suitable; that is, the participants were qualified to meet the requirements of the study (discussed in section 3.3.4).

After receiving the agreement of the participants and recording the meeting time and place of appointments, I rushed to the participants' locations to start the interviews on time. The interviews were conducted face to face, and the duration was within one hour. This helped to avoid participant fatigue and to occupy the participants' work time as little as possible. At the beginning of the interview, I submitted information sheets (appendix 2) to participants, and introduced the purpose, content and development prospects of this research project. I also told participants how to complete the questionnaire during the interview, the problems that may happen and the ways to deal with these issues. With the agreement of these participants, consent forms (appendix 3) were signed to regulate research behaviour during the one-hour sessions.

The main task of the participants in the expert-based interview was to answer my questions. This did not mean that there was no communication in the process. As the participants filled out the questionnaire, I explained the questions in detail and tried to prevent ambiguity. As the questionnaire was simplified to be used in a one-hour session and there was not much in the content, the participants also communicated with me while filling out the questionnaire, to introduce and inform me of the reasons for their answers. Due to the limitations of participants' work characteristics, some questions in the questionnaire could not be answered and they gave up answering questions they did not understand. I believe this situation is acceptable and the interview was effective. In addition, some special reasons may hav caused participants to give up completing the questionnaire, such as lack of patience, and questions involve their working secrets, etc. In this case, participants could resign the consent form (appendix 3) and confirm withdrawal from the study.

3.3.6 Translation and pilot study

The original English version of the questionnaire was reviewed by the ethics group before the pilot study. According to the requirements of ethical documents, the questionnaire was revised and modified. In order to facilitate a quick response, the questionnaire was translated into the native Chinese of the respondents. This is because English is not widely used in China. The Chinese version of the questionnaire ensured clear communication with the respondents. The method of translating the questionnaire into Chinese is direct translation. A mentor in China tested the validity of the meaning of the questionnaire. In addition, as stated in the ethics document, I reviewed the better Chinese terms and expressions of each question to determine the authenticity of the translated Chinese version of the questionnaire.

In addition, pilot studies (Appendix 4) were conducted on a small number of sample participants (1 ETC technical expert, 1 toll road manager and 1 government transportation department expert) in China to improve the questions before final printing. Because the information obtained from the pilot study may be unstructured, for example, the exact criteria were not clear before the interview, I used a semi-structured questionnaire to obtain the information. These improvements included following aspects:

1. Identified and determined ETC attributes that were provided in the process of expert-meetings (discussed in section 2.2.2): costs, working frequency, vehicle speed limits, installation procedures, material, size of tags, battery design of ETC tags, anti-collusion configuration and encryption protocol constraint.

2. Determined the requirements which were usually mentioned by Road Department administrations: high profits, efficient traffic management, reliability, compatibility of safety design and long tag life.

3. Determined criteria that were usually used to measure ETC systems: profit, capability, reliability, compatibility, tag volume and tag life.

After the pilot study, the items in the questionnaire were clearly revised to ensure they were consistent with the participants' perceptions. The next section describes the contents of the questionnaire and the reasons for the design.

3.3.7 Questionnaire design

Following the data collection process in section 3.3.5, the content of the questionnaire was divided into four parts.

Part 1. Confirm the key information of questionnaire

This part of interview was used to confirm the information that was improved on in the pilot study, which includes participant categories, requirements of Road Department administrations, ETC attributes and criteria in decision activities. There are four questions was designed to complete this task. These questions were designed as follows.

Question Q1a. To obtain the category of a respondent, the question was designed as "What is the category of your works?". Three options were designed for participants: 1) ETC technical experts, 2) toll road managers and 3) government transportation department experts. This is a single choice question; participants can only choose one option.

Question Q1b. In order to obtain the requirements in the previous experience of the participants., this question was designed as "In your experience, what requirements were often put forward by Road Department administrations?". The candidate answers were confirmed in the pilot study (discussed in section 3.3.6) as 1) profits, 2) efficient traffic management, 3) reliability, 4) compatibility of safety design and 5) long tag life. Participants can choose more than one option. It should be emphasized that this question also provided participants with the option of supplementary information, which means this question was designed for more requirements that may not have been involved in the pilot study.

Question Q1c. To obtain the ETC attributes, this question was designed as "In your experience, what ETC attributes were often put forward by ETC manufacturers?". The answer options were also confirmed in pilot study (discussed in section 3.3.6) as 1) costs, 2) working frequency, 3) vehicle speed limits, 4) installation procedures, 5) material, 6) size of tags, 7) battery design of ETC tags, 8) anti-collusion configuration and 9) Encryption Protocol constraint. Those options can be multi-selected. The requirements for supplementary information were also designed into options to ensure the completion of the collected data.

Question Q1d. To obtain criteria in decision-making activities, this question was designed as "When you make decision to select suitable ETC systems, which criteria were usually considered?" Potential options were confirmed in the pilot study (discussed in section 3.3.6) as 1) profit, 2) capability, 3) moisture-proof design, 4) compatibility, 5) tag volume and 6) tag life. Like question Q1b and Q1c, participants can choose more than one option, and an additional option for supplementary information was designed for other criteria that were not mentioned in the pilot study.

Part 2. Participation of each ETC attribute

This part of the interview was used to gather the participation of ETC attributes in a performance evaluation to fulfill a Road Department administration requirement. This expert-based interview used the same types of measurement scales to overcome the use of similar measurement problems. Therefore, the present study used semantic scales including some reverse worded items in the questionnaire. Specifically, respondents were asked to give their perceptions of questionnaire items and their opinions were matched to a 5-point semantic scale table ranging from 1 to 5 for five construct measures (section 3.2.2). Missed answers were ignored and were not considered in the data analysis. The questions of this part were designed as follows.

Question Q2a. In order to evaluate the participation of each ETC attribute in the profit calculation, this question was designed as "In your experience, if Road Department administrations want a candidate ETC system with good performance of profit, what ETC attributes should be considered in this decision-making environment?". As the operational definition specifies, nine items (costs, working frequency, vehicle speed limits, installation procedures, material, size of tags, battery design of ETC tags, anti-collusion configuration and encryption protocol constraint) were extracted. Those items were represented as follows.

1.I believe that costs of ETC systems should be considered in profit calculations.

2.I believe that working frequency of ETC systems should be considered in profit calculations.

3.I believe that vehicle speed limits of ETC systems should be considered in profit calculations.

4.I believe that installation procedures of ETC systems should be considered in profit calculations.

5.I believe that material of ETC tags should be considered in profit calculations.

6.I believe that size of ETC tags should be considered in profit calculations.

7.I believe that battery design of ETC tags should be considered in profit calculations.

8.I believe that anti-collision configuration should be considered in profit calculations.

9.I believe that encryption protocol constraints should be considered in profit calculations.

Question Q2b. Like question Q2a, this question needs to be designed to evaluate the participation of each ETC attributes in the traffic management evaluation. The question was “In your experience, if Road Department administrations want a candidate ETC system with efficient traffic management, what ETC attributes should be considered in this decision-making environment?”. As the operational definition specifies, the intensity of the participants' semantics on these nine items needs to be obtained. Those items were represented as follows.

1.I believe that costs of ETC systems should be considered in traffic management evaluation.

2.I believe that working frequency of ETC systems should be considered in traffic management evaluation.

3.I believe that vehicle speed limits of ETC systems should be considered in traffic management evaluation.

4.I believe that installation procedure of ETC systems should be considered in traffic management evaluation.

5.I believe that material of ETC tags should be considered in traffic management evaluation.

6.I believe that size of ETC tags should be considered in traffic management evaluation.

7.I believe that battery design of ETC tags should be considered in traffic management evaluation.

8.I believe that anti-collision configurations should be considered in traffic management evaluation.

9.I believe that encryption protocol constraints should be considered in traffic management evaluation.

Question Q2c. Reliability evaluation also needed to consider the participation of ETC attributes, so the question was designed as “In your experience, if Road Department administrations want a candidate ETC system that is reliable, what ETC attributes should be considered in this decision-making environment?”. The intensity of the participants' semantics on these nine items needed to be obtained. Those items were represented as follows.

1.I believe that costs of ETC systems should be considered in reliability evaluation.

2.I believe that working frequency of ETC systems should be considered in reliability evaluation.

3.I believe that vehicle speed limits of ETC systems should be considered in reliability evaluation.

4.I believe that installation procedures of ETC systems should be considered in reliability evaluation.

5.I believe that material of ETC tags should be considered in reliability evaluation.

6.I believe that size of ETC tags should be considered in reliability evaluation.

7.I believe that battery design of ETC tags should be considered in reliability evaluation.

8.I believe that anti-collision configurations should be considered in reliability evaluation.

9.I believe that encryption protocol constraints should be considered in reliability evaluation.

Question Q2d. To measure the participation of each ETC attribute in compatibility evaluation, this question was designed as "In your experience, if Road Department administrations want a candidate ETC system that has compatibility of safety design, what ETC attributes should be considered in this decision-making environment?". Nine items were extracted. Those items were represented as follows.

1.I believe that costs of ETC systems should be considered in compatibility evaluation.

2.I believe that working frequency of ETC systems should be considered in compatibility evaluation.

3.I believe that vehicle speed limits of ETC systems should be considered in compatibility evaluation.

4.I believe that installation procedure of ETC systems should be considered in compatibility evaluation.

5.I believe that material of ETC tags should be considered in compatibility evaluation.

6.I believe that size of ETC tags should be considered in compatibility evaluation.

7.I believe that battery design of ETC tags should be considered in compatibility evaluation.

8.I believe that anti-collision configurations should be considered in compatibility evaluation.

9.I believe that encryption protocol constraints should be considered in compatibility evaluation.

Question Q2e. To measure the participation of ETC attributes in the tag life evaluation, the question was designed as "In your experience, if Road Department administrations want a candidate ETC system with a long tag life, what ETC attributes should be considered in this decision-making environment?". Nine items were extracted. Those items were represented as follows.

1.I believe that costs of ETC systems should be considered in tag life evaluation.

2.I believe that working frequency of ETC systems should be considered in tag life evaluation.

3.I believe that vehicle speed limits of ETC systems should be considered in tag life evaluation.

4.I believe that installation procedure of ETC systems should be considered in tag life evaluation.

5.I believe that material of ETC tags should be considered in tag life evaluation.

6.I believe that size of ETC tags should be considered in tag life evaluation.

7.I believe that battery design of ETC tags should be considered in tag life evaluation.

8.I believe that anti-collusion configuration should be considered in tag life evaluation.

9.I believe that encryption protocol constraint should be considered in tag life evaluation.

Part 3. Importance of each criterion

Question Q3a. Only one question was designed in this part. This question was designed as "In your experience, how important was each criterion in the decision-making activities?" As the operational definition specifies, six items (profit, capability, moisture-proof design, compatibility, tags volume and tag life) were extracted rating their importance on questionnaire items by a semantic scale ranging from 1 "strongly disagree" to 5 "strongly agree" for the five construct measures.

Part 4. Supplementary information from participants

This part of the survey was designed for supplementary information that could be provided by participants in that one-hour session, and had not been confirmed in the pilot study. In the first part of the questionnaire, corresponding supplementary options were designed in Q1b, Q1c, and Q1d. These supplementary options covered the additional ETC attributes, the requirements of Road Department administrations and criteria. Based on this possibility, the questions in this part needed to be designed to determine 1) the extent to which the new ETC attributes participate in the performance evaluation; 2) the participation of each ETC attribute under the new requirements that were proposed in the first part. 3) The importance of new criteria in the overall decision making. Questions were designed as follows.

Question Q4a. For the additional ETC attributes you provided in Part 1, please indicate the extent to which each participated in the decision making under each requirement that was requested by Road Department administrations.

Question Q4b. For the additional Road Department administration requirements that you provided in Part 1, please indicate the participation of all listed ETC attributes in decision making under that requirement.

Question Q4c. For the additional criteria you proposed in Part 1, please rank the importance in the comprehensive decision making.

CHAPTER FOUR: INFORMATION ANALYSIS AND DECISION SUPPORT MODEL DESIGN

4 Overview

The work of this chapter is to implement the methodology, decision-making process, and data collection provided in Chapter 3. During the model design, we first determined the requirements of the Road Department administrations. These requirements are independent and ultimately determine the direction of the decision making. Then, for each requirement, according to the semantics method, we counted and calculated the impact of the ETC attributes in the performance evaluation. Finally, the characteristics of the criteria were determined and weighted to generate a decision model.

The purpose of this chapter is to:

- Collect information on requirements and describe how they drive performance evaluation (section 4.1).
- Collect the ETC attributes and use the average values to determine participation in the performance evaluation (section 4.2 and section 4.3).
- List information on criteria from the interviews (section 4.2 and section 4.3).
- Discuss the performance evaluation under each requirement (Section 4.4).
- Discuss the characteristics of the criteria and weight them for model creation (section 4.5).

4.1 Requirements of Road Department administrations

The requirements of the Road Department administrations can be one or more in decision-making behaviour. The information collected from expert-based interviews show that participants described their cognition of decision-making behaviour according to their own environment and job position, and described their requirements according to their own understanding. This highlighted the requirements of the Road Department administrations; that is, the goal of decision making, which guides the direction of decision making and may produce different decision-making results.

The expert-based interviews show that ETC system selection should meet five requirements of Road Department administrations: high profit, efficient traffic management, high reliability, compatible safety involvement and long tag life. The decision makers used these requirements to construct their own performance evaluation with the related ETC attributes.

Since each requirement tests the performance of the ETC equipment in a certain aspect, the performance evaluation process is of positive significance to the Road Department administrations. In expert-based interviews, participants also realized that the ideal decision should meet all requirements at the same time and give more comprehensive results. Therefore, to ensure the difference of the criteria, it is necessary to find the characteristics of the criteria under the requirements. In addition, other constraints should be considered and converted into different expressions. This method was generally accepted by the participants, considered appropriate and easy to understand.

4.1.1 High profits

According to Lai (2018), the comprehensive profit of highways includes economic, social, and environmental aspects. Therefore, the potential benefits of an ETC system should be evaluated from these three aspects. After the interviews, most of the participants focused on economic benefits. Due to the limitations of their working environment, they could not focus on the other two aspects. Participants who were working in the government considered environmental and social benefits as also important. "*Obviously, an ETC system can bring social benefits, including improving the traffic management and reducing traffic accidents. At the same time, due to the introduction of electronic payments,* *personnel management defects (operational errors and possible corruption) are avoided.*" Regarding environmental benefits, this participant said: "*In the case of traffic congestion, the vehicle will start and brake continuously, which will lead to harmful gas emissions exceeding the normal driving situation. The emission of harmful gases in front of toll stations is higher than other places, which is caused by the slow driving of vehicles waiting for tolls. If we improve the efficiency of the ETC system and reduce vehicle congestion, it will greatly reduce the emission of harmful gases.*" The results of this interview work showed that all the participants agreed that "in terms of economic benefits, it is necessary to evaluate the performance of ETC systems through cost-benefit analysis. This requires 1. reducing the construction cost of toll stations; 2. reducing the management cost of highways; 3. increasing operating time and revenue".

4.1.2 Efficient traffic management

According to Lai (2018), an effective ETC system can reduce traffic congestion and improve the traffic capacity of highways. At the same time, it can also reduce traffic accidents and reduce maintenance costs of traditional toll collection systems. In terms of environmental benefits, effective ETC management can reduce vehicle fuel consumption, thereby reducing pollutant emissions. Expert-based interviews confirmed Lai's (2018) opinion. All the toll road managers believed that "*an effective ETC system can effectively monitor the operation of the highway. When the vehicle passes through the toll collection station, it only needs to reduce the moving speed to the allowable range, which saves waiting time. In this situation, the driver often does not need to stop, and the vehicle can pass through the toll collection station at a certain speed. This can reduce congestion*". "*In addition to easy management, drivers do not need to stop in front of toll stations, which could reduce the traffic accidents caused by deceleration.*" In terms of environmental benefits, a government transportation department expert explained: "*Vehicles are the largest source of air pollution sources and mobile harmful gases sources. Carbon hydrocarbon (CH), carbon monoxide, nitric oxide, TSP and other pollutants emitted by vehicles are one of the main causes of air pollution. In front of the toll collection station, the vehicle decelerates, which will cause a large volume of polluting gases, thus polluting the environment*". "*An efficient ETC system should improve the moving speed in front of the toll collection station, reduce traffic congestion, and also reduce the emission of harmful gases.*" Therefore, it is very important to improve the capacity of toll stations.

4.1.3 Reliability

Zhang's (2018) research shows that the reasons hindering the promotion of an ETC system include social and technical factors. Among them, technical factors directly affect the performance of an ETC system. In expert-based interviews, respondents' feedback validated Zhang's (2018) findings. "*There are still some reliability problems in the products that manufacturers promote to us; although this cannot question the ability of manufacturers, it pointed out the flaws in the design from the other side*". All interviewees believed that "*the quality of equipment is critical, which is evident in some special areas. In the south, equipment needs to cope with wet weather, while in the north, the cold resistance of equipment could be indispensable. This puts forward new requirements for designers*". This opinion had been confirmed by many ETC technical experts, "*Many Road Department administrations like us put forward equipment improvement requirements, because the equipment in some areas and some special applications are not stable enough. And these conditions, in our initial design stage are unpredictable such as the size of ETC tags. The larger size could bring strong signal transmission performance, but are harder to install on the vehicle*" A government transportation department expert analyzed the problem from a comprehensive opinion, pointing out: "*The reliability of technical factors obviously affects the promotion of equipment.*" When Road Department administrations find that losses due to low reliability, such as outages, congestion, and payment failure, exceed the expected costs, they prefer a mature traditional toll collection method.

4.1.4 Compatibility of safety design

An ETC system is responsible for identifying the identity of transportation carriers, and then implementing corresponding control. Some applications also involve the automatic deduction of machine fees. Therefore, the problem of information security cannot be ignored. In expert-based interviews, all respondents agreed that security settings were a necessary function of ETC systems. "*Deployment and uses of RFID systems should ensure that only authorized users can issue and identify tags, and attackers cannot forge and track these tags in any form.*" ETC technical experts believe that the security of ETC systems is like ordinary computer networks. But the reality is that the security of ETC systems is much more serious. "*This is not only because the cost of RFID products has greatly limited the processing ability and security encryption measures of RFID, but also because RFID technology contains more and more vulnerable insecure nodes than normal computers and network technology. Therefore, the design of a secure, efficient and low-cost RFID security system is still a challenging issue.*" Other toll road managers agree with this opinion: "*The security of an RFID system in the transportation industry includes not only the common characteristics of an ordinary RFID system, but also the special requirements of the transportation industry. Road planning departments must be very careful to consider the relationship between risks and costs.*" At the same time, the mature security design has been popularized in the market, which means the safety design of the tags must conform to existing safety standards to ensure that the device has compatibility.

4.1.5 Long tag life

According to Liu and Ba's (2016) research on the use of vehicle tags, once the tags are installed on the user's vehicle and used, it is necessary to ensure normal operation without maintenance for as long as possible. Therefore, the stability and reliability of the power supply system greatly affects and determines the promotion and cost-benefit of an ETC system in tag design. In expert-based interviews, the government transportation department expert and toll road mangers also confirmed the importance of the ETC tags' service life. "*Generally speaking, vehicle tags are given to drivers in many cases. Because of the cost problem, no drivers are willing to pay extra money for the tags*", *so the vehicle tags are a necessary cost for us. Low-cost power systems may lead to lower total costs, but reduced life expectancy will reduce the user experience. At the same time, frequent replacement of tags will bring additional costs*". *This is mainly the contradiction between the ETC equipment manufacturer and Road Department administrations. For the copyright and profit of circuit design, almost all tags are designed to be non-removable. Battery life becomes very important.*"

4.2 ETC attributes

ETC attributes were collected in the expert-based interviews to measure the performance of ETC equipment under the requirements of the Road Department administrations. In the expert-based interviews we collected the opinions from the participants and summarized ETC attributes for performance evaluation in this chapter. These attributes may independently influence the decision making of Road Department administrations, such as cost. Road Department administrations need to synthesize all aspects of road project investment, and calculate the proportion of ETC systems, to determine whether the systems achieve the cost-benefit assessment. Other attributes, including vehicle speed and equipment installation, do not have the ability to independently influence decision making. Road Department administrations need to consider these attributes comprehensively and find out the relationship between these attributes, to determine the appropriate solution.

4.2.1 List of ETC attributes

There are many attributes that can be used to measure the ETC system, such as frequency, protocol standard, identification distance, identification speed, data transmission rate, storage capacity, anti-collision performance and electronic tag packaging standards. These technical attributes affect and restrict each other.

The attributes of the ETC reader include the working frequency of the reader, the output power of the reader, the data transmission speed of the reader, the form of the output port of the reader and whether the reader is adjustable. Attributes of the ETC tag include the energy requirements, the capacity requirements, the worker of the electronic tag, frequency and data transmission speed, the reading and writing speed, the encapsulation formation, the security, etc.

Here, we have listed the main ETC attributes related to the scope of this research, which were confirmed by the participants in the expert-based interviews. From the information those participants provided, it was found how these ETC attributes affected ETC system performance under the requirements. The following content lists the main ETC attributes and the feedback of the participants.

Costs: Cost is an essential attribute of an ETC system, respondents considered it necessary to be carefully evaluated in the decision-making process. "*Under some important requirements, cost is a necessary condition for decision making although this attribute is not listed as a technical parameter of the ETC system,* " The overwhelming majority of respondents said that cost must be given priority because "*the primary goal of establishing a highway ETC network is to increase revenue, and the selected ETC system must prove capable of generating less overhead, at least less money, than the existing system.*" At the same time, more points of view support the importance of cost: "*Cost is the basis for setting ETC product prices.*" Most ETC designers believe that "*any material cost, labour input and later upgrade services of ETC system will be calculated into ETC product prices, which directly affects the decision making of Road Department administrations.*" "*For example, the price of memory changes, and the storage price in 2017 was twice that of the previous year. This does not mean the change in the value of the ETC system, but the price is indeed rising. This is a huge expense for our customers* ". In addition, "*late maintenance and upgrades are also considered to be an important part of the cost, which includes the costs incurred later. Due to the sustainability of these costs, we need to seriously consider and provide corresponding budgetary surpluses.”* Many respondents also believed that *"cost is an important basis for calculating profits.*" "T*he same ETC system, in different regions may produce different profitability results, and even some regions will have a loss situation.*" "*This does not mean that the design of the system fails, the management and maintenance of the later section will change the profitability of the road at any time.*" Thus, cost is an important essential attribute of ETC, which is evaluated by Road Department administrations and used as a basis for decision making. It not only has a direct impact on income, but also has a relationship with other essential attributes of ETC. Section 4.4.1 elaborates on the relationship and produces corresponding decision criteria.

Working frequency: In China, the ETC system adopts RFID technology, which is also part of the RFID system. The frequency range of wireless communication between the ETC tag and the reader is also the standard range of an RFID system. “*At present, most of the highway ETC systems use high-frequency and ultra-high-frequency transmission modes, that is, 2.45G and 5.8G.*" This does not mean that a system operating in other frequency bands is not within the scope of the study, "a l*ow-frequency system operating frequency is generally lower than 30 MHz, the typical operating frequencies of 125k, 225k, 13.56 m, etc., these low-frequency ETC systems are also supported by the corresponding international application standards. Its advantages are low cost, simple structure and convenient installation for vehicle ETC tags. But it also means that the data stored in the tag is small, the scope of the reader coverage is small and the directivity of the reader antenna is not strong, resulting in a weak transmission signal. Such a system* *is obviously unable to meet the stability requirements.* " High frequency ETC systems are used on most highways and are supported by corresponding international application standards. Compared with low-frequency ETC systems, a high-frequency system has better stability, signal transmission distance is far, usually more than 30 metres. However, "*in order to maintain stable signal transmission, it is necessary to install a power supply on the vehicle tag, which increases the cost.*" At the same time, the data stored in the tags is more abundant, and the function of the system is more than that of the low-frequency system, but the cost is still an important factor to be considered. Thus, the frequency of work affects the decision making of the Road Department administrations, and it is also associated with other ETC attributes. Detailed analysis and description are discussed in Section 4.4.2.

Vehicle speed limits: ETC technical experts usually provide vehicle speed caps for toll road mangers to refer to and help configure related equipment. This does not mean that this attribute comes from the personal preferences of ETC technical experts. The setting of vehicle speed limits is derived from RFID technical parameters and other ETC system attribute limitations. In the expert-based interviews, respondents said that "*high-speed vehicles will reduce the success rate of system identification of ETC tags*". "*There are many reasons for this, the main factor is the signal delay, which involves more technical details, including antenna installation and operating frequency.*" "*We usually calculate the speed limit based on RFID knowledge, other ETC stopping property restrictions and highway field tests. Usually, we will give some surplus on this basis. For example, the system allows a maximum speed of 80 kilometers per hour through toll stations, and we set a speed limit of 60 kilometers per hour.*" The impact of speed on decision making was also confirmed by the respondents, "*High-speed vehicles will occur a system identification failure situation. Normally, we would ask the vehicle to speed down to 20 kilometers per hour, which would ensure a very high success rate. In order to prevent system identification failure, we will set up a blocking device in the traffic lane, only the successful identification and successful deduction of vehicles can be released.*" Nowadays, most of the toll stations in the country are set like this. Even so, the speed limit is still one of the important ETC attributes of Road Department administration decision making. "*Not all drivers will obey the rules of toll gates, and low speed can easily lead to congestion, reduce the efficiency of vehicles, and ultimately affect the benefits of the entire highway.*" In addition, Road Department administrations need to consider the deceleration distance of vehicles passing through toll stations. If a toll station requires a lower vehicle speed, it means a longer deceleration distance, which may increase the construction cost of the toll station. Detailed description and analysis are described in in Section 4.4.2.

Installation procedures: The installation and deployment of ETC systems are not technical parameters of RFID, but they affect the decision making of Road Department administrations. In the expert-based interviews, all the respondents supported this opinion. "*The installation and deployment of an ETC system, especially the installation of readers' antenna, directly affect the stability and effectiveness of the system. Similarly, the ETC tags are required to be installed in the proper location of the vehicle.*" "*This important factor determining the effectiveness and stability of the system includes the coverage of the signal*", and "*a reasonable antenna installation location can maximize the coverage of the signal*". "*Sometimes an antenna can cover multiple traffic lanes, so we can reduce the antenna overhead.*" The installation of ETC tags also affects the success rate of vehicle identification and determine the results of the decision making. "*Usually, tags are installed on the front window of vehicles. This can be easily captured by the readers with only a small amount of external interference.*" However, not all vehicles are required to install tags in this way. "*This involves vehicles transporting special goods, such as cold chain transportation and metal transportation. Signal interference from metal needs to be taken into consideration. This means tags are not suitable for installation inside vehicles.* " "*We need to design detailed installation plans for different types of vehicles. It also raises costs on the other hand.*" Detailed description and analysis are described in Section 4.4.2.

Material: Materials are two-thirds of the cost of ETC tags and play an important role in the ETC systems. This obviously affects the decision of Road Department administrations. The traditional ETC tag with a self-adhesive function is installed on normal vehicles, that is, the tag is packaged into the usual dry glue form. "*For example, the ultra-high frequency RFID windshield tags (model: C116014) for ETC systems is designed by Gottman Electronics. On the back of this passive electronic tag is an adhesive suitable for windshields.*" "*This type of label provides amazing signal distances, and its super compatibility enables the windshield tags to work at various frequencies and has been successfully applied to parking lot management or other access control management.*" "*The traditional self-adhesive adhesive tags are used to complete the packaging process. The tag structure consists of a surface layer, chip line (Inlay) layer,* *glue layer and bottom layer. Paper, PP, PET can be used as that covering material (printing or not printing) and other materials as the surface of the product, the application of coating equipment will be cold gel coated on the inlay layer, plus oil-based plastic material, combined with the printable substrate, and finally forming a large sheet of on-board ETC tags, and then through printing, lamination, and so on. Punching and cutting are formed in accordance with the standard size of the ISO-7810 card.*" Such a production process makes ETC tags have abilities of waterproofness, metal-resistance and heat-resistance. In the discussion performance evaluation, I analyzed the impact of these material attributes on the performance and the principle of affecting the decision process.

Battery design：The power supply system of ETC tags affects the overall stability and reliability of the ETC system, thus affecting the decision making of Road Department administrations. At present, most of China's highway toll collection systems adopt the UHF ETC system. This means that most vehicles' mounted ETC vehicle tags require a battery to maintain stable signal transmission. In the expert-based interviews, participants thought that the life of the battery determines the life of the ETC tag. "*However, the battery power will produce consumption, which includes working consumption and static consumption.*" "I*f the power cannot maintain a stable signal transmission, then it will offset the success rate of vehicle identification, thus affecting the stability and reliability of the system.*" "*Most ETC tag batteries are not allowed to be replaced by drivers themselves, which means that most ETC tags are disposable. When battery power is exhausted, drives need to be provided new tags. This will undoubtedly increase the costs.*". "*Vehicle tags are provided by Road Department administrations, and this investment will be included in the cost.*" Therefore, "*the power supply system is also an important factor in decision making*". In addition to the battery power supply, the circuit design of the power supply system is also very important. "*Usually, batteries are not enough to provide long-term stable use.*" The power supply system circuit design needs "*reasonable distribution to ensure the maximum service life of the tags. For this reason, additional power supply systems, such as solar panels, need to be involved.*"

Anti-collision configuration：Normally, the reader can capture a radio frequency tag in the magnetic field at a certain time. however, when multiple tags enter the RF field of the readers at the same time, the reader must select the one of them for the transaction, which process is called anti-collision. Common anti-collision mechanisms in contactless smart cards are: 1) Bit-oriented anti-collision mechanism. This anti-collision mechanism is used in the ISO14443A protocol, based on the idea that the tag has a globally unique serial number. "*For example, Mifare1 card, each card has the unique 32 binary serial number. For any two-card sequence number, there is always one value that is not the same, that means there is always a unique card, such as one card is marked as "0" and another card is marked as "1";*" 2) Time slot based anti-collision mechanism. This conflict prevention mechanism is used in ISO14443B. The time slot (timeslot) is an ordinal number. The range of the serial number is specified by the reader, which may range from 1-1, 1-2, 1-4, 1-8, 1-16. When more than two cards enter the RF field at the same time, the reader sends a call command to the RF field. The command specifies the time slot range, so that the card randomly selects a number as its temporary identification number within the specified range. Then the reader calls the number from 1, and if only one card picks the number when it calls, I believe this card is selected. If the call number is not answered by a card or more than one card answers, the system will continue to call down. If all the numbers in the range of values are called once and no card is selected, the card is re-asked to randomly select the temporary identification number until a card is called out; 3) conflict prevention mechanism combining bit and time slot. This mechanism is used in ISO15693. On the one hand, each card has a 7-byte global unique serial number; on the other hand, the reader also uses a slot call in the process of conflict prevention, but the number here is not randomly selected by the card, it is the part of the unique serial number of the card (Mutigwe, 2012). Therefore, different anti-collision mechanisms will produce different results, "*will affect the ETC system signal sensitivity and stability, but also to a certain extent affect the cost of ETC tags.*"

Encryption Protocol：In ETC systems, some tags only store simple identification codes, while others store more information, depending on the tag's hardware and additional peripherals. The tag is composed of a microchip and an antenna, and communicates with different electromagnetic frequencies such as low frequency, high frequency, ultra-high frequency, wireless network, infrared and ultrasonic. Generally, there are two types of ETC tags: active and passive. Active tags periodically send radio frequency signals to communicate with the reader. According to the frequency and transmission power, the signals can penetrate walls and other objects. Some tags can even communicate in hundreds of metres of open space and tens of metres of indoor area. At present, most active tags do not support authentication or encryption functions, and it is easy to steal the transmitted data by using compatible readers. Therefore, active tags should be used in a secure operating environment. "*Most passive tags now conform to the EPC Class1 Gen2 standard. However, the EPCClass1Gen2 standard provides very limited security features.*" A 16-bit random number generator for a two-way handshake and data masking is used to lock a given tag and reader session to avoid collisions when multiple tags or readers exist; the value it generates is also used as a key value for simple encryption of passwords and what the reader writes to the tag when executing write commands (Mutigwe, 2012). But it is not used to encrypt the identification data from tags to reader. Here, data information needs to be encrypted in the process of transmission, which requires different encryption modes. In some complex logistics applications, tag encryption has many options. In this research, participants also mentioned relevant issues.

4.2.2 ETC attributes in performance evaluation

ETC attributes are main parameters to measure ETC equipment performance. Those attributes to be evaluated may vary according to the requirements of Road Department administrations. It is necessary to find out which ETC attributes are involved in the performance evaluation. As discussed in section 3.2.2, I used the semantic approach to determine which attributes are considered in the performance evaluation, and to find the intrinsic consistency of participant semantics. The average calculation was applied in this study, to determine the importance of ETC attributes or any unrelated possibilities. This process follows the statistics of individual measurements and the number of participants for each of the variables calculated for the average value, to check the validity of the statistical dimensions and measurements.

In each attribute, there are different fitness indices and some rules of thumb for measuring the required minimum level of ETC attributes participating. However, in this study, interviewees stressed that many different scores had some problems in the evaluation process, and that different categories of interviewees reported different levels of score/value scope, which could lead to a type of preference based on the type of interviewee in the same factors. For example, government transportation department experts and toll road managers are more interested in cost, which is one of the key factors affecting decision making, at least suitable for the goal of profits preference. On the contrary, most ETC technical experts are not concerned about the role of cost. "*Because our work is to design specific ETC devices, the cost has been refined and evaluated by the sales staff. This means that we only need to arrange the details of the equipment* *according to the design plan. This does not mean that all ETC designers will not consider the cost factors, at least the sales and project managers of the ETC manufactures need to devote more attention to the customer's requirements and the design costs of the ETC products*". "*We need to keep in close contact with our customers to ensure accurate collection of requirements information. From experience, cost considerations are necessary, and almost all customers will ask for this problem. Therefore, when we are designing products, we must consider the impact of the cost*". Obviously, semantic preferences are generated from different types of interviewees' perspectives. This might lead to missing some important items when the researcher was collecting information. For example, the ETC technical experts' opinions of cost are different from the toll road managers, which may produce different semantics. To overcome this phenomenon, the researcher needed to classify the respondents and objectively adopt all the respondents' opinions. This means participants of expert-based interviews who are irrelevant to the current factor also need to provide opinions and generate relevant semantic difference tables. This solution can effectively handle the preferences generated during the expert-based interviews. At the same time, based on different types of participants, different opinions on the importance of ETC attributes in decision making are issued, which leads to diverse outcomes. This study synthesized these opinions, to avoid these gaps caused by the different categories of participants and devoting themselves to designing a common decision-making model.

In summary, the expert-based interviews collected participants' judgments on the participation of these ETC attributes and tested the correlation between the requirements and these attributes by average calculation. To assess the differences between each participant, the semantic preference table is used to express the role of attributes in the performance evaluation process. In this work, the values 1 to 5 were used to express the importance of ETC attributes, and 0 indicated that the respondent was not involved in the consideration of this attribute. To realize the overall participation of all factors, the average calculation was used to indicate the degree of participation opinion that the participation of a relative attribute with requirements which are relative to the respondent. If the average value is less than three, it can be considered that the influence would not be involved in the performance evaluation process, and the related ETC attribute would be not included in the model calculation. In contrast, if the average value is greater than three, this attribute could be considered to have a greater influence on the current requirement, and the optimization calculation based on the decision making needs to consider the effect of the related ETC attribute. However, exceptions are considered in the modelling process, and the impact of the attributes is considered uncertain if the average value is equal to three. Therefore, it is necessary to remind interviewees to avoid general assessment as much as possible. The introduction of an average responded to the interviewee's opinion that "*what attributes should be considered when we make decisions, such as costs that affect total profits?*". "*Conversely, costs are rarely considered when we focus on reliability and stability design*." This shows that not all attributes have a relationship with a specific requirement. By obtaining the relationship between attributes and requirements, we can establish the performance evaluation environment in the experts' performance evaluation behaviour.

4.3 Criteria

Criteria are rules for ETC systems' performance evaluation under Road Department administrations' requirements. Information collection shows that the criteria used by Road Department administrations to evaluate ETC system performance include profit, capacity, reliability, compatibility, tag size and tag life. Opinions from participants of the expert-based interviews were described as follows.

Profits: *the primary consideration of most Road Department administrations in selecting ETC equipment is profit. This also is the most frequent requirement that they directly put forward to ETC equipment manufacturers. At the same time, it is an important criterion for us to evaluate the equipment performance. In general, the Road Department administrations expect profits of highways to be as high as possible.*

Capacity: *the capacity of ETC equipment refers to the upper limit of the number of vehicles that an ETC lane can pass through in a unit time. It determines the traffic flow of highways and is often required by the Road Department administrations in traffic management. Generally, the higher the traffic flow per unit time the better the traffic capacity of a system.*

Reliability: *geography, weather and other human factors test the quality of ETC equipment. Usually, the Road Department administrations require that the equipment be able to cope with extreme external environments and operate stably. This requires ETC* *equipment to have the ability to resist external environmental interference, that is, special design of materials is required.*

Compatibility: *ETC equipment must follow some protocols in terms of signal transmission and safety design, which can make the equipment work normally without conflict with other systems. This limits the use of ETC equipment, but it is also one of the criteria of concern to the Road Department administrations.*

Tag volume: *the tag needs to be designed to be of suitable volume so that it can be easily fixed in the vehicle. At the same time, the larger tag volume can accommodate complex antennas and affect the signal transmission ability. Tag volume becomes an important criterion.*

Tag life: *tag life is an important criterion, which is used to indirectly measure the cost of tags. tag replacement frequency is faster with a short life, but also has a higher cost.*

4.4 Performance evaluation

Performance evaluation is to analyze the performance of an ETC system under certain requirements. This work also needs to confirm the characteristics of the criteria and clarify the relationship between the requirements, ETC attributes and criteria in the performance evaluation, according to different requirements, analysis and evaluation of the ETC attributes, to produce a performance value per each criterion. These performance evaluation processes are relatively independent and have their own characteristics. This section standardizes these relatively independent decision-making behaviours into five different evaluation works for the specific requirements of Road Department administrations. Here, we describe these decision environments in detail and discuss the ETC attributes involved in these performance evaluations and possible decision criteria.

4.4.1 Performance evaluation: profit calculation

According to the expert-based interviews, the profit evaluation of ETC systems depends on two factors: 1. ETC equipment and related human costs; 2. highway operation time and its revenue; According to "Economic Evaluation Method and Parameters of

Highway Construction Projects" (2006), the profits of ETC use are directly related to the number of drivers. An efficient system can bring more drivers, which enables the vehicles on a highway to pass through toll stations with high speed, thus shortening the driving time. And this has resulted in higher revenue, the expert-based interviews show that the costs of ETC systems is the main ETC attribute affected in profit calculation. These attributes can be subdivided into many parameters in practical applications. I used the PCS (Salisbury, 2006) model to evaluate the average ranking from the expert-based interviews, and the statistical results were shown in following table.

Table 4.4.1 Average Ranking of profit calculation

ETC attributes	Average ranking		
	ETC technical expert	Toll road manager	Government transportation department expert
Costs (Average ranking)	Important (5)	important (5)	Important (5)

The above table shows that all participants believe that the cost of ETC equipment is an important attribute and needs to be considered in the profit calculation. (See comments on Appendix 7, Table 7.2) As another decision factor, revenue was not included in the ETC attributes, because the concept of road revenue covers a wide range of content. It not only includes the revenue from ETC systems, but is also determined by the toll rate and policies (section 2.4.2 and section 2.4.3). In this research, revenue is an important element included in profit calculations, and relates to ETC cost ultimately generated by decision output. This is discussed as a factor other than ETC attributes in Chapter 5.

4.4.1.1 Analysis of ETC attributes: costs

Cost is a monetary valuation used to assess the consumption of resources in activities or commodity production processes (O'Sullivan, 2003). According to the classification of cost, it can be divided into planned cost, unplanned cost and persistent cost.

Planned cost: planned cost refers to the resource consumption that can be clearly calculated in the process of activity and commodity production. For example, Mireia et al. (2006) listed four attributes of family medicine that influence the Road Department administrations' satisfaction, the possible DSS were improvement in the medical service from patient health in costs. Through the expert-based interviews, all the toll road managers and government transportation department experts confirmed that the planned costs should be considered "*in the stage of highway planning*", "*It is necessary to count* *the number of traffic lanes and how many devices should be used. This is mainly the number of reader deployments.*"

Unplanned cost: Unplanned cost refers to the consumption of resources that cannot be calculated or predicted in the process of activity and commodity production. Typical research comes from Barreto et al. (1998). In their study, they used enumeration to calculate predicted costs in timber production. But there are exceptions, for example, they needed to use two algorithms to calculate the predicted cost, which would result in different cost budgets. Through the expert-based interviews, all the toll road managers and government transportation department experts pointed out "*Unpredictable expenses often occur in some special situations, such as equipment failure caused by disasters, extreme climate and human damage. These losses cannot be estimated in advance. We often set aside certain funds to deal with those emergencies.*"

Persistent cost: Persistent cost are the repeated costs required to use and maintain the value of physical assets. Typical research comes from Grossman and Hart (2006). Their study proposed two methods of cost calculation: the horizontal approach and the longitudinal approach. The horizontal method is like the enumeration, and longitudinal calculation is based on the horizontal method, which has an added time factor, because researchers of this paper believe that costs could not only be generated immediately, but also may continue to produce by an unpredictable factor. Through the expert-based interviews, the toll road managers and government transportation department experts confirmed "*Continuous costs are necessary, including the cost of technicians. We must ensure that they can maintain the stable operation of the ETC systems.*"

4.4.1.2 Cost estimates

Cost estimates need to consider the cost details involved in this study, such as the information provided in the previous description, which must be considered in terms of planned costs, unplanned costs and persistent costs. In highway construction, the cost of planning often includes many aspects. It can be found in the feasibility reports of highways that an ETC system only takes up a small part of it. The basic investment of road construction includes land, building materials, early planning and so on. Secondly, the road environment; construction departments need to consider the impact of the project on the surrounding environment, as well as the impact on the environment after the completion of the project. Finally, the cost of maintenance and modification is estimated.

As a part of road facility construction, the investment of an ETC system is involved in three aspects of cost estimation, which is an indispensable part of the total investment.

In the initial stage of ETC system deployment, the highway constructor needs to consider the cost of equipment purchase and installation. These costs can be clearly estimated and calculated into planned costs. As part of the pre-construction planning, these investments are clear, because the equipment and maintenance costs will be detailed in the feasibility report and planning statement of the project. The road administration department will get the approximate cost of the planned cost after simple addition. Estimation of non-planned costs is more complex, involving many factors that are not considered. At present, to promote an ETC system in China, the government will subsidize the cost of on-board units for drivers, which will be included in the cost of the ETC system. As China is a developing country, the number of private vehicle ownerships will grow by a certain percentage each year, and the number of ETC drivers will also grow by a certain percentage. This leads to uncertainty because the percentage is not fixed, and growth is not linear. In this study, I referred to other studies and the Ministry of Transport's survey reports (ITS China, 2014) to obtain relevant parameters, which ensure that the data are authoritative and can produce satisfactory results for Road Department administrations. However, these results are not absolute due to uncertainties. Some uncertainties may lead to unpredictable situations. For example, road policies affect changes in parameters. Towards the end of this study, the State Council issued a plan to promote the development of an ETC system, hoping to produce positive results by the end of 2019. This will lead to a significant change in the ETC driver growth percentage. Continuous cost is also an indispensable step in cost consideration, which is related to the cyclical cost generated by ETC. Here, I believe that the persistent cost of an ETC system is mainly related to the cost of maintenance personnel and operators. At the same time, the change of toll lane and toll operator caused by an ETC system are also related to the persistent cost. It should be noted that we do not consider equipment maintenance costs as continuous costs, which are usually included in the feasibility study report and in the initial cost of the project. Therefore, I believe that cost estimates need to satisfy the following equation.

$$C_{total} = C_{planned} + C_{unplanned} + C_{persist} \qquad (4.4.1a)$$

For planned costs, we used $C_{planned}$ to represent the maintenance cost and cost of all readers in a specific highway. For unplanned costs, I used C_{tags} to represent the tag cost of a road; For persistent costs, we used C_{salary} to represent the human costs of a toll station. In China, the government is responsible for the installation of ETC tags, which is determined by the ownership of highways (China ITS, 2015). Drivers can also buy ETC tags themselves, but the resulting costs will not be in the scope of this study. Therefore, we can derive the ETC costs (C_{total}) formula as follows.

$$C_{total} = C_{tags} + C_{readers} + C_{salary} \quad (4.4.1b)$$

Another important factor is revenue, which belongs to the road environment (section 2.4.2 toll rate), but were considered in our research. Revenue refers to the total inflow of economic benefits formed in the daily activities of an enterprise, which will lead to the increase of the owner's rights and interests and have no activities with the capital invested by the Road Department administrations. According to the nature of daily activities of enterprises, revenue can be divided into sales income, service income and transfer of assets property. The revenue generated by an ETC system comes from the operating income of a toll-free highway as an ETC system cannot possibly generate labour income and asset appreciation. This leads to the simplicity and uniqueness of revenue calculation. In Chapter 5, I find that ETC revenue depends on the mileage ETC vehicles drive, toll rates on the highway and traffic volume during the statistical period. Here, we use R_{ETC} to represent the ETC revenue of a toll road. In the performance evaluation of profit calculation, it must satisfy the following relationships.

$$P = R_{ETC} - C_{salary} - C_{reader} - C_{tags} \quad (4.4.1c)$$

Among them, P represents the comprehensive profits of ETC systems. Because the profit of an ETC system is only related to the toll rate and mileage of the highway, to improve the profit, it is necessary to reduce the cost as much as possible.

4.4.1.3 Performance outcome and criteria

Formula 4.4.1c indicated the evaluation method used by experts in profit analysis. It produced a result that reflects the return of funds, which is the estimated profit of a candidate ETC system. For the performance evaluation of profit calculation, Road Department administrations make a selection among several candidate ETC systems to find the optimal profitable system. At the same time, the system of persistent losses was not be favoured by road operators. Thus, an ETC system must satisfy the requirement P > 0, when it is in operation for a period. Moreover, corresponding to other candidate systems, the selected ETC system should have the highest profit.

Therefore, we believed that if system profits set E has n candidate ETC systems, it satisfies $E \in \{P_1, P_2 \ldots, P_n\}$. We need to take the ETC system that generates the maximum benefit P_{max} as the output of the decision. The relationship of criteria, requirement and ETC attributes on this performance evaluation should be presented as follows.

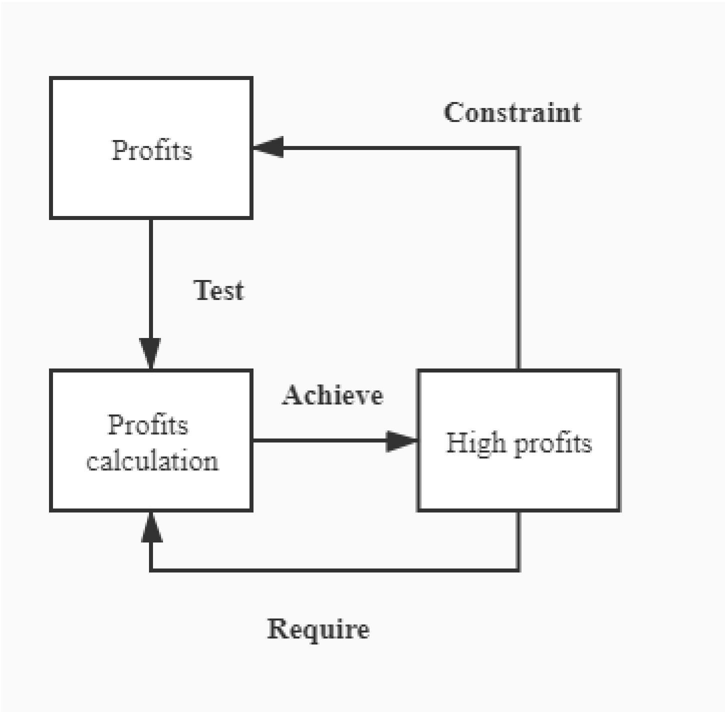

Figure 4.4.1 Performance evaluation of profit calculation

The above diagram indicates the outcome of this decision environment and points out that profit is an important criterion of decision making.

4.4.2 Performance evaluation: traffic management evaluation

Lai's (2018) research shows that solving the traffic congestion in front or toll collection stations, will bring social and economic benefits, and thus will effectively improve the traffic management capacity. An effective ETC system can significantly improve or solve the congestion problem at toll collection stations. Road Department administrations can reduce queuing waiting time by using those ETC systems (Feng, 2010).

Traffic safety is affected to some extent by the setting of toll collection stations on highways. Traffic accidents such as rear-end collisions, and side crashes often occur in toll collection areas. Payment methods, number of traffic lanes, acceleration of vehicles and cross-lane traffic flow are the main factors affecting traffic safety (Feng, 2010). Effective uses of ETC can reduce the occurrence of these accidents. Drivers do not stop or slow down to reduce queuing waiting time, thus avoiding possible accidents, and improving traffic conditions. Besides that, an effective ETC system uses efficient electronic money to pay road tolls, which fundamentally reduces manual errors and delays (Group IRC, 2016).

In terms of environmental benefits, an effective ETC system improves traffic conditions and reduces traffic congestion, thereby reducing the time of vehicles starting and braking due to queuing. This will greatly reduce the emission of harmful gases and reduce noise (Feng, 2010). The results of the expert-based interviews show that vehicle speed and ETC reader installation are the main ETC attributes which affect the traffic volume of toll lanes and social benefits. Interviewee ranking had been introduced into the PCS (Salisbury, 2006) model and the statistical results are shown in following table.

Table 4.4.2 Average ranking for traffic management evaluation

ETC attributes	Average ranking		
	ETC technical expert	Toll road manager	Government transportation department expert
Speed limitation	3 (Fundamentally important)	5 (Important)	5 (Important)
Equipment installation	5 (Important)	5 (Important)	3.2 (Fundamentally important)

The above table shows that all respondents from the expert-based interviews believed that speed limits and reader installation affected traffic management. However, respondents had different views on the technical details and importance of these attributes. ETC technical experts believed that speed restriction is an important technical index to determine the performance of an ETC system, but it is less important than the reader installation mode. A government transportation department expert believes that a speed limit is necessary, less importance on installation procedures. The toll road managers point out that both attributes are important (See comments in Appendix 7, Table 7.3).

4.4.2.1 Analysis of ETC attributes: speed limitation

From the actual situation of highway toll collection stations, although ETC technology is widely used in toll collection stations, the manual and semi-automatic toll collection mode is still the most effective highway payment method in China. Therefore, it is necessary to discuss the capacity of traditional toll collection methods as a technical reference (Yang, 2011). According to the definition of traffic capacity, the capacity of a single traffic line refers to the maximum flow rate of a single standard vehicle passing through a toll collection station under suitable traffic conditions without queuing. According to the traffic characteristics of traditional toll collection, its capacity can be expressed by the charging service time and departure time of normal cars. The equation is presented as follows (Yang, 2011):

$$C_{ETC} = \frac{3600}{T_d + T_a + T_v} \qquad (4.4.2a)$$

C_{ETC} represents the capacity of vehicles in front of the toll station; T_d represents the time required for deceleration from highway driving into the toll station; T_a represents the time required for vehicle acceleration when driving out of the toll station; T_v indicates the speed at the vehicle travels when trading in ETC lanes; “3600” means one hour has 3600 seconds.

From equation 4.4.2a, it can be concluded that the capacity of a single ETC lane is mainly related to the performance of the vehicle and the time of passing the toll collection station and is inversely proportional to the deceleration time and acceleration time of the vehicle passing through the toll station. The equation assumes the highway is working under good conditions, which means that the width of the traffic lane must conform to the national standard, and the driving toll collection station must ensure that the driver's vision is wide and the distance between vehicles meets the requirements of continuous traffic. When a vehicle passes through a toll station, the speed limit must be met to ensure that the transaction can proceed smoothly. This requires a certain acceleration to ensure that the speed changes. In the relevant research provided by “ETC system testing summary of the National Highway Network” (ITS China, 2014), the acceleration and deceleration of vehicles are different. Therefore, we need to determine the time for vehicles to pass the toll station according to the actual situation of the toll station.

For the types of toll station in China, there are two kinds of classification: closed and opened toll systems (section 2.4.2 open and closed toll systems). No matter which charging mode is used, the change of vehicle speed must follow these rules.

1. For a highway with a closed toll system, toll stations are equivalent to a gate across a highway, which is used to control the entry and exit of vehicles. Because the vehicle travels faster on the highway, the law of velocity variation is shown in the following figure.

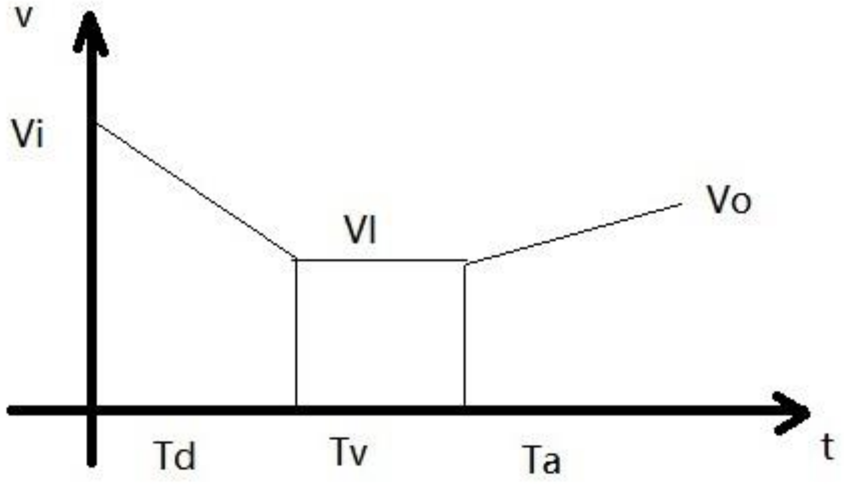

Figure 4.4.2a. Drive off the highway with low-speed limit in transaction

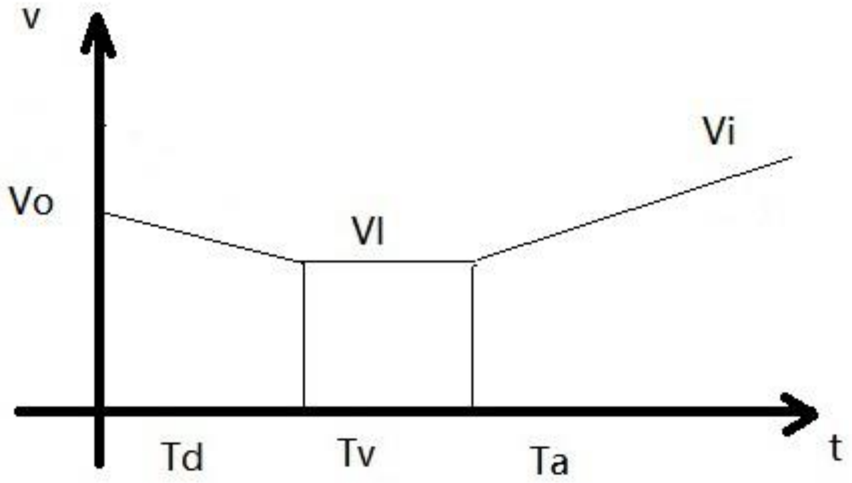

Figure 4.4.2b. Drive into the highway with low-speed limit in transaction

The above two sketches illustrate the speed changes of vehicles entering or leaving the highway. In the figure, V_i represents the speed at which the vehicle travels on the highway, V_l represents the speed at which the vehicle passes through the toll station, and V_o represents the speed at which the vehicle travels on the ordinary road. These speed changes indicate that, in most cases, the speed of vehicles travelling at toll stations is lower than that of normal highways. The normal operation of the existing ETC system in

China is conditionally limited. For example, the moving speed of vehicles using an ETC tag must be lower than speed limitation of the ETC line, because the reader receives the corresponding signal of the trigger coil for a certain time to interact, and the sensitivity of the equipment cannot be satisfied if the vehicle's moving speed is too fast.

However, the above situation is not absolute. In Chapter 5, I selected ETC samples for demonstration. From the information of these samples, the vast majority of ETC products require that the speed of vehicles be controlled within 80 km/h, while in China, the speed limit of ordinary roads is mostly 50 km/h (China ITS, 2015). This may lead to a situation where the speed limit of vehicles may exceed the speed limit of ordinary roads to meet the maximum capacity of ETC lanes on a toll station. This situation can be represented by the following pictures.

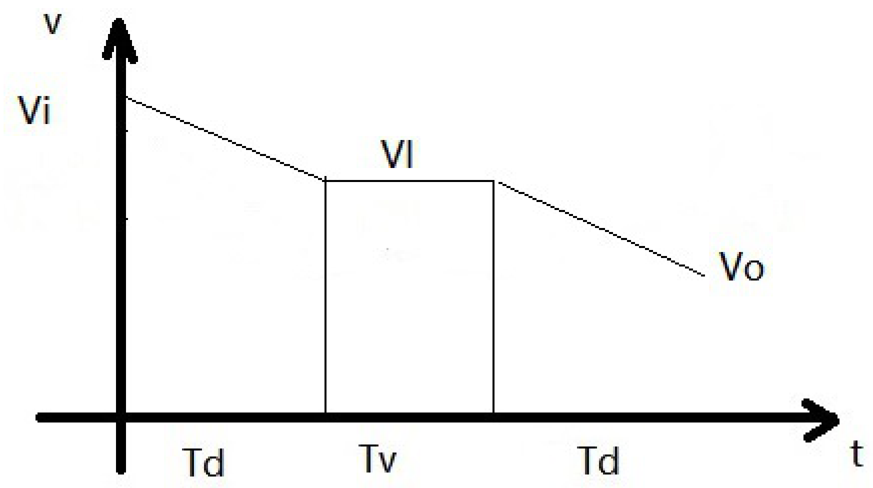

Figure 4.4.2c. Drive off the highway with high-speed limit in transaction

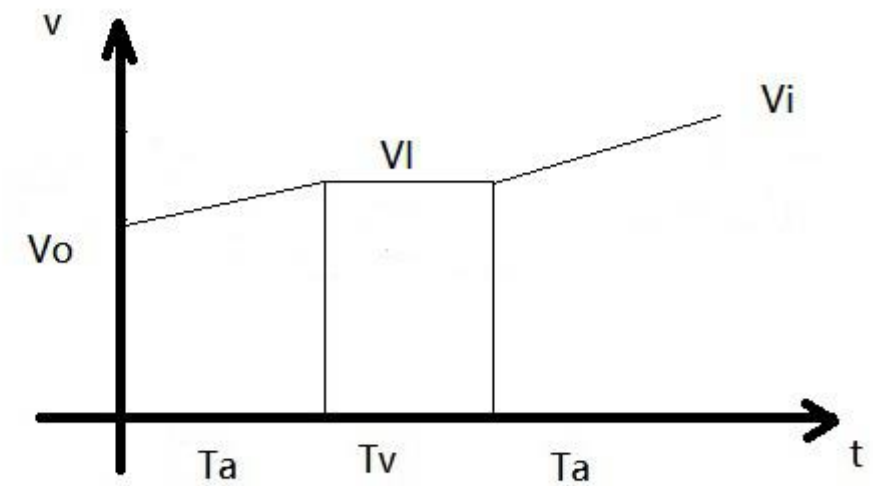

Figure 4.4.2d. Drive into the highway with high-speed limit in transaction

The above figure shows that, in this case, the vehicle is always in an accelerating state when it enters the highway and is always in a decelerating state when it leaves the highway.

2. For the open toll system, the road administration department uses the main station which is set on the highway to deal with the driver. This prevents these vehicles from leaving the highway and they may continue to travel through toll stations at a higher speed. Therefore, in this case, the variation of velocity is shown in the following figure.

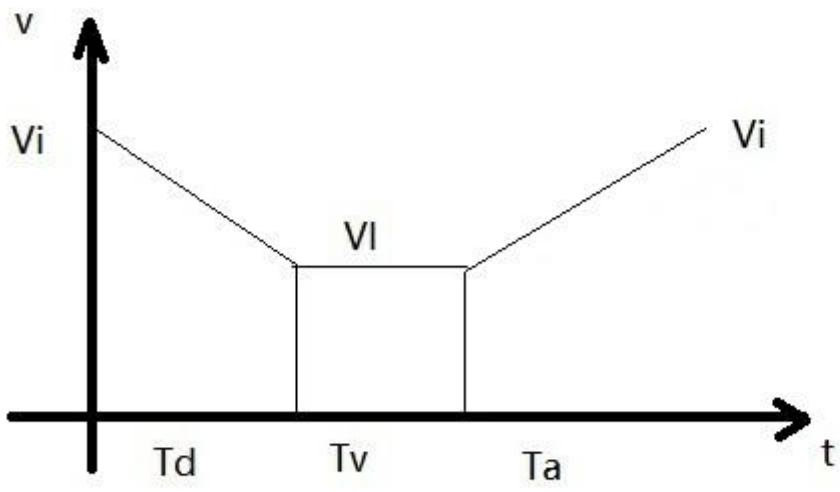

Figure 4.4.2e. Drive through the main toll station

The above situation is within the scope of this study. For the acceleration and deceleration of vehicles, detailed information is provided in the research report issued by the Ministry of Transportation (ITS China, 2014). At the same time, we can also found the ETC Lane speed limit standards at toll stations. This standard is quite different from the equipment parameters in our demonstration work of Chapter 5. This means that the actual speed limit of an ETC system may be different from the standard and equipment parameters of the Ministry of Transportation, to reach the upper limit of toll station capacity. Here, if I assume that the actual speed limitation at the toll station is V_l, it must satisfy the following equation.

$$V_l = \frac{D}{T_v} \tag{4.4.2b}$$

$T_v$indicates the speed the vehicle travels when in ETC lanes, D denotes the distance that a vehicle travels at this speed limit. For this distance, several aspects of ETC device installation should be analyzed.

4.4.2.2 Analysis of ETC attributes: equipment installation procedure

When a vehicle moves into a toll station, it must keep in touch with the reader on the ETC lane. In the process of continuous contact with the signal, the vehicle and toll station server can complete the transaction. This requires that the vehicle must enter a stable signal range. However, at present, readers in the market have different signal transmission distances. This means that the uses of these readers may affect the traffic flow and capacity of toll stations because, according to the standards of the Ministry of Transportation (ITS China, 2014), the width of traffic lanes and the width of separation zones between traffic lanes are certainties. Therefore, according to the actual situation, these ETC equipment must meet the following conditions.

1. When the signal transmission range of the reader can only cover one traffic lane, I believe that distance (D) of vehicle travelling at this speed limit, must satisfy the following situation.

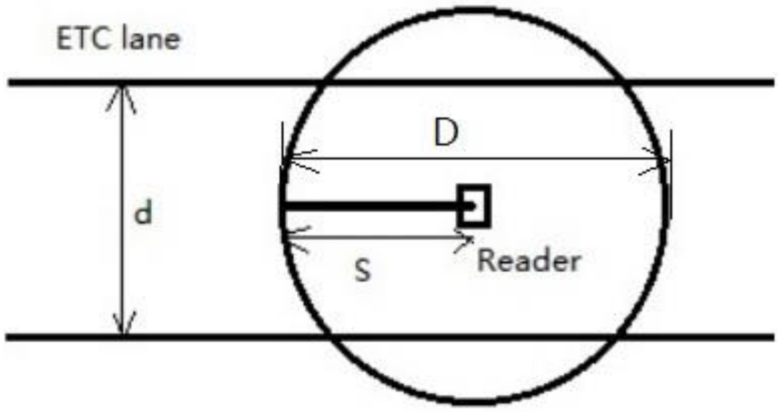

Figure 4.4.2f. Top view of single ETC lane

From above diagram, d is the width of the ETC lane and S is the radius of reader antenna signal coverage. I assume that the vehicle is always driving in the centre of the traffic lane. When the vehicle enters the toll station, the signal distance affect to the vehicle should be 2S. And this relationship can be presented as follows.

$$D = 2S \tag{4.4.2c}$$

2. However, the situation may change in a dual ETC lane. In order to save cost, the equipment installation scheme can be adopted for the reader whose antenna signal coverage is far away. The top view of the reader signal in this scheme is shown below.

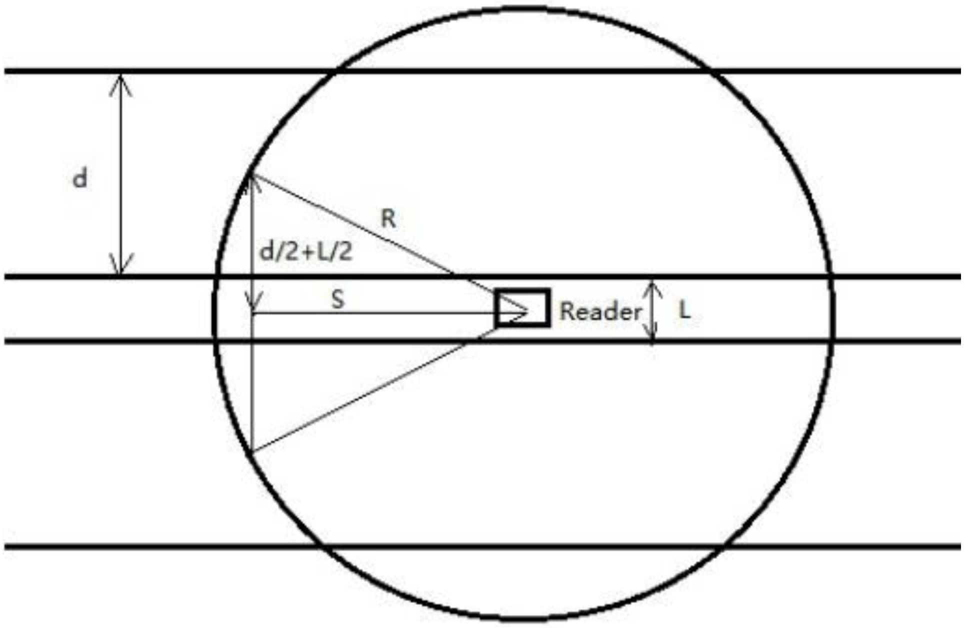

Figure 4.4.2g Top view of double ETC lane

From above diagram, d is the width of the ETC lane and R is the radius of signal coverage. We assume that the vehicle is always in the centre of the lane. When the vehicle enters the toll station, the signal distance affect to the vehicle will be different from that of scheme 1. Because the reader antenna is installed in the isolation area between two ETC lanes, the width of the isolation area L will inevitably affect the signal coverage of the antenna to the vehicle. As can be seen from the figure, S and R have certain angles. The value of S can be calculated by trigonometric function, and the distance of the vehicle to be operated by the reader should be 2S (S<R). This relationship can be presented as follows.

$$D = 2\sqrt{R^2 - \left(\frac{D+L}{2}\right)^2} \qquad (4.4.2d)$$

3. By analogy, when the reader's signal transmission distance is long enough and can cover more than two ETC lanes, the effective distance for the vehicle to travel under the speed limit is satisfied by the following equation.

$$D = 2\sqrt{R^2 - (n-1)^2\left(\frac{d+L}{2}\right)^2} \qquad (4.4.2e)$$

where n denotes the number of ETC lanes covered by the reader signal.

4.4.2.3 Analysis of ETC line Capacity

Formula 4.4.2b indicates the relationship between speed and time. At the same time, section 4.4.2.2 gives the conversion formula of the distance D of the vehicle in the toll station. Based on these studies, I found that for a specific ETC reader, the distance D of a vehicle driving at a speed is certain and it can be converted based on the signal coverage of the reader. This shows the relationship between vehicle speed and time as shown in the following figure.

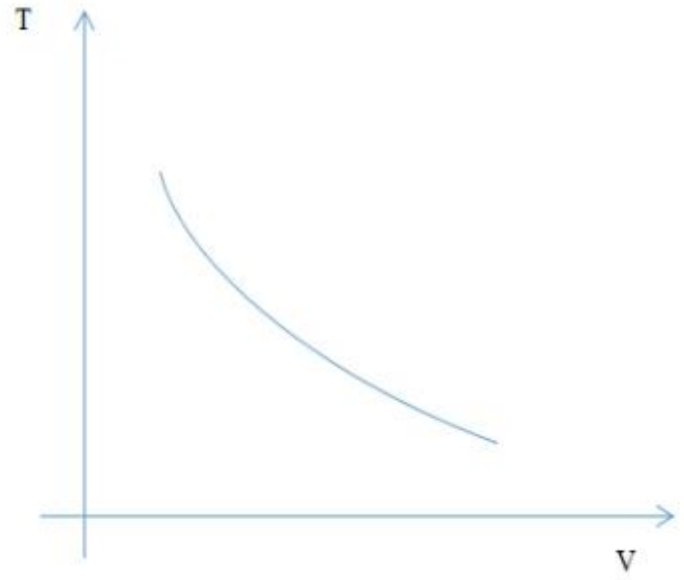

Figure 4.4.2h Relationship between vehicle speed and travelling time in toll station

The above figure shows how the speed of the vehicle is inversely proportional to the driving time in the toll station. To get the least driving time, the driver is required to pass the toll station as fast as possible. However, the higher speed will reduce the reliability of the ETC system and the success rate of tag capture by the readers. Therefore, all ETC products provide the design speed. Here, we define this design speed as V_{max}. At the same time, the driving time of the vehicle is also limited. It must ensure that the tag and reader complete the signal transmission and wait for the background system to complete the transaction work. Here, we define this necessary time as T_{min}. Normally, the speed limit of vehicles in toll stations should meet $\frac{D}{T_{min}}$, which will lead to different speed limits for different ETC products. For convenience and unified management, the speed limit of most ETC lanes is set at 20 km/h (Ministry of transportation, 2019). For most cases, the relationship between vehicle speed and driving time should be as follows:

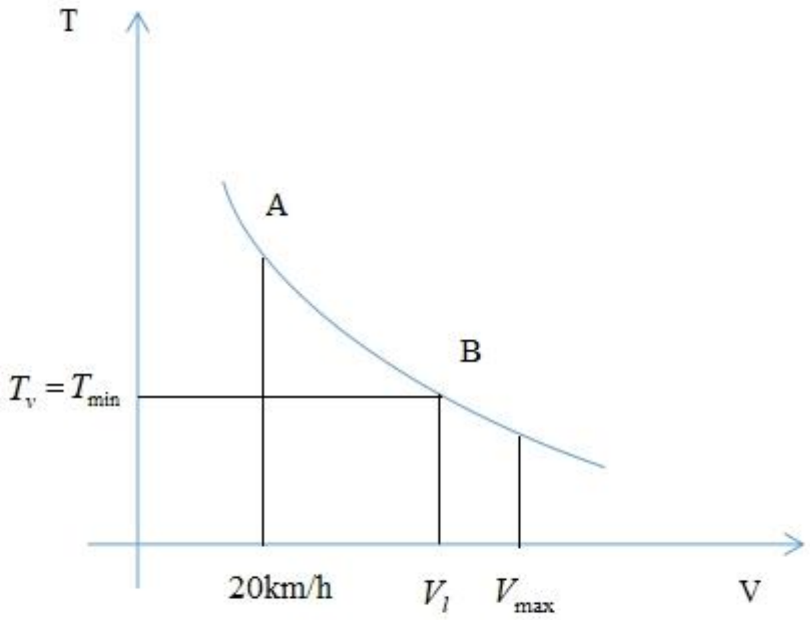

Figure 4.4.2i Relationship between vehicle speed and travelling time ($T_v = T_{min}$)

The above figure shows many cases when the time and velocity range is above point B and the arc is projected on the horizontal and vertical axes. This means from $T_v = T_{min}$, the speed of the vehicle at the toll station needs to be less than V_l; this also means that the capacity of the toll lane can be calculated by the speed of V_l. We can deduce the capacity formula as follows@

$$C_{ETC} = \frac{3600}{\frac{V_i - V_l}{a_d} + \frac{V_o - V_l}{a_a} + T_{min}} \tag{4.4.2e}$$

In above equation, V_i represents the speed at which the vehicle travels on the highway, V_l represents the speed at which the vehicle passes through the toll station, V_o represents the speed at which the vehicle travels on the ordinary road, a_d represents the deceleration of the vehicle, and a_a represents the acceleration of the vehicle.

The following figure shows the situation of $\frac{D}{T_{min}} > V_{max}$, where the range of time and velocity changes is projected on the horizontal and vertical axes at point C. This means that in this case, $T_v = T_{min}$, the speed of the vehicle at the toll station needs to equal V_{max}; this also means that the capacity of the toll lane can be calculated at the speed of V_{max}.

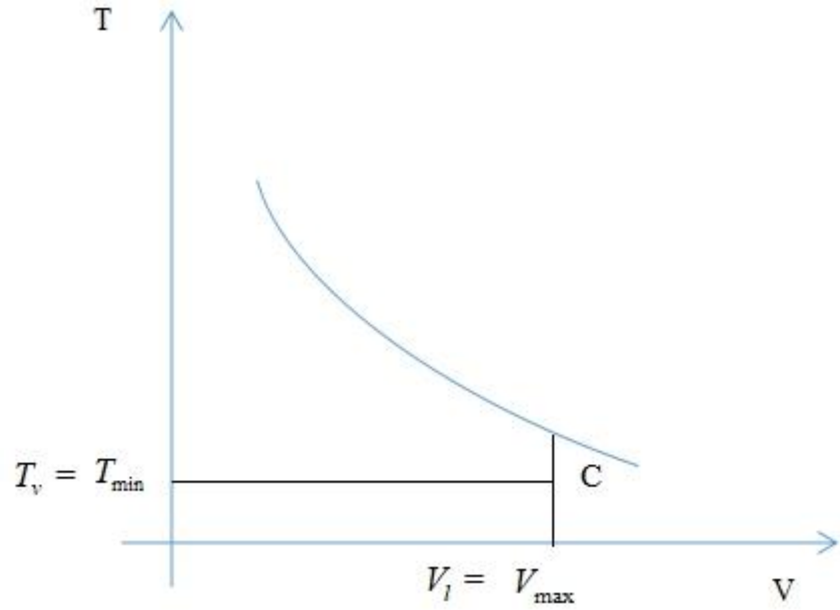

Figure 4.4.2j Relationship between vehicle speed and travelling time ($\frac{D}{T_{min}} > V_{max}$)

We can deduce the capacity formula as follows.

$$C_{ETC} = \frac{3600}{\frac{V_i - V_{max}}{a_d} + \frac{V_o - V_{max}}{a_a} + T_{min}} \quad (4.4.2f)$$

According to formulas 4.4.2e and 4.4.2f, we can deduce the relationship between ETC lane capacity and vehicle speed, as shown in the following figure.

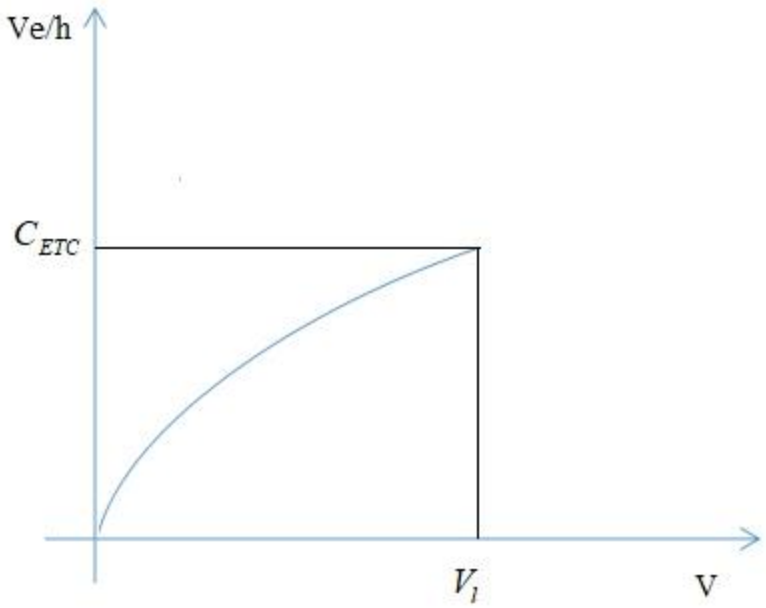

Figure 4.4.2k Relationship between vehicle speed and capability of ETC lane

The above figure shows that ETC lanes can reach the upper limit of traffic capacity when the speed of vehicles reaches V_l in toll stations.

4.4.2.4 Outcome and criteria

Formulas 4.9 and 4.10 indicate the calculation method of ETC Lane capacity. When we calculate this capacity, C_{ETC}, we need to judge the impact of the decision output on the overall decision-making model. There are two situations to be discussed:

1. Usually, Road Department administrations provide the traffic thresholds, such as those specified by the Guangdong Transportation Group (2016), "*When more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes*". Here we define this threshold as C_0. When ETC lane capacity meets $C_{ETC} > C_0$, we believe that the system meets the expectations of Road Department administrations.

2. We can also use the unit time traffic volume (V_e) of toll lanes to calculate the number of ETC lanes, which is presented as $\frac{V_e}{V_{ETC}}$, to determine the impact of the ETC system on cost which is described in section 4.4.1. According to section 4.4.2.2, it can be determined that there is a positive correlation between ETC lanes and the number of ETC readers.

Therefore, the output of this decision-making environment restricts the traffic management in this section, which makes Road Department administrations pay attention to the unit time traffic volume. The relationship of criteria, requirement and ETC attributes on this performance evaluation can be represented as follows:

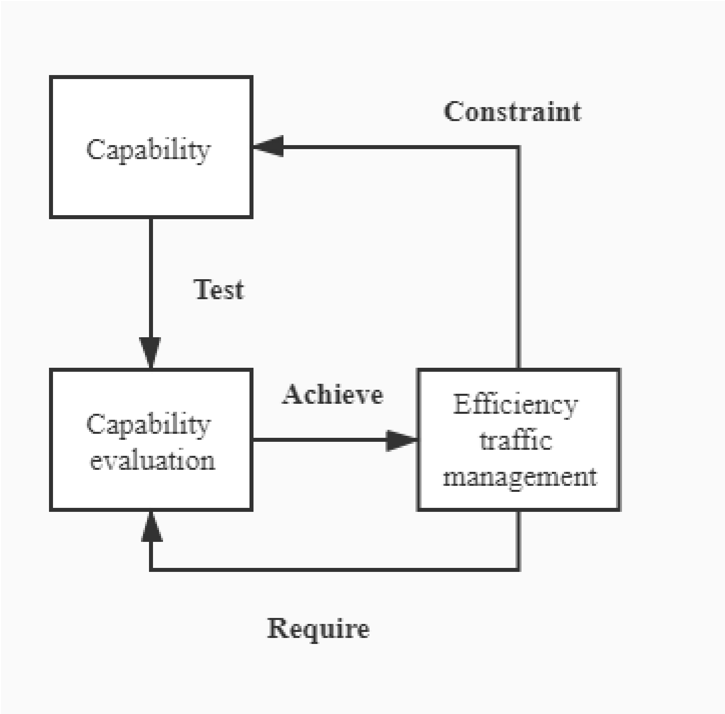

Figure 4.4.2l Evaluation of traffic management

The above diagram indicates the outcome of this traffic management analysis, and points out that the capacity of the ETC lane is an important criterion of decision making.

4.4.3 Performance evaluation: reliability

Zhang's (2018) research shows that some social and technological factors hinder the promotion of ETC systems. Among them, technical factors were confirmed by all respondents in the expert-based interviews. This is mainly at the product design stage. ETC designers did not evaluate the working environment of the equipment, resulting in instability of the equipment, which seriously affects the use of Road Department administrations.

China's vast area and complex geographical climate lead to many factors, which sometimes affect the operation of ETC systems. For example, the humid and warm climate in the south may cause the reader to reduce the success rate of vehicle recognition. The same situation can happen in coastal cities, where high salinity and corrosive water vapour can affect tags and toll collection equipment. In northern China, the temperature is usually below -20 degrees in winter, and the battery activity of vehicle tags may be unable to work because of the decrease in temperature (Huang, 2014).

In use scenarios, some special applications require that tags should resist metal interference. This often happens in some special logistics projects. When the goods transported by vehicles have the characteristics of signal interference, the on-board tags need to be specially designed (Li, 2019). All of these put forward higher requirements for ETC designers. Similarly, a government transportation department expert involved in planning also needs to achieve assessment and give accurate judgments. In the expert-based interviews, all respondents believed that the material of tags affected the reliability of the system. We introduced their feedback into the PCS (Salisbury, 2006) model to evaluate the average ranking of each related ETC attribute, and the statistical results were shown in following table.

Table 4.4.3a. ETC attributes in reliability evaluation

ETC attributes	Average ranking		
	ETC technical expert	Toll road manager	Government transportation department expert
Working frequency	3.1 (Fundamentally important)	5 (Important)	5 (Important)
Material of tags' design	5 (Important)	5 (Important)	5 (Important)
Volume (Size of tags)	5 (Important)	5 (Important)	5 (Important)

The above table points out that three ETC attributes participated in the Road Department administration's reliability assessment: frequency, material of tag design and tag volume (See comments on Appendix 7, Table 7.4). In the following sections, we discuss the values of these attributes and the representation of participating in this performance evaluation.

4.4.3.1 Analysis of ETC attributes: Working frequency

The paper "Radio-Frequency Identification (RFID) applications: A brief introduction." describes the range of RFID working frequencies, which means that many RFID systems work within this range. Meanwhile, the working frequency determines the transmission distance of the signal. However, it does not mean that high frequency and long-distance systems are preferred. Each country has unified standards on the use of RFID systems, mainly to improve the compatibility of signal transmission. These unified standards for different countries are shown on the following table.

Table 4.4.3b ETC working frequency for different countries

Frequency	Countries
125–134 kHz	USA, Canada, Japan, Europe

13.56 MHz	USA, Canada, Japan, Europe
433.05–434.79 MHz	In most of USA and Europe and under consideration in Japan
865–868 MHz	Europe
866–869 and 923–925 MHz	South Korea
902–928 MHz	USA
952–954 MHz	Japan (for passive tags after 2005)
2400–2500 and 5.725–5.875 GHz	USA, Canada, Japan, Europe

The industry report "*ETC System Testing Summary of the National Highway Network*" (MOT, 2014) regulates that China's ETC system use Europe standards. This means that many of Chinese ETC systems use 433MHz, 2.4GHz and 5.8GHz working frequencies. Only a few areas use other frequencies, which are considering the special climatic conditions, but this also brings compatibility issues and will mean more costs.

In the paper "*The Design of Reliable Protocols for Wireless Traffic Signal System*." Huang and Miler (2002) describe the successful design of their system, and at the same time, they mention the impact of the external environment on signal transmission. Although extreme weather has no ability to affect the working frequency, it has an impact on the range of signal transmission. In addition, both these papers mentioned that systems operating at some special frequencies are superior to others in stability.

The above three papers conclude the following characteristics of working frequency:

- The RFID system can operate over a wide range of working frequencies, including LF, HF, UMF and other different frequency bands.
- Due to the compatibility requirements from customers, various regions have unified the operating frequency bands. China's ETC system generally adopts European standards, and some regions use other bands to adapt to extreme climate.
- If there is a wide frequency range to select from and a suitable external environment, a high working frequency can bring long transmission distance.

The following equation describes the frequency range of ETC tags; that is, in China's road environment, ETC tags need to run in this frequency range to meet the compatibility requirements.

$$F_{frequency} \in \{F_{2.4G}, F_{5.8G}, F_{900M}\} \quad (4.4.3a)$$

This equation clarifies that there are currently three working frequencies available in China.

4.4.3.2 Analysis of ETC attributes: Material

According to the expert-based interviews, all respondents believed that the ETC tag material determined the reliability of the ETC systems. However, the scope and scenario of the material in ETC design have not been clearly marked in the existing research. According to the descriptions of the respondents, this study made a unified summary of the scope of application, trying to provide Road Department administrations with a clear guidance in selecting the appropriate ETC systems. Respondents in the expert-based interviews believe that China's vast geographical environment determines the diversity of ETC tag material design. "*The first challenge is the temperature. In the same season, the temperature gap between the north and the south is more than 40 degrees. This is not easy to design for. Moreover, this does not consider that vehicles may travel through multiple provinces, through multiple temperature change areas.*" "*The second challenge is humidity, close to the sea in the east of China, the humidity is high. The tag material needs to be corrosion resistant. But the western region does not need this extra design, it can reduce costs*". "*Finally, anti-metal interference, which requires tags to be able to adapt to a variety of work scenarios*." At the same time, most ETC designers have proposed that "*the volume of the tag can also determine the success rate of vehicle recognition; however, the tag cannot be infinitely enlarged, because portability is also a factor to be considered*."

To express this relationship conveniently, the following equation can be used.

$$M_{Material\_tags\_design} \in \{M_{Heat\_resisting}, M_{Moisture\_proof}, M_{Anti\_interference}, M_{size}\} \quad (4.4.3b)$$

This equation shows that there are four designs of tag material in the decision: heat resistance, moisture proofness, interference, and volume. According to the descriptions of the respondents, we can get the possible values of these subdivisions. Each subdivision can be described by the following equations.

$$M_{Heat\_resisiing} \in \{Yes, No\} \quad (4.4.3c)$$

$$M_{Moisture\_proof} \in \{Yes, No\} \quad (4.4.3d)$$

$$M_{Anti\_interference} \in \{Yes, No\} \quad (4.4.3e)$$

$$M_{Volume} \in \{Big, Small\} \quad (4.4.3f)$$

Feedback from the participants shows the possibility of these tag designs:

Heat-resistance: Heat-resistance is one of the important parameters of ETC products and has been mentioned many times in the feedback from participants at interviews. This is mainly reflected in the feedback difference between toll road managers. "*The geographical conditions of China are different temperatures, especially the difference between the south and the north*". Almost all ETC technical experts provide similar descriptions in the expert-based interviews. "*The difference of temperature could change the performance of ETC systems.*" "*While a vehicle travels from north to south, the rise of temperature may bring some physics changes on tags, but so far we have not received any information on this topic from drivers*". "*Heat-resistance is generally described as a parameter in some product manuals*".

Moisture proofness: Moisture proof design is one of the important parameters of ETC products and has been mentioned many times in the feedback reports of participants of the expert-based interviews. This is reflected in the feedback from toll road mangers. "*The geographical conditions in China have brought about the difference in humidity, especially in the east and west*." ETC technical experts provide similar descriptions in the expert-based interviews. "*The eastern region is often affected by the rainy season and the climate is very humid, which significantly improves the failure rate of ETC tags. The failure rate in the eastern region should be significantly higher than the western region.*" This indicated that humidity affects the performance of the system. "*Sometimes the humidity change caused by the season will cause the system's failure rate to change in a curve*". Moisture proof design should be necessary and listed as a parameter on ETC product manuals.

Anti-interference: Anti-interference had been mentioned many times in the feedback reports of Road Department administrations. This is reflected in the ETC technical experts' feedback. "*Anti-interference design is often required to be applied to a particular logistics environment*". In the expert-based interviews, toll road mangers provided similar descriptions. "*This situation usually happens in metal transportation; the failure rate will be increased. A lot of reports show that vehicles are unable to pass individual toll stations due to the transportation of metal objects. But what needs to be specified is that this phenomenon is not universal. It shows a possibility. We do not know how much metal interference has played here.* " This indicated that metal interference will affect ETC performance in some special applications.

Volume: The volume of tags is often limited because of the limited space of the OBU. This is mainly reflected in the ETC technical experts' feedback." *The volume of the ETC tags needs to meet certain requirements, that is, it can be safely installed on the vehicle and keep stable operation.*"

4.4.3.3 Discuss on reliability evaluation

Before this study, I participated in a project for the Ministry of transport, "*Research on Key Technologies and Coding System of Radio Frequency Identification (RFID) Application Safety Testing in Transportation Industry*" (Project No. 2011-364-813-060). This project included an experiment on single tag detection at different speeds. However, existing industrial reports show large numbers of the same experiments had been completed, and all those test results had been submitted to the Ministry of Transportation in China. In this case, the original experiment therefore became less important. In comparison, the existing data from industrial tests is more authoritative and more widely used. As the result, this experiment was more focused on the impact of weather changes on signal distance and tag detection and trying to find the relationship between changing weather conditions and system reliability. Finally, the result of this project was published as a conference paper "*A Useful Decision Support Model for Road Owners to Select ETC tags Based on C4.5 Algorithm.*" (Gu, 2018)

In this experiment, 13 different types of tags were selected as test samples. In theory, the same tags will produce the same experiment results, but in reality, the external environment and tags design quality caused different test values. The working frequencies of these tags were 900MHz, 2.45GHz and 5.8GHz. Although most highway ETC systems are using 2.45GHz and 5.8GHz as their working frequency, the diversity of experiment results made it easier to determine the system performance on tag detection distance.

Report "*ETC System Testing Summary of the National Highway Network*" provided their experiment data under different outer environments. Those samples are listed in the following table.

Table 4.4.3c Experiment results

Number	Frequency	Heat resistance	Moisture proof	Anti-interference	Tags' size	Successful

Sample1	5.8G	Yes	Yes	Yes	Thin	True
Sample2	5.8G	No	No	Yes	Thin	false
Sample3	5.8G	Yes	Yes	No	Thin	True
Sample4	5.8G	Yes	Yes	Yes	Big	false
Sample5	5.8G	No	Yes	No	Big	false
Sample6	5.8G	No	Yes	Yes	Thin	True
Sample7	2.4G	Yes	Yes	Yes	Thin	True
Sample8	2.4G	Yes	No	Yes	Thin	false
Sample9	2.4G	Yes	Yes	No	Thin	True
Sample10	2.4G	No	Yes	No	Big	false
Sample11	900M	Yes	Yes	Yes	Thin	True
Sample12	900M	Yes	Yes	No	Thin	True
Sample13	900M	No	Yes	Yes	Big	false

I used the C4.5 algorithm to classify these tag designs and listed these design attributes that affect the performance of ETC systems. Compared with other decision-making methods, we used the C4.5 algorithm for the following reasons:

1. This method is suitable for data classification and can provide clear results.

2. The decision tree model produced by this method can provide a decision path to easy understand how to select a reliable ETC system.

3. The classification information generated by this method is easy to understand

1. Firstly, we introduced the C4.5 algorithm to calculate the information entropy.

$$Information(entropy) = \sum_{i=1}^{n} \frac{Successful}{Sum} \times log_2 \frac{Successful}{Sum} \quad (4.4.3g)$$

For each sub-attribute, the information entropy is shown in the following table.

Table 4.4.3d Information entropy

Frequency	Heat resistance	Moisture proof	Anti-interference	Volume
0.916	0.779	0.715	0.945	0.779

2. The information gain is calculated by using following equation.

$$gain(sub\_attribute) = entropy(Sum) - entropy(sub\_attribute) \quad (4.4.3h)$$

For each sub-attribute, the information gain is shown in the following table.

Table 4.4.3e. Information gain

Frequency	Heat resistance	Moisture proof	Anti-interference	Volume
0.080	0.217	0.281	0.042	0.281

3. According to the C4.5 algorithm, information gain is an effective function to

measure the optimal ETC attributes, but it tends to select those attributes with many different values, which cannot guarantee suitable prediction results. Therefore, new indicators are required to overcome this difficulty. Spit information can compensate for this issue. It reflects the information of the attribute itself. In fact, it normalizes the information gain. Here, we introduce the equation as follows:

$$split(attribute) = -\sum_{i=1}^{n} \frac{|Current|}{|Sum|} \times log_2 \frac{|Current|}{|Sum|} \quad (4.4.3i)$$

For each sub-attribute, the split information is shown in the following table.

Table 4.4.3f. split information

Frequency	Heat resistance	Moisture proof	Anti-interference	Volume
0.080	0.217	0.281	0.042	0.281

4. Finally, we use the following formula to calculate the node information.

$$GR(attribute) = \frac{Gain(attribute)}{Split(attribute)} \quad (4.4.3k)$$

For each sub-attribute, the node information is shown in the following table.

Table 4.4.3g. node information

Frequency	Heat resistance	Moisture proof	Anti-interference	Volume
0.052	0.244	0.453	0.044	0.316

5. Generate the decision tree by using above node information. The decision tree is shown in following picture.

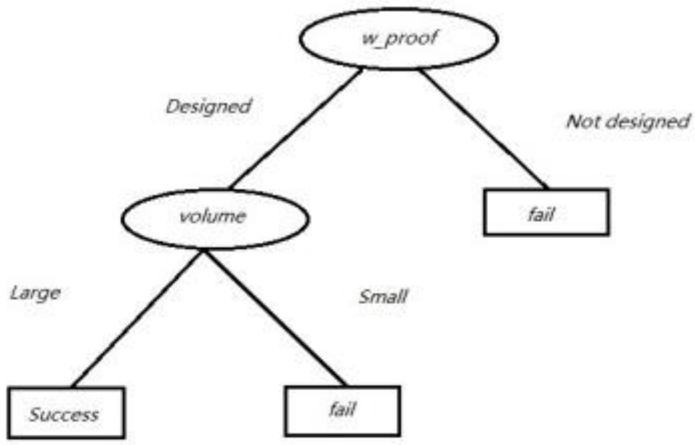

Figure 4.4.3 Decision tree on reliability (Gu, 2018)

The model shows the decision-making process of experts in reliability evaluation. This process starts with the root of the decision tree in Figure 4.4.3. When determining the reliability of a product, the Road Department administrations should first inspect the material of the ETC tags. When the tags are moisture proof designed, Road Department administrations will continue to evaluate another ETC tag attribute, volume, otherwise the tag will be considered unreliable. When evaluating the tag volume, the Road Department administrations will use the volume of the vehicle on-board unit (OBU) as a reference (MOT, 2014). When the tag volume is no more than the OBU's size and can be integrated into that OBU, I believe that the tags meet the requirements. The decision-making process of the Road Department administrations is carried out step by step according to the instructions in Figure 4.4.3 until it is determined whether the tags meet the requirements.

4.4.3.4 Outcome and criteria

The model in Figure 4.4.3 shows the decision-making process based on stability. Two important ETC attributes are mentioned: working frequency and material. Another important factor is also considered: the volume of vehicle OBUs. These factors interact with each other and influence the decision making of Road Department administrations. In this performance evaluation, Road Department administrations need to consider the following three aspects when selecting from candidate ETC systems:

1. The working frequency of the tag must be the same as the reader. This makes it related to the previous studies and produces mutual constraints.
2. Tag materials must be moisture proof designed to cope with the external environment.
3. The volume of the tag needs to be designed as large as possible, but also should be controlled within a certain range to meet the design requirements of the on-board vehicle unit.

Tags that satisfy the above requirements are the result of optimization and the outcomes of performance evaluation. In this case, there may be more than one optimization result; that is, all eligible tags will be selected. The relationship of criteria, requirement and ETC attributes in this performance evaluation should be presented as follows.

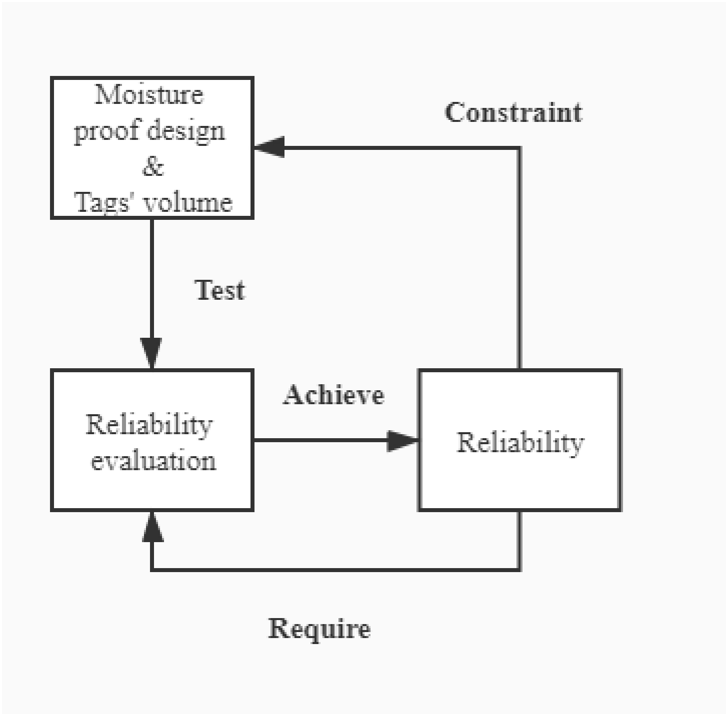

Figure 4.4.3 Reliability evaluation

The above diagram indicates the outcome of this decision environment, and points out that moisture proof design and limited volume of tags are important criteria for decision making.

4.4.4 Performance evaluation: Compatibility on safety design

The expert-based interviews showed that the safety of an ETC system mainly depends on the design of the chip. This requires ETC manufacturers to lay out the functions of the system in advance. An ETC system with basic safety functions should have reasonable ETC chip design, an anti-collision function, and a data encryption function. All respondents agreed with this and confirmed that the ETC systems on the market have the above elements. The following table shows how well the respondents understand the relevant ETC attributes and the importance of compatibility (See comments on Appendix 7, Table 7.5).

Table 4.4.4 Attributes in compatibility of safety design

ETC attributes	Average ranking		
	ETC technical expert	Toll road manager	Government transportation department expert
Delay on anti-collusion	5 (Important)	5 (Important)	5 (Important)
Protocol of anti-collusion	5 (Important)	5 (Important)	5 (Important)

Protocol of data encryption	5 (Important)	5 (Important)	5 (Important)

4.4.4.1 Analysis of ETC attributes: impact of anti-collision design

According to He (2018), the background of this research is that when the fast-moving tag group passes through the RF area of the reader, the tag in the range of the reader may change dynamically, and new tags are added to the recognition range of the reader at any time, thus will affect the anti-collision processing of the system. Through the research on the process of ISO18000-6 Type C anti-collision algorithms, Li (2013) found that the algorithm does not deal with the fast-moving tag group effectively. To solve this issue, Li (2013) put forward their improvement model based on the ISO18000-6 Type protocol.

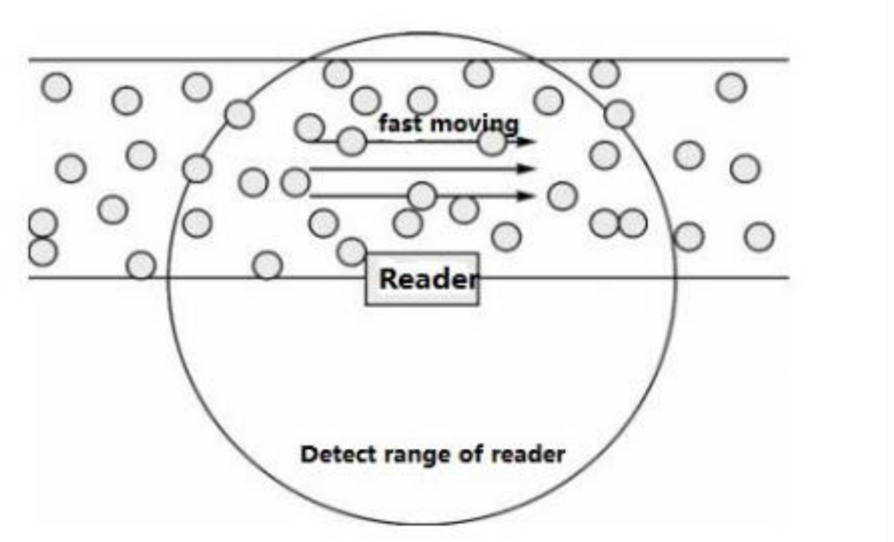

Figure 4.4.4 Anti-collision mechanisms (Li, 2013)

As shown in above figure, when many tags quickly enter the reader’s signal range, according to the working process of the RFID reader, when the reader starts tag recognition, it first sends a “Query” command to open a reading and writing cycle, and when a high-speed moving tag enters the recognition range of the reader, the tag power is turned on to sleep. The reader chooses some tags to enter the reading and writing cycle within the recognition range. Some tags are not selected and remain dormant, waiting for the next reading and writing cycle. When the last read-write cycle is over, the reader will resend the “Query” command to open a new read-write cycle. At this time, new tags will be added to the reader's recognition range, and the reader will randomly select some tags from all tags to enter the read-write cycle. This shows that the tags cannot be recognized by the reader at the same time under the anti-collision mechanism; the anti-collision mechanism uses the gaps between the readers to quickly identify activities and arrange them into read-write sequences.

For the moment, I did not consider that the time spent on fee transactions mentioned in section 4.4.2. If it is defined that the moving speed of the moving tag group is V, and the moving distance of these tag is D in the range of card reader recognition, the time of the tag in the range of recognition is:

$$t = \frac{d}{v} \quad (4.4.4a)$$

If the reader identifies one tag for a time T and in a unit period the number of tags is n (n is a positive number), then each tag can be recognized as:

$$T = \frac{t}{n} = \frac{d}{v} \times \frac{1}{n} \quad (4.4.4b)$$

From the above equation, according to the characteristics of the RFID reader, I determine that the reader recognition distance and capacity are constant. It can be concluded that the data transmission cycle is inversely proportional to the moving speed. When the vehicle moves too fast, the ETC system will fail to respond due to the time of collision avoidance and recognition.

4.4.4.2 Analysis of ETC attributes: Data encryption

Although both ISO and EPC GEN2 stipulate strict data encryption formats and user-defined bits and, at the same time, RFID technology also has relative security information processing capabilities, some researchers still believe that the safety of RFID is not reliable according to Adi Shamir, an American cryptography expert (O'Connor, 2006) who believes there is no safety in RFID at present, and it is simply unimpeded. He claimed that he had cracked the password of most of the mainstream RFID tags on the market and can attack almost all the current RFID chips without obstacles. In China, there are also many people who believe that safety is one of the important reasons hindering the promotion of RFID technology (Zhang, 2018).

Safety and cost are irreconcilable contradictions. Road Department administrations must consider both benefits and limits. In RFID applications such as bank cards and electronic passports, there is a high level of encryption, which is often used in ETC authentication. Sometimes, when low-cost products are needed, safety is sacrificed. Of course, normal RFID devices also have some underlying protection. For example, EPC adds Password and other functions, or burns OKP into tag chips, so,once the tag breaks, it cannot be used. However, the reality is that no technology is always safe, and so it is with RFID tags. Security is important, but not absolute (Zhang, 2018). In addition to continually promoting encryption technology to deal with possible risks, I also need to rely on a security management system, which also requires data management to adopt a distributed structure, not often to change the data management model and rely on the continuous work of data managers to maintain data security. For example, most ETC tags can use chip storage technology to store more information, but in fact, the tag only stores basic data, and the rest is stored in the corresponding database. The association between tags and databases can be established by authorized IDs. This ensures that hackers cannot get "valuable" information from tags.

To solve the security problem of traceability of RFID, we must solve it systematically at all levels of the RFID system. Any single-level solution is not comprehensive, which may lead to obvious security weaknesses and vulnerabilities in the RFID system. Therefore, in addition to selecting the appropriate level of authentication that can be encrypted, we should also choose some auxiliary means to further optimize the RFID system. At the same time, to ensure security – scalability, manageability and system overhead should be considered comprehensively. The secure RFID system should satisfy the requirements of confidentiality, information leakage protection and traceability prevention. These additional designs make tag compatibility problematic, which at the same time reduces the reliability of the system. Therefore, “the safety specifications of Vehicle tags (OBU) must meet the requirements of ISO/IEC 18000-6C and EPC Class 1 Gen 2” (Ministry of Transportation, 2019).

4.4.4.3 Outcome and criteria

Formula 4.4.4b shows how long the collision avoidance process takes. This time may consist of multiple collision avoidance cycles, but it may affect the toll station's capacity. Corresponding to Formula 4.4, I can calculate the speed at which the vehicle needs to travel at a uniform speed in data transmission. Similarly, safety design focuses on data encryption. When different encryption designs are adopted, the design cost is different. This leads to two output standards:

1.The working time of the collision avoidance algorithm must be counted into the transaction time when the vehicle passes through the toll gate. This operation is related to the research in section 4.4.2, which affects the traffic management capability of toll stations.

2. Corresponding to the encryption design, the different encryption technology will affect the input of tags. In section 4.4.4.2, the policy from the Ministry of Transportation regulated that the safety specifications of vehicle tags (OBUs) must meet the requirements of ISO/IEC 18000-6C and EPC Class 1 Gen 2. (Ministry of Transportation, 2019).

According to the above criteria, Road Department administrations can choose the optimal result from the candidate ETC system. The relationship of criteria, requirement and ETC attributes on this performance evaluation can be presented as follows.

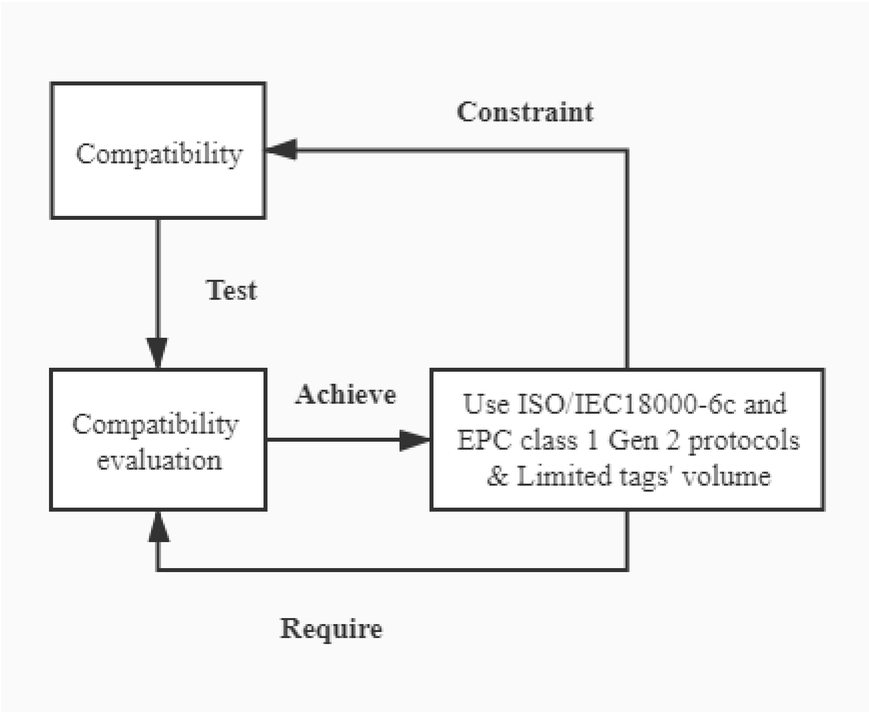

Figure 4.4.4a Compatibility evaluation

4.4.5 Performance evaluation: tag life

According to the research of Liu and Ba (2016), the design of the power supply system plays a decisive role in the service life of ETC tags. At present, only six manufacturers in China have the capability of research and development and production of ETC equipment, and they have strict control over the confidentiality of related technologies. As a result, other manufacturers are facing great difficulties in research and development and production of ETC equipment, especially in vehicle tags with high performance-price requirements.

In the design of vehicle tags, the structure and implementation of the power system largely affect and determine the choice of key components of the tag and the structure and implementation of the functional circuit, thus deciding the cost and market characteristics of the tag. Therefore, a high cost-effective power supply system is one of the most important and difficulties in tag design.

In ETC applications, some special systems require that tags should resist metal interference. This often happens in some special logistics projects; these applications often consume more electricity to maintain the transmission and acquisition of signals. Similar applications can occur in extreme climatic environments. This will greatly reduce the life of the ETC tags and increase related maintenance costs. The following table shows how well the respondents understand the relevant ETC attributes and the importance of the attributes to service life.

Table 4.4.5. Importance level in each group of Road Department administrations (tags life)

ETC attributes	Average ranking		
	ETC technical expert	Toll road manager	Government transportation department expert
Battery life	5	5	none

The above table reflects the considerations of Road Department administrations regarding tag life and the main ETC attributes to be used. All respondents in the expert-based interviews believed that the power design of the tag affected the tag life. However, respondents had different opinions on the technical details and importance of these attributes. ETC technical experts believed that a complex and fully functional power design can bring better performance, especially the maintenance work of ETC manufacturers is reduced and can provide a better experience. The government transportation department expert did not participate in tag design, and thus did not provide feedback (See comments on Appendix 7, Table 7.6).

4.4.5.1 Analysis of ETC attributes: Battery life

According to the "*Electronic Charge Special Short-range Communications Standard Part 4: Equipment Application GB/T 20851.4-2007: Reliability - Average Failure-free Operation Time of Vehicle tags should be more than 50,000 hours*"; "*Average Maintenance-free Time: Average Maintenance-free & Time of Vehicle tags should not be* *less than two years (calculated by 10 transactions per day)*". Moreover, all ETC equipment manufacturers on the market claim that the tag life is not less than five years (Liu & Ba, 2016).

When analysing the ETC trading process comprehensively, it is assumed that the time from wake-up to transmission is T_1, from the end of the transaction to sleep mode is T_2, the time for completing a transaction is T, the tag voltage is U, the working current and static current are T_1 and T_2, respectively, and the number of transactions per day is N.

According to Liu and Ba's (2016) research, the state of the tags can be divided into two types: working state and static state. The working state is the tag interacts with the reader and deduct transaction; the static state is the tag is in the standby mode.

Liu and Ba (2016) defined that the average daily power consumption (W_{work}) in the working state is:

$$W_{work} = U \times I_2 \times 10^{-3} \times N \times (T + T_1 + T_2) \quad (4.4.5a)$$

The average daily power consumption (W_{static}) in the static state should satisfied by:

$$W_{static} = U \times I_1 \times 10^{-6} \times [86400 - N(T + T_1 + T_2)] \quad (4.4.5b)$$

Liu and Ba (2018) also pointed out that at present, ETC manufacturers in China can ensure that T is 0.25 s, according to the national standard, wake-up time is less than 5 ms, and according to this threshold, the values of T_1 and T_2 are 5 ms. In equation 4.4.5b, the number "86400" means there are 86400 seconds per day. At the same time, ETC drivers have an average daily usage limit of 10 transactions, the static current is 5 µA and the working current is 100 mA. The annual power consumption should satisfy:

$$W = 365 \times (W_{work} + W_{static}) \quad (4.4.5c)$$

4.4.5.2 Decision outcome and criteria

Formula 4.4.5c can calculate the annual power consumption of ETC tags. I assumed the power of the batteries on the market is W_{total}. For ETCs using tags, I can use the following relationship to calculate the service life of tags.

$$Y = \frac{W_{total}}{W} \tag{4.4.5d}$$

There are two possibilities of exploiting this relationship:

1. The power supply meets the requirements of Road Department administrations. I will select the optimal tags as the decision output.

2. An additional power supply system would be a viable solution when all the power supplies in the market fail to meet the requirements of the Road Department administrations.

I will compare the candidate tags and use the tags with additional power supply design as the optimal choice.

In addition, the power components must meet the volume requirements of the OBU, which is also related to the research of section 4.4.2. The relationship of criteria, requirement and ETC attributes in this performance evaluation can be presented as follows.

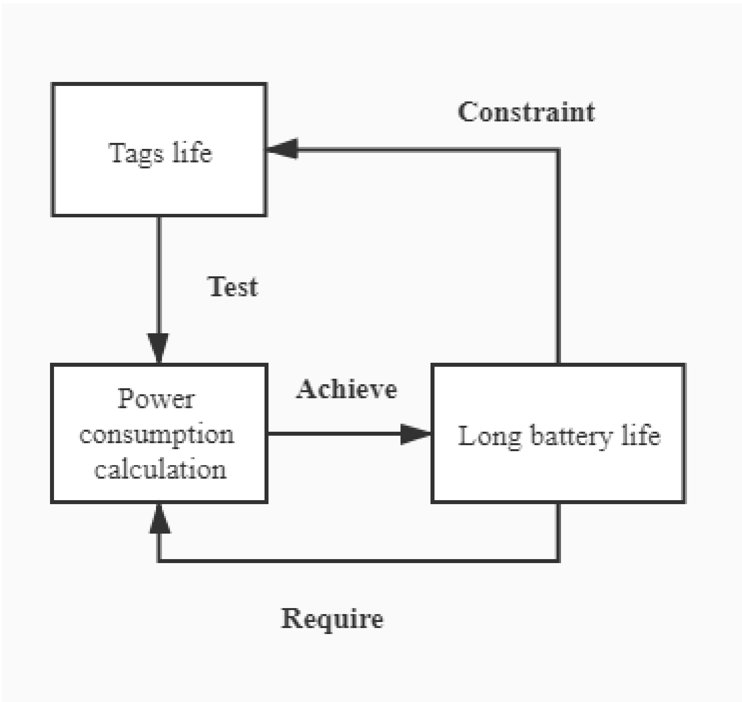

Figure 4.4.5 Performance evaluation of tags life

4.5 Overall decision-making model design

The previous section classified the Road Department administrations' decision into five independent performance evaluations. For each evaluation of performance, there are corresponding attributes, requirements, and evaluation outcomes. Meanwhile, I presented the relationship of criteria, requirement and ETC attributes in graphical modelling, which intuitively shows the decision-making process of Road Department administrations in their respective decision-making environments. I also discussed the outcome of these performance evaluations. Here, I define these outputs into criteria for evaluating ETC systems performance and design the overall decision support models.

4.5.1 Define criteria

Despite the interview work collecting rough information of criteria from participants (section 4.3), it is consistent with the results of section 4.4. We still believe that it is important to give an accurate definition of the criteria, which helps to ensure that the research work does not overflow the scope (section 1.6). In addition, it is necessary to elaborate the characteristics of the criteria to ensure the data range in the later demonstration work (Chapter 5).

Profit: This criterion is for measuring the total income from ETC systems on specific toll roads. This study only considers ETC's profit, which comes from the revenue and cost of the road section. A higher profit will bring higher satisfaction to the Road Department administrations.

Capacity of ETC lane: ETC lane capacity is the criterion to measure the impact of an ETC system on traffic management at toll stations; that is, the unit time traffic flow of an ETC lane. The higher the traffic volume in the ETC lane will bring the high capacity of the ETC system as more vehicles can pass the toll gate in unit time and these ETC lanes are relatively smooth. By calculating the speed of vehicles running under the ETC system through toll stations, we can calculate the traffic volume per unit time of the ETC system to reflect the traffic capacity of these lanes.

Tag life: Because ETC tags used in this research are provided by Road Department administrations, and the batteries of these tags are non-removable, change of frequency of ETC tags affects the cost of the ETC system (Ministry of Transportation, 2019). The ETC product description contains the battery's power consumption, which can be used to calculate the tag life. The longer the tag life, the lower the replacement frequency and the lower the cost. Therefore, ETC tag life, as a requirement of Road Department administrations in the ETC system, is an important criterion to measure the system.

Tag volume: Section 4.4.3 shows that tag size determines the success of signal transmission. Experiment shows that larger tag volume will bring a higher success rate of tag signal transmission. However, the volume of ETC tags must follow the upper limit of OBU design. Once this limitation is exceeded, candidate tags are not acceptable by Road Department administrations. Therefore, as a criterion to measure the performance of an ETC system, the tag volume cannot exceed the upper limit of the OBU.

Moisture proof design: Moisture-proof design is discussed in Section 4.4.3; this research shows that tag moisture-proof design is necessary. Only those tags that have been designed as moisture proof can be accepted by Road Department administrations. This is also a criterion for experts to make decisions.

Compatibility: Section 4.4.4 discussed the anti-collision design and safety design of ETC tags. As compatibility requirements, Road Department administrations require that ETC tags must be able to work under ISO/IEC 18000-6C and EPC Class 1 Gen 2. Due to different technologies adopted by different manufacturers, ETC equipment that meets both security protocols is accepted by Road Department administrations.

4.5.2 Characteristics of criteria

As the previous section described, all criteria (profit, capacity, tags life, tags volume, moisture proof design and compatibility) are confirmed for decision making. They have their own characteristics and are involved in the concepts of the multi-criteria decision-making model.

The values of the candidate ETC system under a specific criterion can be expressed in many ways, and the experts will select the values according to their characteristics. These criteria have the following characteristics.

1. Maximum: The candidate ETC system with the maximum value under a certain criterion will be preferred by experts. The criteria that meet this characteristic include profit and the capacity of the ETC lane.

2. Threshold: The candidate ETC must satisfy a threshold under a certain criterion before it can be considered and selected by the experts. Typical examples are that many Road Department administrations want tags to last at least five years, which means that only ETC tags with a battery life of more than five years can be selected as candidate devices, and then experts will choose the option with the longest life among these candidate tags. In addition to tag life, criteria with threshold characteristics include tag volume and ETC lane capacity.

3. Max order: The criterion with the characteristics of selecting the maximum value also has the feature of max order. That means, under these criteria, the experts rank the candidate ETC system with the max order and sets the priority according to that order.

4. Yes or no: Some criteria have the alternative characteristic of yes or no. Under the effect of the criteria with this characteristic, an ETC system can be a candidate system for experts' decision making only if it meets the criteria, otherwise it will be excluded from the selection activities. Criteria with such characteristics are compatibility and moisture proof design.

4.5.3 Effect of road environment and define decision-making goals

The decision-making model developed in this study will be applied to toll highways. The toll stations in this road environment include traffic volume, toll rate, open and closed toll systems (introduced in section 2.4.2). The impact of the environment on decision making includes the following aspects.

1). Toll highways provide data of road PCU and toll station PCU, which is the key information of traffic volume for calculating the revenue and cost of an ETC system (Jiancheng, 2010). The calculated revenue, under the influence of the profit criterion, can determine decisions by Road Department administrations.

2). Toll highways provide ETC lane width, which can be used by Road Department administrations to determine the number of ETC lanes at toll stations and affect the profit of an ETC system.

3). Road policies (section 2.4.3) impact criteria for toll roads, including tag life, compatibility settings and moisture-proof design. For example, road construction policy requires tags to last at least five years, must have moisture-proof designs, and be able to operate under ISO/IEC 18000-6C and EPC Class 1 Gen 2 protocols. This affects the yes or no characteristics of the criterion (section 4.4.4).

4). OBUs should meet the national standard, which means the volume of ETC tags needs to be controlled within a certain range. This affects the threshold characteristics of the criterion.

For Road Department administrations, their decision-making goal is to select the optimal ETC deployment scheme for a specific application environment. The decision criteria determine the optimal ETC deployment scheme, which involves the following two decision states:

1.When only one performance evaluation can satisfy the requirements of Road Department administrations, a single criterion judgment can complete the decision-making behaviour. At this time, the decision-making model is in a single optimal decision-making state, which does not belong to multi-criteria decision making.

2.When the Road Department administration needs more than one performance evaluation to participate in decision-making behaviour, the decision-making model needs to set importance on the decision-making state of multi-criteria judgment. In this state, we need to set weights and ranks for each criterion to eventually produce uniform evaluation results.

4.5.4 Implement: criteria weighting

Chapter 3 described the approach of decision making and how to measure the importance by semantics. In the expert-based interviews, experts ranked those semantics' importance by using a 6-point semantics method and to differentiate their weights in decision making. As described in section 3.3.3, 28 participants were invited for the expert-based interviews, and I distinguish their types by job position. This information is shown in following table.

Table 4.5.4a Type of participants

Type of participants	Number of participants
ETC technical experts (RO1)	17
Toll road managers (RO2)	10
Government transportation department expert (RO3)	1

Importance issues are included in the expert-based interviews; that is, feedback was given immediately after completing the importance ranking of the criteria. Like section 4.4, I introduced the PCS model (Salisbury, 2006) to calculate the average assessment of the importance by each group of participants (original data see appendix 7, Table 7.7). This information is shown in following table.

Table 4.5.4b Average weight by each group of participants

Type of participants	Profit	Capability	Moisture-proof design	Compatibility	Tags volume	Tags life
RO1	3.2	3.9	5	5	4.2	4
RO2	3.6	5	5	5	4.4	4.7
RO3	5	4	5	5	5	5

The information in the above table shows that all participants ranked a "5" weight to moisture-proof design and compatibility. This means candidate ETC systems satisfy the requirement of moisture-proof design and compatibility, to be considered by Road Department administrations. Therefore, we remove these two criteria from the weight evaluation and mark them as constraints of decision making to limit the scope of ETC selection. I simplify the table 4.5.6b as follows:

Table 4.5.4c Group weighting of each criteria

Type of participants	Profit	Capability	Tags volume	Tags life
RO1	3.2	3.9	4.2	4
RO2	3.6	5	4.4	4.7
RO3	5	4	5	5

I used the entropy method (section 3.2.2) to determine the weight of the criteria, which can avoid the influence of subjective factors. By introducing the data in table 4.5.4c, I calculated the weights of each criterion as shown in the following table.

Table 4.5.4d Weights of each criterion

	Profit (C1)	Capability (C2)	Tags volume (C3)	Tags life (C4)
Weights of each criterion	0.58	0.2	0.09	0.13

Then, I introduced the weights information listed in the above table and generated the total formula model (equation 2.5.3) as the following equation. The satisfaction S_j on each candidate ETC system is:

$$Max(S_j) = Max\left(P_j \times 0.58(C1) + P_j \times 0.2(C2) + P_j \times 0.13(C3) + P_j \times 0.09(C4)\right) \quad (4.5.4)$$

$$Constraint: Moisture\_proof \;\&\; Compatibility \;\&\; (Tags\_volume \leq Threshold) \quad (4.5.4a)$$

From the above equation, the integer j is any number from 1 to m. It presents there are m (total number) ETC systems provided by manufacturers, and j is the sequence number of the system.

CHAPTER FIVE: DEMONSTRATION AND SENSITIVITY EVALUATION

5 Overview

The main work of this chapter is to demonstrate and evaluate the sensitivity of the decision model proposed in Chapter 4. In the data analysis phase, this chapter cites the feasibility reports and academic studies from three toll road projects in real-world. Using the data provided in these documents and the parameters provided by ETC systems in the market, This research introduce the decision model developed in Chapter 4 into three case studies. From the perspective of Road Department administrations, the decision-making behaviour is carried out and the decision-making results obtained. The decision results were recorded and compared with ETC systems in real-world and analyzed to see whether the decision model achieved the expectations of Road Department administrations. Sensitivity assessment evaluated the relationship between decision results and input elements. I believed that there were influences that needed to be found out in decision behaviour, which included both criteria and threshold of the decision input.

The purpose of this section is to:

- Determine the decision-making process in demonstration (section 5.1).
- Determine assumptions for data preparation (section 5.1.1).
- Provide information of candidate ETC systems (section 5.1.2).
- Explain the data preparation (section 5.1.3).
- Demonstrate decision making (sections 5.2, 5.3 and 5.4).
- Evaluate sensitivity by criteria and threshold (section 5.6).

5.1 Demonstration

Demonstration is based on the content of Chapter 4. It analyzed and studied the process of parameter changes in mathematical models and how to lead to various related consequences. In this study, the main objective of demonstration is to identify the factors that affect Road Department administrations' decision making, and to verify the specific role of these factors. This process involves changing the input values of the model to verify where the output is worth changing. I believe that if some hypothetical ETC system is not implemented or only partially implemented, it is also considered as an effect that tends to achieve goals. This part demonstrates the potential activities in each performance evaluation to determine whether the mathematical model achieves the expectations of Road Department administrations. Here, This research obtained three real cases and applied the decision model to these decision scenarios to verify whether the decision results are consistent with reality.

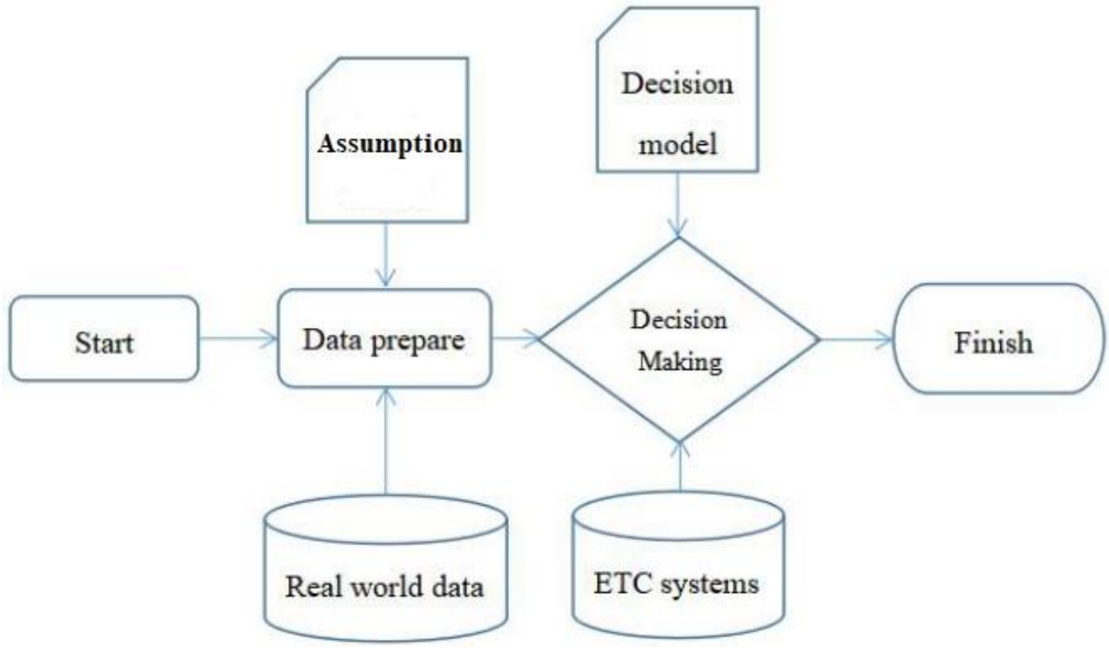

Figure 5.1 Demonstration developed from decision making

The above figure shows the process of demonstration. Unlike general experiments and tests, the real-world data obtained in this study are from the feasibility reports and research literature of highway construction projects, and the deployment of ETC systems is only a part of these projects. Therefore, a large amount of data needs to be converted and can meet the input requirements of the decision model which was developed in section 4.5. This research executed the model from the perspective of the Road Department administrations and obtained the demonstrated results. Before the demonstration process, the following elements need to be clarified and used to assist later work.

5.1.1 Assumptions from the road environment and policies

Because of effects of the road environment and policies, the original data of ETC attributes which were provided by the case studies cannot be directly used as input to the total decision-making model, which requires data preparation and conversion into data suitable for decision input. Therefore, This research list these hypotheses to prepare the data for later demonstration.

5.1.1.1 PCU

Passenger Car Unit (PCU) is a metric used in Transportation Engineering to assess traffic-flow rate on a highway. A PCU is essentially the impact that a mode of transport has on traffic variables (such as headway, speed, density) compared to a Minibus (Highway Engineering Committee of China Engineering Association Standardization Association， Highway department, 2004). Here, the "Code for Maintenance and Design of Asphalt Pavement on Highway" (2019) points out the Minibus refers to a Minibus with under seven seats. The typical values of PCU are presented in following table.

Table 5.1.1 Typical value of PCU (Ministry of Transportation, 2019)

Vehicle types	PCU value (Cf_{pcu})	Critical load
Minibus	1.0	Less than 7 seats
Bus	1.5	More than 7 seats
Van	1.0	Carrier mass less than 2 tons
Medium truck	1.5	2 tons < load mass ≤7.0 tons
Large truck	3.0	7 tons < load mass ≤14 tons
Trailer	3.0	Including semi-trailer and flat trailer

5.1.1.2 Toll rates of highway

Toll rate is the ratio at which fees are paid. Highway toll rates for vehicles are classified depending on type of vehicle and the mileage that vehicle had driven. With the same mileage, the higher the tonnage in trucks and the more seats in the buses will bring the more initial charges and highway pay rates ("National Highway Toll Standard", 2018). For the demonstration of this research, I inquired the toll rates of G40 highway, Sutong Bridge and Qixian-Lishi highway, and listed the information in the following table.

Table 5.1.1a. Highway toll rates ("National Highway Toll Standard", 2018)

Vehicle types	Pay rates

	(Rt_{type})
Minibus	0.675 Yuan/km
Bus	0.9 Yuan/km
Van	0.675 Yuan/km
Medium truck	0.9 Yuan/km
Large truck	1.35 Yuan/km
Trailer	1.35 Yuan/km

5.1.1.3 Vehicle type proportion

Vehicle type proportion refers to the radio of each type of vehicle to the total PCUs. Ma (2018) provided the forecast data of highway vehicle type, which cannot show all the conditions of the highway, but is usually used as an important basis for feasibility reporting of PCUs and revenue. The following table shows the proportion of vehicle types in 2020, 2027 and 2035.

Table 5.1.1b. Proportion of vehicles (Ma, 2018)

	Minibus (Cf_{type})	Bus (Cf_{type})	Van (Cf_{type})	Medium truck (Cf_{type})	Large truck (Cf_{type})	Trailer (Cf_{type})
2020	71.50 %	5.50%	3.70%	6.80%	7.00%	5.50%
2027	72.94%	5.20%	3.96%	6.34%	5.80%	5.76%
2035	74.62%	4.40%	4.44%	5.86%	4.36%	6.32%

5.1.1.4 Toll station traffic lane configurations

When more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes. (Guangdong Transportation Group, 2016)

Ma (2018) pointed out that in order to facilitate statistics, most current research adopts a fixed day-night statistic method, that is 12-hours for day to night rotation, and assume that the fixed traffic per hour is consistent between daytime and nighttime as in Figure 5.1.1. The ratio of daytime traffic to nighttime traffic is 0.85:0.15 (Ministry of Transportation, 2019).

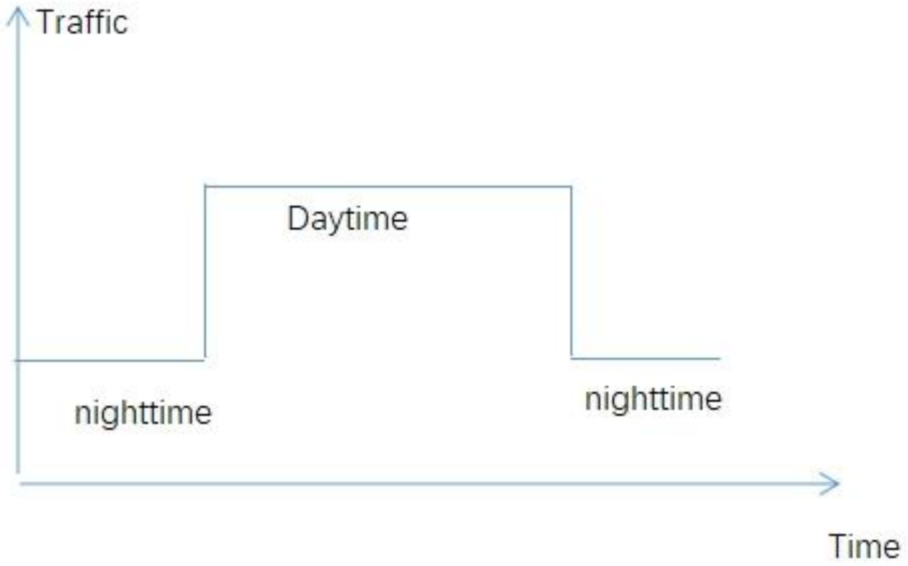

Figure 5.1.1 Traffic per hour in the day's consistent

Three operators should be set up for each manual toll lane to facilitate rotation, and one ETC maintenance staff should be set up for each toll station. (Guangdong Transportation Group, 2016)

5.1.1.5 Tag cost-based road length

Highway construction in China depends entirely on the government financial allocation, and the ownership of highways is also clear: state ownership. With the establishment of a highway toll system, including government loan repayment highways, domestic and foreign social capital is paid through the BOT (construction-operation-transfer) or TOT (transfer-operation-transfer) mode to participate in the operational highway. According to the traffic department reports, as of 2016, there were 298 kilometers (Nantong Transportation Bureau, 2016) of highway in Nantong, 111 kilometers of highway in Taizhou (Taizhou Transportation Bureau, 2016) and 206 kilometers of highway in Luliang (Wu, Sun & Zhang, 2017). Since 2016, in most areas, vehicle on board units (OBUs) have been provided by the highway operation department, and that costs were apportioned to the cost of road construction (Intellectual Research Consulting Group, 2016). For this reason, I assumed that the proportion of mileage in the demonstration project to the total highway length in the project area determines the weight of ETC tags (Costs) allocation, and it must satisfy the following relationship.

$$C_{tags} = \frac{D_{section}}{D_{total}} \times Ve_{increase} \times C_{unit\_price} \qquad (5.1.1)$$

In the above equation, C_{tags} represents the tags costs of the demonstration project,

C_{unit_price} represents the price of each ETC tag, $D_{section}$ represents the mileage of the demonstration project, D_{total} represents the total highway length of the project region, and $Ve_{increase}$ represents the increment of ETC users in the project region.

Therefore, 1) the costs of tags are borne by the government; 2) these costs are allocated to each road section by length of road.

5.1.1.6 Number of ETC tags

According to the statistics of the Ministry of Transportation, the number of ETC users accounts for 30% of all drivers in China (Ministry of Transportation, 2019). I assume this ratio will not change, as research "The barriers are difficult to overcome and hinder ETC network traffic construction in China"(2014) stated complex procedures for opening an ETC account and the complex process of ETC recharge hinders ETC development. Without policy changes, the proportion of ETC users will not change significantly.

Due to the rapid economic development, the number of vehicle ownerships increases at an average rate of 5% every year (Ministry of Transportation, 2019). In 2016, the number of vehicles in the Nantong area was 1487 826 (Nantong Transportation Bureau, 2016), while that in Taizhou area it was 858 263 (Taizhou Transportation Bureau, 2016). In 2018, the number of vehicles in the Luliang area reached 350,000 (Wu, Sun & Zhang, 2017).

5.1.1.7 Cost of salaries and staff allocation

The monthly salary of toll station operators (including MTC and ETC) is 5000 Yuan (2018), while China's GDP growth rate is 6.6% (Ministry of Transportation, 2019). Therefore, for the three characteristic years 2020, 2027 and 2035, the salaries of operators should be 5682-yuan, 8888 yuan and 14820 yuan, respectively.

Three operators should be set up for each manual toll lane to facilitate rotation, and one ETC maintenance staff is set up for each toll station (Guangdong Transportation Group, 2016).

5.1.1.8 Traffic status

The speed limit of the highway is 120 km/h and that of an ordinary highway is 50 km/h (Ministry of Transportation, 2019). The average deceleration of vehicles is 5 m/s2, and the average acceleration is 3 m/s2. The average transaction time for ETC vehicles is 2.76s, many tags' anti-collusion frequency is 100times per second (Zhang,2017).

The size of the whole vehicle on board unit (OBU) is controlled in the space of 100×60×10mm. The service life of a vehicle tag power supply must be no less than 5 years (Wang, 2019). The average number of vehicle tag transactions is 10 times a day (Liu & Ba, 2016). At present, the safety specifications of vehicle tags must meet the requirements of ISO/IEC 18000-6C and EPC Class 1 Gen 2 (Ministry of Transportation, 2019).

5.1.1.9 Tag life

Section 4.4.5 pointed out that ETC tags have two states: working state and static state. In the working state, the ETC tag is in transaction with the reader; the static state refers to waiting for the signal transaction. Both states cause energy loss. In the working state, the energy loss will satisfy the following relationship.

$$W_{work} = U \times I_2 \times 10^{-3} \times N(T + T_1 + T_2) \quad (5.1.1a)$$

In the static state, the energy loss will satisfy the following relationship

$$W_{static} = U \times I_1 \times 10^{-6} \times \left(86400 - N(T + T_1 + T_2)\right) \quad (5.1.1b)$$

From above two equations, I assumed that the time from wake-up to transmission is T_1, from end of transaction to sleep is T_2, and the time for completing a transaction is T; the tag voltage is U; the working current and static current are I_1 and I_2, respectively; and the number of transactions per day is N. Chapter 4's research also pointed out that at present, ETC manufacturers in China can ensure that T is 0.25 s, according to the national standard, and wake-up time is less than 5 ms ; and according to this threshold, the values of T_1 and T_2 are 5 ms. At the same time, ETC drivers have an average daily usage limited to 10 transactions, the static current is 5 μA and the working current is 100 mA. The working voltage of the lithium batteries for ETC tags is 3.6 V.

Therefore, the energy consumption of a tag in one year should satisfy the following equation.

$$W = 365 \times (W_{work} + W_{static}) \quad (5.1.1c)$$

5.1.1.10 Vehicle identification

The toll collection process is based on vehicle classification alone. For vehicle identification, tags are installed on vehicles, and readers are installed on toll gates. When the vehicle enters the ETC lane, the tag communicates with the reader to initiate two-way data transmission. The system reads the vehicle's licence plate number and the on-board vehicle classification information (Ma, 2018). The mechanism of vehicle identification is presented as follows (ETC system testing summary of the National Highway Network, 2014):

1. The back-end system initializes vehicle tags and writes the car licence plate number, vehicle type, and toll rate to the tag, and then establishes the customer files.

2. After the vehicle enters the ETC lane, the system activates the antenna and reads the identification information on the tag, and then sends it to the central server for verification.

3. If the vehicle is legal, then toll charges are issued.

4. After payment is complete, the account balance is updated, and a transaction invoice is sent to road users.

5. The system sends out an alarm signal when an illegal vehicle attempts to pass through. In this situation, the vehicle will be stopped at a barred toll station. Otherwise, a blacklist will be sent to the traffic police department.

5.1.2 Sample database

The contents of the database are mainly sample information selected by Road Department administrations, which are selected from ETC systems in the real world. In this study, I visited Taobao, which is China's largest e-commerce platform, to collect the more common ETC readers on the market. The following table shows the main technical parameters and approximate cost of these readers.

Table 5.1.2. Candidate ETC readers

	Frequency	Signal range	Speed limit (Designed)	Price
Reader 1	900Mhz	6 meters	80 km/h	1000 Yuan
Reader 2	900Mhz	15 meters	80 km/h	1500 Yuan
Reader 3	900Mhz	20 meters	80 km/h	2580 Yuan
Reader 4	2.4G or 5.8Ghz	100 meters	80 km/h	2750 Yuan

I recorded the commonly used ETC tag information, detailed parameters of these tags are shown in the following table.

Table 5.1.2a Candidate ETC tags

	Frequency	RF protocol	Water-proof design	Size (mm)	Battery energy	Price
Tag 1	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	120×29×0.4	None	5 Yuan
Tag 2	900 MHz	EPC Class 1 Gen 2	No	85.6×53.98×1.0	None	10 Yuan
Tag 3	900 MHz	EPC Class 1 Gen 2	Yes	23×2.5	3V, 75mA	2 Yuan
Tag 4	900 MHz	EPC Class 1 Gen 2	No	86×54×0.25	None	2 Yuan
Tag 5	900 MHz	ISO/IEC 18000-6C	Yes	55×17×0.3	None	2 Yuan
Tag 6	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	52×52×14	3V, 120mA	20 Yuan
Tag 7	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	No	92×26×0.25	None	2 Yuan
Tag 8	900 MHz	EPC Class 1 Gen 2	Yes	85×54×0.8	None	25 Yuan
Tag 9	900 MHz	EPC Class 1 Gen 2	Yes	40×30×1.0	None	25 Yuan
Tag 10	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	88x56×5	3V, 210mA	15 Yuan
Tag 11	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	118×35× 6.6	3.6V, 700mA	40 Yuan
Tag 12	900 MHz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	141×32 × 34	3.6V, 1200mA	90 Yuan
Tag 13	2.4G or 5.8Ghz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	85.5×54×4	3.6V, 1200mA	60 Yuan
Tag 14	2.4G or 5.8Ghz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	90×31×10	1.5V, 1600mA	30 Yuan
Tag 15	2.4G or 5.8Ghz	ISO/IEC 18000-6C，EPC Class 1 Gen 2	Yes	86×54×4.5	2.2V, 1600mA	50 Yuan

It should be noted that, before selecting samples, this study merged the same items and eliminated the redundant products with the same RFID parameters (products with same attributes but made from different manufactures). Due to the limitations of this research scope, the equipment price mentioned in Table 5.1.2 includes the costs of antennas and ETC readers. The equipment cost mentioned in Table 5.1.2a is the price of the OBUs, which includes tag elements, both RFID equipment and external interfaces (as discussed in Chapter 2).

The information provided in tables 5.1.2 and 5.1.2a illustrated the data in the sample database, which is the object of decision model selection. These devices are matched according to their working frequency, and thus 39 equipment combinations as candidate ETC systems were generated.

5.1.3 Data preparation

In this study, the road environment of demonstration work comes from the feasibility report of highway construction in the real world. These reports are the decisive work before the determination of road construction projects. They are the scientific demonstration of the comprehensive technical and economic analysis of the proposed projects before the investment decision of the whole project. In the investment management, the feasibility study refers to the investigation and division of the natural, social, economic and technological aspects, to analysis, comparison and prediction of social and economic benefits after completion. On this basis, it demonstrates the necessity of project construction, financial profitability, economic rationality, technological advancement and adaptability, and the possibility and feasibility of construction conditions, to provide a scientific basis for investment decision making. It can be seen that the feasibility report covers a wide range of contents, not only focusing on the deployment and design of ETC systems, but also including the road environment of that road project. Therefore, it is necessary to convert the data in the report into the data required for the demonstration work, to prepare for the decision-making behaviour. Here, I refer to the data provided in the feasibility report as direct data, and the transformed data to demonstrate the decision model.

Direct data: The road environment data provided in the feasibility report are PCU value, road length, width of traffic lanes, and the width of the isolation zone between these traffic lanes. It should be emphasized that for a closed highway, PCU information includes cross-road measurement data and toll station measurement data, which are different. The following table describes the symbols and units of measurement of these data.

Table 5.1.3 Direct data

	Symbol	Measurement
PCUs	PCU	pcu/unit time
Road mileage	$D_{mileage}$	kilometers
Traffic lane width	d	meters
Isolation zone width	L	meters

The transformed data were not directly given by feasibility reports, but they are input information before performance evaluation is required. As described in Chapter 4, only by transforming the road environment data to the performance evaluation inputs, can the total decision model be carried out and the effective decision-making output produced. This study noted the difference between the road environment of real-world data and decision input, and then provided detailed information about these transformed data, as well as the process of converting from direct data.

These transformed data should meet the input requirements of the five performance evaluation environments mentioned in Chapter 4.

Table 5.1.3a Transformed data

	Symbol	Measurement	Source
ETC revenue	R_{ETC}	Yuan	Calculated by direct data and assumptions
Costs of tags	C_{tags}	Yuan	Calculated by direct data, sample database and assumptions
Costs of readers	$C_{readers}$	Yuan	Calculated by sample database and assumptions
Costs of salary	C_{salary}	Yuan	Calculated by assumptions
Traffic lines in Toll station	n	Number	Calculated by direct data, sample database and assumptions

3. Preparation for decision making

Direct data (Table 5.1.3) provided by feasibility reports may not be able to participate in the demonstration as decision input. The solution is to convert these direct data into transformed data (Table 5.1.3a). This process of transformation is called data preparation. It mainly converts PCU values into road revenue, salary cost, reader cost, tag cost and the number of traffic lanes for decision-making behaviour; these transformed data together with assumptions in section 5.1.1 will be considered as input for decision making.

5.1.4 Classification outcomes

The initial results generated by the performance evaluation has five meanings, which should meet the requirements of Road Department administrations mentioned in Chapter 4. This means that the target ETC system generated by the decision system has the characteristics of profit, ETC lane capacity, reliability, compatibility to safety standards, and tag life. In this study, two types of situation need to be considered. The first type of situation focuses on the experience and practical application of Road Department administrations. This research directly imported the data from the sample database into the performance evaluation environments which was discussed in Chapter 4 and used the real-world data and policy constraints to generate decision-making output. Correspondingly, the second type of situation focused on the overall decision-making model which was developed in Chapter 4. The output of each decision environment will be optimized by using a multi-criteria method, and the criteria weight and rating will be used to output the satisfactory value of the candidate ETC system. The Optimization ETC system must satisfy both above situations.

5.1.4.1 Decision output filtered by constraints

As described in Chapter 4, two criteria had been set as constraints. By inputting transformed data, only if candidate ETC systems are satisfied these constraints, can they be selected by Road Department administrations.

For reliability design, when the candidate sample meets the moisture-proof design, it was set as "qualified", otherwise it was set as "unqualified". When the volume of the candidate sample is controlled in the size of 100×60×10 mm, I set it as "qualified" in this respect, otherwise it is set as "unqualified". In terms of reliability design, only when the candidate ETC system is satisfied as “qualified” on both moisture-proof design and volume (the set of results {qualified, qualified}), will I believe that the ETC system meets the reliability criteria.

There are two categories of compatibility design. Firstly, the anti-collision design is discussed in Chapter 4. When the anti-collision mechanism is activated, the time of vehicles passing through toll stations should be involved in the time for the transaction. This means that collision avoidance time was needed because of the calculation of the original toll station capacity. Therefore, when the anti-collision mechanism time was included in the vehicle transaction time, I believe that ETC design is "qualified", otherwise it is "unqualified". For safety design, I believe both the anti-collision and data encryption mechanism must be run under the protocol EPC Class 1 Gen 2 and ISO/IEC 18000-6C. When the safety protocol satisfies both EPC Class 1 Gen 2 and ISO/IEC 18000-6C protocol, I believe that the safety design is "qualified", otherwise it is "unqualified". That is, only when the candidate system satisfies these two types of result (set of {qualified, qualified}), does, I believe, the ETC system conform to the safety design specification.

5.1.4.2 Maximum of satisfaction

Chapter 4 discussed the output states of the other three decision-making environments and set them as criteria for decision making. A multi-criteria decision model was created and required to produce optimal output according to the model. These three criteria considered by the decision model are profit, ETC lane capacity and tags life. In the sample ETC database, they are given specific weights and normalized into Road Department administration satisfaction scores. Here, I need to take satisfaction into account, and they should satisfy the following relationships. That is, the Optimization ETC system must be satisfied as maximum value of that satisfaction.

$$Max(S_j) = Max\left(P_j \times 0.58(C_1) + P_j \times 0.2(C_2) + P_j \times 0.13(C_3) + P_j \times 0.09(C_4)\right) \quad (5.1.4)$$

From above equation, the integer j is any number from 1 to m. It presents there are m (total number) ETC systems provided by manufacturers, and j is the sequence number of a system.

5.2 Case analysis: G40 (Pingchao-Guangling Section) reconstruction and extension project

This research case comes from the reconstruction and extension project of the G40 Shanghai-Shanxi Highway (Pingchao-Guangling Section). The project was approved by the Jiangsu Environmental Protection Department in April of 2018 and implemented by the Jiangsu Highway Management Center.

The G40 Shanghai-Shaanxi Highway is the “eighth horizontal” traffic line in the national key highway construction project of "thirteen vertical and fifteen horizontal traffic lines". This project is in G40’s area, which is along the Yangtze River in the north of Jiangsu Province. It passes through Nanjing City, Yangzhou City, Taizhou City and Nantong City. And it is the skeleton of the major traffic corridor along the Yangtze River in the north of Jiangsu Province. The Jiangsu section of G40 Shanghai-Shaanxi Highway is composed of the Tongqi Highway, the Ningtong Highway, the Yongliu Highway, the Nanjing Circumferential Highway and the Ninghe-Hefei Highway. The starting point of this project relates to the Tongqi Highway and the end point is connected with the Jiangguang Section of the Ningtong Highway (Beijing-Shanghai Highway Co-line

Section).

Figure 5.2 G40 Shanghai-Shaanxi Highway

At present, the road traffic in the project area has reached saturation, and the congestion is serious. In the future, with the continuous development of economy and society, and the further deepening of cross-region integration, regional traffic volume is bound to continue growing. After the completion of this project, it can optimize the connection conditions of bridges crossing the Yangtze River, divert traffic pressure from the Jiangyin Bridge and the Sutong Bridge. At the same time, the improvement of travel conditions of the East-West Highway in Jiangbei can attract the East-West travel demand in some areas of Jiangnan to the north of Jiangsu Province, alleviate the traffic pressure on the East-West Highway in southern Jiangsu Province, and help guide a more reasonable distribution of traffic flow in the region.

The route of this project starts at Pingchao North Junction of the Xitong Highway North Connection and the G40 (not implemented in this project), passes westward through Taixing City, Jingjiang City of Taizhou City, Tongzhou District and Rugao City of Nantong City, and ends at the Guangling Junction of the G40 and the G1515. The total length of the route is 48.925 km. The way is Tongzhou District of Nantong City, Rugao City, Jingjiang City of Taizhou City and Taixing City. There are about 2.7 km in Tongzhou District, 29.4 km in Rugao City, 10.1 km in Jingjiang City and 6.8 km in Taixing City. At present, the investment in the project is 4818 million Yuan, and construction started in early 2019. The project is planned to be completed and opened to traffic by the end of 2020, with a construction period of about two years.

5.2.1 Direct Data

Direct data provided in this road section are:

1. This project predicts PCU information for the three characteristic years 2020, 2027 and 2035. This information is provided directly by the feasibility report, as shown

in the table below. Here, the "pcu/d" were used to measure the average PCU value of each day. Here, it must be emphasized that three characteristic years PCUs (tables 5.2.1 and 5.2.1a) are the data recorded by traffic departments at different observation points at different times and generated by conjecture. It is not associated with the section 5.1.1.6, assumption "Number of ETC tags".

Table 5.2.1 PCU per day in Pingchao North Hub to Jiuhua Interchange

Road segment	Section mileage ($D_{mileage}$)	Characteristic year 2020 (PCU)	2027 (PCU)	2035 (PCU)
Pingchao North Hub to Jiuhua Interchange	3 km	19968 pcu/d	36667 pcu/d	59529 pcu/d
Jiuhua Interchange to Rugao Port Interchange	14 km	28110 pcu/d	47346 pcu/d	72726 pcu/d
Rugao Port Interchange to Shizhuang Interchange	6.2 km	28000 pcu/d	47056 pcu/d	71771 pcu/d
Shizhuang Interchange to Geshi Interchange	4.3 km	27192 pcu/d	45895 pcu/d	70034 pcu/d
Geshi Interchange to Jishi Interchange	17.1 km	27368 pcu/d	46047 pcu/d	69595 pcu/d
Jishi Interchange to Guangling Interchange	7.3 km	28007 pcu/d	46464 pcu/d	69934 pcu/d
Guangling Interchange-Guangling Hub	1.9 km	27869 pcu/d	46264 pcu/d	69248 pcu/d

2. The feasibility report mentioned that there six toll stations in this road section. The PCU information of the toll stations is as follows.

Table 5.2.1a PCU per day of each G40 project toll station

Toll stations	2020 Drive-in (PCU)	2020 Drive-out (PCU)	2027 Drive-in (PCU)	2027 Drive-out (PCU)	2035 Drive-in (PCU)	2035 Drive-out (PCU)
Jiuhua toll station	9980 pcu/d	4620 pcu/d	15548 pcu/d	7890 pcu/d	17816 pcu/d	9850 pcu/d
Rugao Port toll station	4444 pcu/d	3064 pcu/d	7587 pcu/d	4754 pcu/d	9512 pcu/d	5822 pcu/d
Shizhuang toll station	2285 pcu/d	1064 pcu/d	4189 pcu/d	1952 pcu/d	5936 pcu/d	2669 pcu/d
Geshi toll station	3180 pcu/d	2565 pcu/d	5830 pcu/d	4201 pcu/d	7632 pcu/d	5301 pcu/d
Jishi toll station	2783 pcu/d	1774 pcu/d	5256 pcu/d	3330 pcu/d	7183 pcu/d	4551 pcu/d
Guangling toll station	2934 pcu/d	1916 pcu/d	5379 pcu/d	3515 pcu/d	6820 pcu/d	4398 pcu/d

3. Other direct data are shown below.

Table 5.2.1b Other direct data in Pingchao North Hub to Jiuhua Interchange

	Symbol	Value
Traffic lane width	d	3.75 meters
Isolation zone width	L	0.75 meters

5.2.2 Decision inputs

According to the description of the "Data preparation" (section 5.1.3), I converted the direct data to the input of decision making, that is the transformed data, which are the revenue, cost of tags, cost of toll station operators' salaries and the number of toll station traffic lanes.

5.2.2.1 Revenue calculation

In order to calculate the revenue of a highway segment in a characteristic year, (1) I needed to first determine the PCU value of each type of vehicle; (2) When I calculate the PCU number of each type vehicle, I need to convert that data into the number of traffic entities of each type of vehicle; In this case, the section 5.1.1.1 assumption "PCU" provided the PCU value for each type of vehicle; (3) Finally, using the number of these traffic entities, the toll rate of the highway provided in Table 5.1.1a (Section 5.1.1.2 assumption "Pay rates of highway") and the mileage of the segment provided in Table 5.2.1, I can calculate the revenue of the road segment.

Here, I have taken the Pingchao North Hub to Jiuhua Interchange segment as an example to calculate the revenue generated in 2020 (Table 5.2.1).

Step 1. Firstly, I determine the PCU of each type of vehicle in this segment. Information on PCU value is provided in Table 5.2.1, and the proportion of vehicles is provided in Table 5.1.1b (section 5.1.1.3 assumption "vehicle type proportion"). The following equation can help to calculate the results.

$$PCU_{type} = Cf_{type} \times PCU \qquad (5.2.2)$$

In the above equation, PCU_{type} denotes the PCU number of each type of vehicle, Cf_{type} denotes the proportion of each type of vehicle to the total PCU (Table 5.1.1b), and PCU denotes the total passenger car units of this road segment (Table 5.2.1). Here, I take the minibus as an example. In the section 5.1.1.3 assumption "Vehicle type proportion", Table 5.1.1b indicates that the proportion of minibuses to total PCUs is 71.5% in 2020. Table 5.2.1 indicates that the total PCU value of this segment is 19968 pcu/d. Then, when I introduce these data into equation 5.2.2, the calculation process is as follows.

$19968 \times 71.5\% = 14277\ pcu/d$

Therefore, in the Pingchao North Hub to Jiuhua Interchange segment, the PCU number per day of minibuses is 14277 pcu/d. Using the same method, I calculated the PCU value of buses, vans, medium trucks, large trucks, and trailers as 1098 pcu/d, 738 pcu/d, 1358 pcu/d, 1398 pcu/d and 1098 pcu/d, respectively.

Step 2. Then, I determine the number of traffic entities for each type of vehicle in the segment. The following equation can help to calculate the results.

$$Ve_{type} = PCU_{type} \div Cf_{type} \quad (5.2.2a)$$

In the above equation, PCU_{type} denotes the PCU value of each type of vehicle (calculated in step 1), Cf_{type} denotes the PCU value for each type of vehicle (Table 5.1.1 in the section 5.1.1.1 assumption “PCU”), Ve_{type} denotes the number of each type vehicle in this road segment. Here, I still take the minibus as an example, because in the first step, I calculated the PCU value per day of this road segment was 14277 pcu/d; in the section 5.1.1.1 assumption “PCU”, Table 5.1.1 indicates that the PCU value of this type of vehicle is 1. Then, when I introduce these data into equation 5.2.2a, the calculation process is as follows.

$14277 \div 1 = 14277\ Ve/d$

Therefore, in the Pingchao North Hub to Jiuhua Interchange segment, the number of minibuses passing through this segment is 14277 vehicles every day (Ve/d). Using the same method, I calculated the number of traffic entities of buses, vans, medium trucks, large trucks, and trailers as 732 Ve/d, 738 Ve/d, 904 Ve/d, 465 Ve/d and 365 Ve/d, respectively.

Step 3. Finally, I calculated the revenue of the Pingchao North Hub to Jiuhua Interchange segment in 2020. The following equation can help to calculate the results.

$$R_{segment} = 365 \times \sum_{i=1}^{n}\left(Rt_{type} \times D_{mileage}\right) \quad (5.2.2b)$$

Here, $R_{segment}$ represents the revenue of the road segment, Rt_{type} represents the toll rate of the highway, and $D_{mileage}$ represents the mileage of the vehicles driving on that road section. Here, I take the Pingchao North Hub to Jiuhua Interchange segment as the example, because in the second step, I calculated the traffic entities of minibuses, buses, vans, medium trucks, large trucks and trailers as 14277 Ve/d, 732 Ve/d, 738 Ve/d, 904 Ve/d, 465 Ve/d and 365 Ve/d, respectively. Table 5.2.1 indicates that the mileage of the Pingchao North Hub to Jiuhua Interchange segment is 3km; Table 5.1.1a indicates the toll rate of minibuses, buses, vans, medium trucks, large trucks and trailers as 0.675 Yuan/km, 0.9 Yuan/km, 0.675 Yuan/km, 0.9 Yuan/km, 1.35 Yuan/km and 1.35 Yuan/km, respectively; the initial payment of minibuses, buses, vans, medium trucks, large trucks and trailers as 5 Yuan, 20 Yuan, 15 Yuan, 20 Yuan, 30 Yuan and 30 Yuan, respectively. Then, when I introduce these data into equation 5.2.2b, the calculation process is as follows.

$$[0.675 \times 3 \times 14277 + 0.9 \times 3 \times 732 + 0.675 \times 3 \times 738 + 0.9 \times 3 \times 904 + 1.35 \times 3 \times 465 + 1.35 \times 3 \times 365] \times 365 = 21569674\ Yuan$$

Therefore, in 2020, the revenue of the Pingchao North Hub to Jiuhua Interchange segment is 21569674 Yuan. Using the same method, I calculated the whole road section revenue in three characteristic years as per the following table.

Table 5.2.2 Transformed data-G40 revenue in three characteristic years

	2020	2027	2035
G40 revenue (R_{ETC})	219350958 Yuan	358282784 Yuan	520582442 Yuan

5.2.2.2 Traffic line calculation

To calculate the traffic line numbers of each toll station in a characteristic year, (1). I need to first determine the number of traffic entities of each toll station. Table 5.2.1a shows the detailed information of PCUs per day in each toll station, so, using same method as **section 5.2.2.1 steps 1 and 2**, I can calculate the traffic entity numbers. The details of that information are shown in the following table.

Table 5.2.2a Traffic entity numbers of each toll station (G40)

Toll stations	2020		2027		2035	
	Drive-in	Drive-out	Drive-in	Drive-out	Drive-in	Drive-out
Jiuhua toll station	8739 Ve/d	4546 Ve/d	13752 Ve/d	6978 Ve/d	15938 Ve/d	8812 Ve/d
Rugao Port toll station	3891 Ve/d	2683 Ve/d	6710 Ve/d	4205 Ve/d	8509 Ve/d	5208 Ve/d
Shizhuang toll station	2001 Ve/d	932 Ve/d	3705 Ve/d	1726 Ve/d	5310 Ve/d	2388 Ve/d
Geshi toll station	2785 Ve/d	2246 Ve/d	5156 Ve/d	3716 Ve/d	6828 Ve/d	4742 Ve/d
Jishi toll station	2437	1553 Ve/d	4649	2945 Ve/d	6426	4071 Ve/d

Guangling toll station	Ve/d 2569 Ve/d	1678 Ve/d	Ve/d 4758 Ve/d	3109 Ve/d	Ve/d 6101 Ve/d	3934 Ve/d

(2). **Section 5.1.1.4 assumption** "*Toll station traffic lane configurations*" state: "*when more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes. The ratio of day traffic volume to night traffic volume is 0.85:0.15*". Taking the Jiuhua toll station in 2020 as an example, table 5.2.2a shows that the number of driving-in entities is 8739; the number of driving entities is 8379*85% = 7122 Ve/d, when 85% of the vehicles are in the daytime traffic entities; similarly, the number of driving-out vehicles in the daytime is 4546*85% =3864 Ve/d.

Here, I set a daytime of 12 hours. Meanwhile, the section 5.1.1.6 assumption is "*Number of ETC tags*" state: "*the number of ETC users accounts for 30% of all drivers in China*". (Ministry of Transportation, 2019). Therefore, in 2020, the ETC vehicles daytime entering at Jiuhua toll station were 7122*30% = 2136Ve, the ordinary vehicles daytime entering were 7122*70%=4895Ve, the ETC vehicles daytime driving out were 3864*30%=1159Ve, and the ordinary vehicles daytime driving out were 3864*70%=2704Ve.

Finally, in 2020, the number of ETC lanes in the direction of drive-in is $\frac{2136}{12\times300}\approx 1$, the number of MTC (manual toll collection) lanes in the direction of entry is $\frac{4895}{12\times300}\approx 2$; the number of ETC lanes in the direction of drive-out is $\frac{1159}{12\times160}\approx 1$, and the number of MTC lanes in the direction of drive-out is $\frac{2704}{12\times160}\approx 2$.

Using the same method with this section step 2, the number of traffic lanes in each toll station (G40) is shown in following table.

Table 5.2.2b. Number of traffic lines in each toll station (G40)

Toll stations	2020		2027		2035	
	Drive-in	Drive-out	Drive-in	Drive-out	Drive-in	Drive-out
Jiuhua toll station	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 2	MTC: 3 ETC: 2
Rugao Port toll station	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1
Shizhuang toll	MTC: 1	MTC: 1	MTC: 1	MTC: 1	MTC: 1	MTC: 1

station	ETC: 1	ETC: 1	ETC: 1	ETC: 1	ETC: 1	ETC: 1
Geshi toll station	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1
Jishi toll station	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1
Guangling toll station	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 1 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1

5.2.2.3 Human costs calculation

To calculate the human costs of the highway in a characteristic year, I needed to first determine the total number of toll lanes on the highway. Then, according to the staff allocation rules of toll lanes (Section 5.1.1.7, assumption "Costs of salaries and staff's allocation"), determine the number of operators and, finally, calculate the human cost according to the salary standard (Section 5.1.1.7, assumption "Costs of salaries and staff's allocation").

(1) Table 5.2.2b shows the information and deployment of toll lanes on the highway in three characteristic years. In 2020, for example, there will be 26 toll lanes on this highway section: 14 MTC lanes and 12 ETC lanes.

(2) **Section 5.1.1.7, assumption** "*Costs of salaries and staff's allocation*" stated: "*The monthly salary of toll station operators (including MTC and ETC) is 5000 Yuan (2018), while China's GDP growth rate is 6.6%. Therefore, for the three characteristic years 2020, 2027 and 2035, the salaries of operators should be 5682-yuan, 8888 yuan and 14820 yuan respectively. Three operators should be set up for each manual toll lane to facilitate rotation, and one ETC maintenance staff should be set up for each toll station*". The staffing allocation of this highway in 2020 should meet the following equation.

$$N_{total\_operaters} = 3 \times N_{mtc\_lines} + N_{toll+station} \quad (5.2.2c)$$

Here, $N_{total\_operaters}$ denotes the total number of operators on the highway, N_{mtc_lines} denotes the number of MTC lanes on this highway, and $N_{toll+station}$ denotes the number of toll stations on the highway. I substituted the information of step 1 of this section into formula 5.2.2c and calculated the following results.

$$N_{total\_operaters} = 3 \times 16 + 6 = 48$$

Therefore, this highway hired 48 operators.

(3) According to Section 5.1.1.7, assumption "Costs of salaries and staff allocation", the operator's monthly salary in 2020 is 5682 yuan. From this, I calculated that the human cost in 2020 is $C_{salary} = 5682 \times 12 \times 48 = 3272832$ yuan. Using the same method, the costs of toll station operators are shown in following table.

Table 5.2.2c. Salary expenses (operators) for three characteristic years

	2020 (C_{salary})	2027 (C_{salary})	2035 (C_{salary})
Salary expense	3272832 Yuan	7359264 Yuan	13871520 Yuan

5.2.2.4 Reader costs calculation

Like the human cost calculation, the reader cost is also calculated based on the number of toll lanes provided in Table 5.2.2b. As described in Chapter 4, I usually deploy one ETC reader on each ETC lane. The top view of the ETC lane in Scheme 1 is shown as follows.

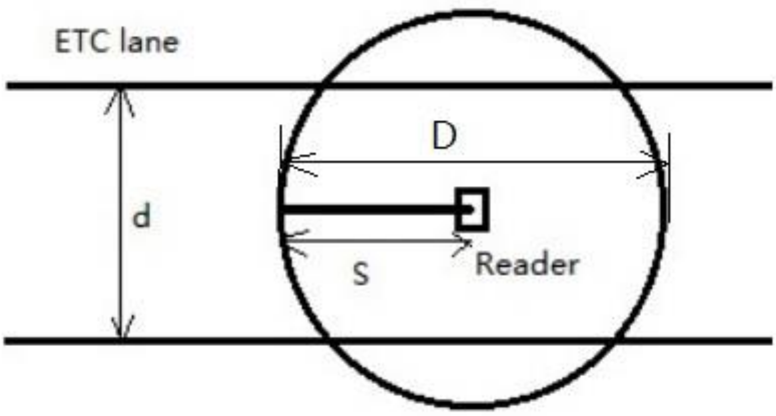

Figure 5.2.2 scheme 1 (Installation of ETC readers)

For this deployment mode, the reader cost should satisfy the following equation.

$$C_{readers} = C_{r\_price} \times N_{etc\_lines} \quad (5.2.2d)$$

Here, $C_{readers}$ denotes the cost of the reader, C_{r_price} denotes the price of each reader, and N_{etc_lines} denotes the number of ETC lanes. Taking 2020 as an example, Table 5.1.2 (Section 5.1.2 Sample database) provides the price of reader 1 is 1000 Yuan. In 2020, there were 12 ETC lanes in the project section (Table 5.2.2b). Therefore, the deployment cost of reader 1 in 2020 should be as follows:

$1000 \times 12 = 12000\ Yuan$

Using the same method, the costs of ETC readers in scheme 1 is as follows.

Table 5.2.2d Costs of readers in scheme 1 (G40)

	2020 ($C_{readers}$)	2027 ($C_{readers}$)	2035 ($C_{readers}$)
Reader 1	12000 Yuan	12000 Yuan	14000 Yuan
Reader 2	18000 Yuan	18000 Yuan	21000 Yuan
Reader 3	30960 Yuan	30960 Yuan	36120 Yuan
Reader 4	33000 Yuan	33000 Yuan	38500 Yuan

It should be pointed out, in 2035, due to the substantial increase in vehicle ownership, the number of ETC lanes cannot meet the traffic requirement. According to the information provided in Section 5.1.1.4 assumption “Toll station traffic lane configurations”, an additional ETC lane needs to be opened at Jiuhua toll station. In the sample database, readers 2, 3 and 4 have a long signal transmission distance, which allows a single reader to be installed across the traffic lanes.

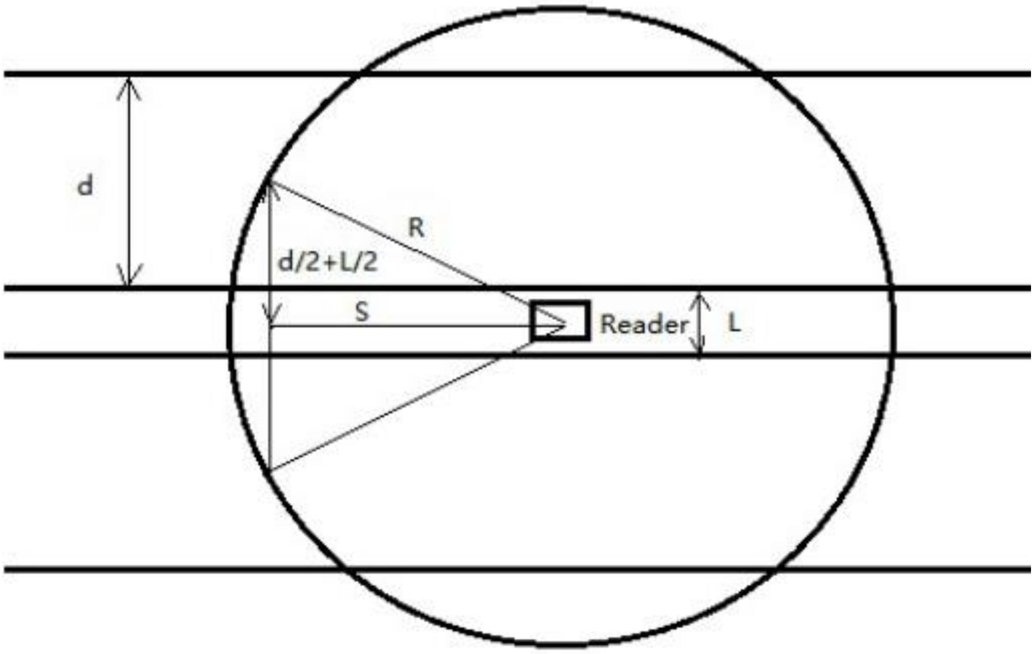

Figure 5.2.2a scheme 2 (Installation of ETC readers)

Therefore, the costs of the readers in 2035 may vary according to the installation mode of the device. For readers 2, 3 and 4, there is no need for additional equipment with additional lanes, which can reduce the cost from Table 5.2.2e. The following table calculates the cost of the readers using a method like Formula 5.2.2d.

Table 5.2.2e Costs of readers in scheme 2 (G40)

	2020 ($C_{readers}$)	2027 ($C_{readers}$)	2035 ($C_{readers}$)
Reader 1	12000 Yuan	12000 Yuan	14000 Yuan

Reader 2	18000 Yuan	18000 Yuan	18000 Yuan
Reader 3	30960 Yuan	30960 Yuan	30960 Yuan
Reader 4	33000 Yuan	33000 Yuan	33000 Yuan

5.2.2.5 Cost of tags

In China, the cost of tags is borne by Road Department administrations. Drivers usually go to designated locations to open an ETC service. The operators are responsible for installing the OBU integrated with ETC tags on the front window of the vehicle. This means that the cost of tags will be included in the profit's assessment. **Section 5.1.1.6 assumption** "*Number of ETC tags*" stated: "*According to the statistics of the Ministry of Transportation, the number of ETC users accounts for 30% of all drivers in China. Due to the rapid economic development, the number of vehicle ownership increases at an average rate of 5% every year. According to the public information of traffic management departments in these two regions, in 2016, the number of vehicles in Nantong area was 1487 826, while that in Taizhou area was 858 263.*". **Section 5.1.1.5 assumption** "*Tag cost-based road length*" stated: "*According to the traffic department reports of Nantong and Taizhou, as of 2017, there were 298 kilometers of highway in Nantong and 111 kilometers of highway in Taizhou*".

The above information indicates that three steps are needed to complete the calculation of tag costs: (1) Determine the ETC driver increment in the project area in this characteristic year; (2) Determine the proportion of the mileage of this project to the total highway mileage in this area; (3) Use the increments generated in step 1 and the proportion generated in step 2, I can calculate the costs of the ETC tags.

(1) According to the statement of **Section 5.1.1.6 assumption** "*Number of ETC tags*", using 2020 as the example, the increment of ETC drivers can be calculated as.

$(1487826 + 858263) \times (2020 increment - 2019 increment) \times 30\%$=38798Ve

(2) According to the statement of **Section 5.1.1.5 assumption** "*Tag cost-based road length*", using 2020 as the example, the proportion of the mileage of this project can be calculated as.

$\frac{48.925}{298+111} \times 100\% = 12\%$

(3) Using the increments generated in step 1 and the proportion generated in step 2, if the

Road Department administration selected tag 13 as a part of the candidate ETC system for compatibility reasons, I believe that all drivers driving on this road project were using tag 13 as their OBU's RFID component. I can then calculate the tag costs in 2020 as:

$C_{tags} = 38798 \times 12\% \times 60 = 279346$

Using the same method, the cost of ETC tags is as follows:

Table 5.2.2f Costs of ETC tags issued in characteristic years (G40)

ETC tags	2020	2027	2035
Tag 1	23279 Yuan	36599 Yuan	50320 Yuan
Tag 2	46558 Yuan	73198 Yuan	100641 Yuan
Tag 3	9312 Yuan	14640 Yuan	20128 Yuan
Tag 4	9312 Yuan	14640 Yuan	20128 Yuan
Tag 5	9312 Yuan	14640 Yuan	20128 Yuan
Tag 6	93116 Yuan	146396 Yuan	201281 Yuan
Tag 7	9312 Yuan	14640 Yuan	20128 Yuan
Tag 8	116394 Yuan	182995 Yuan	251601 Yuan
Tag 9	116394 Yuan	182995 Yuan	251601 Yuan
Tag 10	69837 Yuan	109797 Yuan	150961 Yuan
Tag 11	186231 Yuan	292791 Yuan	402562 Yuan
Tag 12	419019 Yuan	658781 Yuan	905765 Yuan
Tag 13	279346 Yuan	439187 Yuan	603843 Yuan
Tag 14	139673 Yuan	219594 Yuan	301922 Yuan
Tag 15	232788 Yuan	365989 Yuan	503203 Yuan

5.2.2.6 Other decision inputs

Other decision inputs are directly derived from the data in section 5.1.1.8 and sample data in section 5.1.2, as listed in the following table.

Table 5.2.2g Other decision inputs (G40)

	Symbol	Value	Source
Highway speed limit	V_{in}	120 km/h	Section 5.1.1.8 assumption "Traffic statues"
Normal road speed limit	V_{out}	50 km/h	Section 5.1.1.8 assumption "Traffic statues"
Deceleration	a_d	5 m/s^2	Section 5.1.1.8 assumption "Traffic statues"
Acceleration	a_a	3 m/s^2	Section 5.1.1.8 assumption "Traffic statues"
Traffic lane width	d	3.75 meters	Direct data
Isolation zone width	L	0.75 meters	Direct data
Water-proof design	W_proof	Y/N	Sample database
Encryption	$C_{encryption}$	EPC Class 1 Gen 2	Section 5.1.1.8 assumption "Traffic statues"
Usage	T_{usage}	5 year	Section 5.1.1.8 assumption "Traffic statues"

5.2.3 Performance evaluation

5.2.3.1 Profit calculation

Section 5.2.2 mentioned, in 2035, that two ETC lanes will be set up at the Jiuhua toll station in this consideration, to cope with the increased traffic volume. This means that a reader with far signal transmission capability will be redeployed. There were two deployment schemes. No matter which equipment deployment scheme will be used, the profit calculation must satisfy the following equation which was developed in Chapter 4.

$$P = R_{ETC} - C_{salary} - C_{tags} \quad (5.2.3)$$

P represents the comprehensive profits of ETC systems, R_{ETC} represents the revenue of the road, C_{salary} represents the human cost of the road, $C_{readers}$ represents the reader cost of the road, and C_{tags} represents the tag cost of the road.

For scheme1, using reader 1 in the 2020 deployment as an example, Table 5.2.2 indicated that revenue of this highway in 2020 is 219350958 Yuan; Table 5.2.2c indicated that human cost in 2020 is 3272832 Yuan; Table 5.2.2e indicated that readers cost in 2020 is 12000 Yuan; Table 5.2.2f indicated that tag cost is 23279 Yuan. Therefore, I introduce this information into formula 5.2.3, and the results are as follows.

$$219350958 - 3272832 - 12000 - 23279 = 216042847\ Yuan$$

Using the same method the results of profit calculation performance evaluation (scheme 1) are shown in the following table.

Table 5.2.3 Results of profit calculation (G40 - scheme 1)

ETC systems	2020	2027	2035
Reader 1+Tags 1	216042847 Yuan	350874921 Yuan	506646602 Yuan
Reader 1+Tags 2	216019568 Yuan	350838322 Yuan	506596282 Yuan
Reader 1+Tags 3	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 4	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 5	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 6	215973011 Yuan	350765124 Yuan	506495641 Yuan
Reader 1+Tags 7	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 8	215949732 Yuan	350728525 Yuan	506445321 Yuan
Reader 1+Tags 9	215949732 Yuan	350728525 Yuan	506445321 Yuan
Reader 1+Tags 10	215996290 Yuan	350801723 Yuan	506545961 Yuan
Reader 1+Tags 11	215879895 Yuan	350618729 Yuan	506294360 Yuan
Reader 1+Tags 12	215647107 Yuan	350252740 Yuan	505791156 Yuan
Reader 2+Tags 1	216036847 Yuan	350868921 Yuan	506639602 Yuan
Reader 2+Tags 2	216013568 Yuan	350832322 Yuan	506589282 Yuan
Reader 2+Tags 3	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 4	216050815 Yuan	350890880 Yuan	506669794 Yuan

Reader 2+Tags 5	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 6	215967011 Yuan	350759124 Yuan	506488641 Yuan
Reader 2+Tags 7	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 8	215943732 Yuan	350722525 Yuan	506438321 Yuan
Reader 2+Tags 9	215943732 Yuan	350722525 Yuan	506438321 Yuan
Reader 2+Tags 10	215990290 Yuan	350795723 Yuan	506538961 Yuan
Reader 2+Tags 11	215873895 Yuan	350612729 Yuan	506287360 Yuan
Reader 2+Tags 12	215641107 Yuan	350246740 Yuan	505784158 Yuan
Reader 3+Tags 1	216023887 Yuan	350855961 Yuan	506624482 Yuan
Reader 3+Tags 2	216000608 Yuan	350819362 Yuan	506574162 Yuan
Reader 3+Tags 3	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 4	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 5	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 6	215954051 Yuan	350746164 Yuan	506473521 Yuan
Reader 3+Tags 7	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 8	215930772 Yuan	350709565 Yuan	506423201 Yuan
Reader 3+Tags 9	215930772 Yuan	350709565 Yuan	506423201 Yuan
Reader 3+Tags 10	215977330 Yuan	350782763 Yuan	506523841 Yuan
Reader 3+Tags 11	215860935 Yuan	350599769 Yuan	506272240 Yuan
Reader 3+Tags 12	215628147 Yuan	350233780 Yuan	505769038 Yuan
Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506068579 Yuan
Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506370501 Yuan
Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506169220 Yuan

This performance evaluation results on scheme 2 are shown in the following table.

Table 5.2.3a Decision output of profit calculation (G40 - scheme 2)

ETC systems	2020	2027	2035
Reader 1+Tags 1	216042847 Yuan	350874921 Yuan	506646602 Yuan
Reader 1+Tags 2	216019568 Yuan	350838322 Yuan	506596282 Yuan
Reader 1+Tags 3	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 4	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 5	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 6	215973011 Yuan	350765124 Yuan	506495641 Yuan
Reader 1+Tags 7	216056815 Yuan	350896880 Yuan	506676794 Yuan
Reader 1+Tags 8	215949732 Yuan	350728525 Yuan	506445321 Yuan
Reader 1+Tags 9	215949732 Yuan	350728525 Yuan	506445321 Yuan
Reader 1+Tags 10	215996290 Yuan	350801723 Yuan	506545961 Yuan
Reader 1+Tags 11	215879895 Yuan	350618729 Yuan	506294360 Yuan
Reader 1+Tags 12	215647107 Yuan	350252740 Yuan	505791156 Yuan
Reader 2+Tags 1	216036847 Yuan	350868921 Yuan	506642602 Yuan
Reader 2+Tags 2	216013568 Yuan	350832322 Yuan	506592282 Yuan
Reader 2+Tags 3	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 4	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 5	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 6	215967011 Yuan	350759124 Yuan	506491641 Yuan
Reader 2+Tags 7	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 8	215943732 Yuan	350722525 Yuan	506441321 Yuan
Reader 2+Tags 9	215943732 Yuan	350722525 Yuan	506441321 Yuan
Reader 2+Tags 10	215990290 Yuan	350795723 Yuan	506541961 Yuan
Reader 2+Tags 11	215873895 Yuan	350612729 Yuan	506290360 Yuan
Reader 2+Tags 12	215641107 Yuan	350246740 Yuan	505787158 Yuan
Reader 3+Tags 1	216023887 Yuan	350855961 Yuan	506629642 Yuan
Reader 3+Tags 2	216000608 Yuan	350819362 Yuan	506579322 Yuan
Reader 3+Tags 3	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 4	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 5	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 6	215954051 Yuan	350746164 Yuan	506478681 Yuan

Reader 3+Tags 7	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 8	215930772 Yuan	350709565 Yuan	506428361 Yuan
Reader 3+Tags 9	215930772 Yuan	350709565 Yuan	506428361 Yuan
Reader 3+Tags 10	215977330 Yuan	350782763 Yuan	506529001 Yuan
Reader 3+Tags 11	215860935 Yuan	350599769 Yuan	506277400 Yuan
Reader 3+Tags 12	215628147 Yuan	350233780 Yuan	505774198 Yuan
Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506074079 Yuan
Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506376001 Yuan
Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506174720 Yuan

5.2.3.2 Traffic management evaluation

For the performance evaluation environment of traffic management, the traffic volume per toll lane was the decision output. In this case, two reader deployment schemes were adopted in the Jiuhua toll station, which results in two output results in 2035. It should be emphasized that the signal transmission range of reader 1 was relatively close. Under the fixed transaction time, the speed of the vehicles under scheme 2 was very slow, which was not much different from the manual system. Therefore, under scheme 2, I did not focus on the output of reader 1. The signal transmission range of readers 2, 3 and 4 is larger than that of reader 1. Under scheme 2, vehicles can pass through toll stations at a faster speed. No matter which equipment deployment scheme is used, the traffic management evaluation must satisfy the following equation developed in Chapter 4.

$$C_{ETC} = \frac{3600}{T_a+T_v+T_d} \quad (5.2.3a)$$

C_{ETC} represents the capacity of vehicles in front of the toll station; T_d represents the time required for deceleration of ordinary vehicles; T_a represents the time required for normal vehicle acceleration; T_v indicates the speed the vehicle travels when trading in ETC lanes.

1. For scheme1 (Figure 5.2.2), I used reader 1 as the example. Table 5.2.2g indicated that T_v is 2.76s, a_d is 5 m/s^2, a_a is 3 m/s^2 , V_{in} is 120km/h, V_{out} is 50km/h, d is 3.75m and L is 0.75m. Table 5.1.2 (**Section 5.1.2** sample database) indicated that reader 1's signal range S is 6m. The speed limit of vehicles must satisfy the following equation developed in Chapter 4.

$$V_l = \frac{D}{T_v} = \frac{2S}{T_v} \quad (5.2.3b)$$

T_v indicates the speed the vehicle travels when trading in ETC lanes, D denotes the distance that a vehicle travels at this speed limit. For this distance, I had to discuss several aspects of ETC device installation. I introduced those data into equation 5.2.3b, and the results were as follows:

$$V_l = \frac{2 \times 6}{2.76} = 15.62\ km/h$$

The time spent for deceleration of vehicles is.

$$T_d = \frac{V_{in} - V_l}{a_d} = \frac{120\ km/h - 15.62km/h}{5m/s^2} = 5.8s$$

The time spent for deceleration of vehicles is.

$$T_a = \frac{V_{out} - V_l}{a_a} = \frac{50\ km/h - 15.62km/h}{3m/s^2} = 3.18s$$

Finally, the reader 1's traffic line capacity is.

$$C_{ETC} = \frac{3600}{T_a + T_v + T_d} = \frac{3600}{5.8 + 3.18 + 2.76} = 306\ Ve/h$$

Using the same method the following table lists the decision outputs for scheme 1.

Table 5.2.3b. Capability of readers in the scheme 1 (G40)

	Drive out	Drive in	Speed limit
Reader 1	306 ve/h	289 ve/h	15.62km/h
Reader 2	417 ve/h	331 ve/h	39.13km/h
Reader 3	534 ve/h	389 ve/h	52.17km/h
Reader 4	464 ve/h	390 ve/h	80km/h

The above table show the traffic capacity of an ETC lane; that is the maximum traffic volume per hour. It shows that ETC lanes cause congestion when traffic exceeds this threshold. To ensure the traffic efficiency of toll station vehicles, it is necessary to open up new traffic lanes on this basis. Taking reader 1 as an example, I calculated the ETC lane of Jiuhua toll station in 2035 by using the same method as section 5.2.2.2. In 2035, Jiuhua toll station's ETC traffic volume will be 15938*30%=4781Ve; the ordinary vehicles daytime entering will be 7122*70%=11156 Ve, the ETC vehicles daytime driving out will be 8812*30%=2643 Ve, and the ordinary vehicles daytime driving out will be 3 3864*70%=6169 Ve; The number of ETC lanes in the direction of drive in will be $\frac{4183}{12\times289} \approx 2$, the number of MTC (manual toll collection) lanes in the direction of entry will be $\frac{11156}{12\times300} \approx 3$; the number of ETC lanes in the direction of drive out will be $\frac{2643}{12\times306} \approx 2$, and the number of MTC lanes in the direction of drive out will be $\frac{6169}{12\times160} \approx$

3.

Using the above methods, I calculated the number of ETC lanes based on ETC lane capacity in Jiuhua toll station as shown in the following table. It was pointed out that I had not changed the MTC lane settings, because I still need to use the traffic lane configuration policy which was provided in the **section 5.1.1.4 assumption** "*Toll station traffic lane configurations*", to set up the MTC lane.

Table 5.2.3c. Number of traffic lanes by setting reader 1 in Juhua toll station (G40)

Readers	2020		2027		2035	
	Drive-in	Drive-out	Drive-in	Drive-out	Drive-in	Drive-out
Reader 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 2	MTC: 3 ETC: 1

The above table shows that, in 2035, if I use reader 1 as the ETC lane equipment, it can reduce one ETC lane in the drive out direction, which can save related equipment costs. Similarly, for other readers, I calculated the ETC lane settings at Jiuhua toll station as shown in the table below.

Table 5.2.3d. Number of traffic lanes by setting all readers in Juhua toll station (G40)

Readers	2020		2027		2035	
	Drive-in	Drive-out	Drive-in	Drive-out	Drive-in	Drive-out
Reader 1	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 2	MTC: 3 ETC: 1
Reader 2	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 2	MTC: 3 ETC: 1
Reader 3	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1
Reader 4	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1

It can be found that the ETC lane settings of Jiuhua toll station changed in 2035 from Table 5.2.2b, which made the deployment of four readers in ETC lane different, and affected this performance evaluation of section 5.2.3.1 "Benefit calculation evaluation".

The following figure shows the relationship between the numbers of drive out direction ETC lanes and the capacity of readers under Scheme 1.

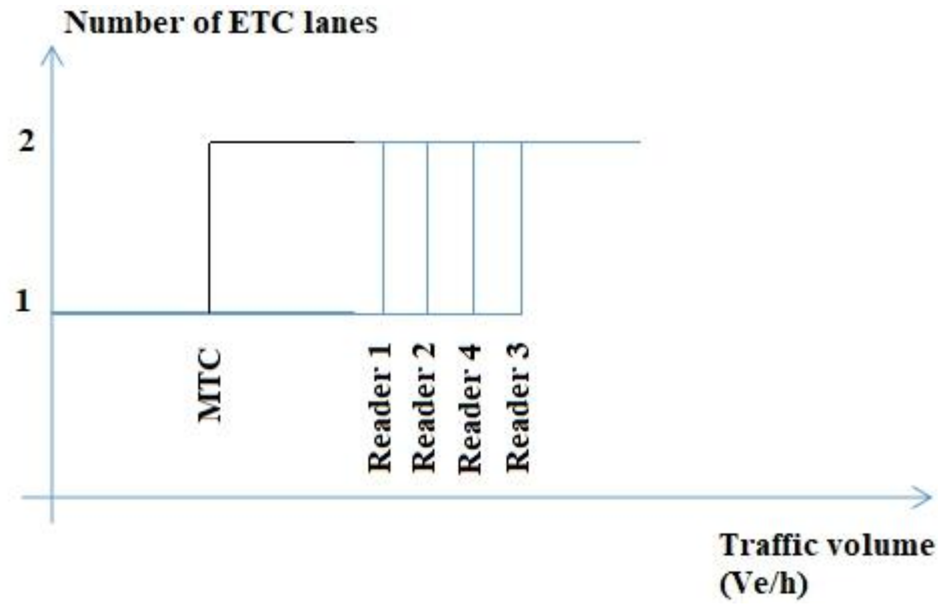

Figure 5.5a Drive out direction ETC lane settings under scheme 1

The following figure shows the relationship between the number of drive-in direction ETC lanes and the capacity of readers under scheme 1.

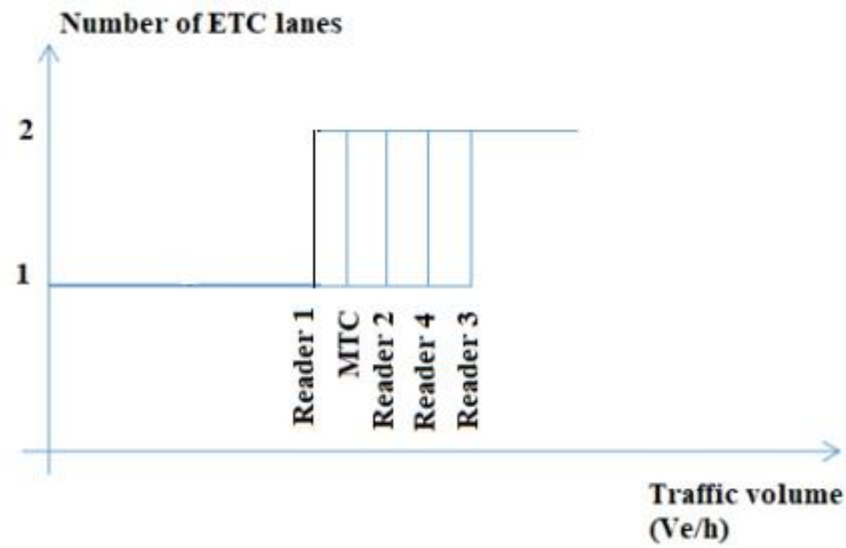

Figure 5.5b Drive in direction ETC lane settings under scheme 1

Therefore, according to equation 5.2.3a provided in section 5.2.2.4, I can deduce that under scheme 1, the cost of ETC equipment is expressed as the following equation.

$$C_{reader} = C_{r\_price} \times \sum \frac{C_{ve}}{C_{ETC}} \quad (5.2.3c)$$

Here, C_{reader} denotes the cost of the reader, C_{r_price} denotes the price of each reader, C_{ETC} represents the capacity of the ETC lane in front of the toll station, and C_{ve} is the traffic volume of the toll station.

Still taking 2035 as an example, because **section 5.1.1.4 assumption** “Toll station traffic lane configurations” stated: “when more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes.” I find that the driving out performance of reader 1 cannot meet the requirements of the MTC lane, which is not allowed in ETC lane settings. Therefore, taking reader 2 as the reference, Jiuhua toll station will set up two ETC lanes and one ETC lane. The costs of ETC reader 2 in Jiuhua toll station will be $1500 \times 3 = 4500$Yuan, and total costs of reader 2 in 2035 should be $4500 + 3000 \times 5 = 19500$ Yuan. This is cheaper than the cost estimated in Table 5.2.2d (Section 5.2.2.4). Therefore, traffic management constraints leading to performance evaluation of profit calculation could be changed (section 5.2.3.1) as shown in the following table.

Table 5.2.3e performance evaluation results of modified profit calculation (G40 - scheme 1)

ETC systems	2020	2027	2035
Reader 2+Tags 1	216036847 Yuan	350868921 Yuan	506639602 Yuan
Reader 2+Tags 2	216013568 Yuan	350832322 Yuan	506589282 Yuan
Reader 2+Tags 3	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 4	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 5	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 6	215967011 Yuan	350759124 Yuan	506488641 Yuan
Reader 2+Tags 7	216050815 Yuan	350890880 Yuan	506669794 Yuan
Reader 2+Tags 8	215943732 Yuan	350722525 Yuan	506438321 Yuan
Reader 2+Tags 9	215943732 Yuan	350722525 Yuan	506438321 Yuan
Reader 2+Tags 10	215990290 Yuan	350795723 Yuan	506538961 Yuan
Reader 2+Tags 11	215873895 Yuan	350612729 Yuan	506287360 Yuan
Reader 2+Tags 12	215641107 Yuan	350246740 Yuan	505784158 Yuan
Reader 3+Tags 1	216023887 Yuan	350855961 Yuan	506624482 Yuan
Reader 3+Tags 2	216000608 Yuan	350819362 Yuan	506574162 Yuan
Reader 3+Tags 3	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 4	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 5	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 6	215954051 Yuan	350746164 Yuan	506473521 Yuan
Reader 3+Tags 7	216037855 Yuan	350877920 Yuan	506654674 Yuan
Reader 3+Tags 8	215930772 Yuan	350709565 Yuan	506423201 Yuan
Reader 3+Tags 9	215930772 Yuan	350709565 Yuan	506423201 Yuan
Reader 3+Tags 10	215977330 Yuan	350782763 Yuan	506523841 Yuan
Reader 3+Tags 11	215860935 Yuan	350599769 Yuan	506272240 Yuan
Reader 3+Tags 12	215628147 Yuan	350233780 Yuan	505769038 Yuan
Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506068579 Yuan
Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506370501 Yuan
Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506169220 Yuan

2. For scheme 2 (Figure 5.2.2a), using reader 2 as the example, Table 5.2.2g indicated that reader 1’s signal range S is 12m. According to the research in Chapter 4, under this scheme, the distance of a vehicle running at uniform speed needs to satisfy the following equation.

$$D = 2 \times \sqrt{R^2 - \left(\frac{d+L}{2}\right)^2} \tag{5.2.3d}$$

Then, I introduced parameters as step 1, the results were shown in follows.

$$D = 2 \times \sqrt{15^2 - \left(\frac{3.75 + 0.75}{2}\right)^2} = 29.66m$$

I substituted this parameter into equation 5.2.3b and obtained the following results.

$$V_l = \frac{D}{T_v} = \frac{29.66m}{2.76s} = 38.69km/h$$

The time spend for deceleration of vehicles was:

$$T_d = \frac{V_m - V_l}{a_d} = \frac{120km/h - 38.69km/h}{5m/s^2} = 4.52s$$

The time spend for deceleration of vehicles was:

$$T_a = \frac{V_{out} - V_l}{a_a} = \frac{50km/h - 38.69km/h}{3m/s^2} = 1.05 \text{ s}$$

Finally, the reader 1's traffic line capacity was:

$$C_{ETC} = \frac{3600}{T_a + T_v + T_d} = \frac{3600}{4.52 + 1.05 + 2.76} = 432Ve/h$$

Using the same method the following table listed the decision outputs of scheme 2.

Table 5.2.3f Decision output of Jiuhua toll station in 2035 (Traffic management)

	Drive out	Drive in	Speed limit
Reader 2	432 ve/h	329 ve/h	38.69 km/h
Reader 3	541 ve/h	389 ve/h	51.84 km/h
Reader 4	463 ve/h	390 ve/h	80 km/h

Using same method as scheme 1, I calculated the ETC Lane settings at Jiuhua toll station as shown in the table below.

Table 5.2.3g. Number of traffic lines by setting all readers in Juhua toll station (G40-scheme 2)

Readers	2020		2027		2035	
	Drive-in	Drive-out	Drive-in	Drive-out	Drive-in	Drive-out
Reader 2	MTC: 2	MTC: 2	MTC: 3	MTC: 3	MTC: 3	MTC: 3
	ETC: 1	ETC: 1	ETC: 1	ETC: 1	ETC: 2	ETC: 1
Reader 3	MTC: 2	MTC: 2	MTC: 3	MTC: 3	MTC: 3	MTC: 3
	ETC: 1	ETC: 1	ETC: 1	ETC: 1	ETC: 1	ETC: 1

Reader 4	MTC: 2 ETC: 1	MTC: 2 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1	MTC: 3 ETC: 1

It was pointed out that under scheme 2, a reader can deploy more than two toll lanes, depending on their signal coverage, ETC lane width and the width of lane isolation zone. This shows that in 2035, I can deploy one reader in the drive-in direction at Jiuhua toll station, which further reduces the cost. At the same time, reader 3 and reader 4 only need one ETC lane to meet the traffic demand of the toll station because of their strong traffic capacity. These changes of profit calculation are shown in the following table.

Table 5.2.3h performance evaluation results of modified profit calculation (G40 - scheme 2)

ETC systems	2020	2027	2035
Reader 2+Tags 1	216036847 Yuan	350868921 Yuan	506642602 Yuan
Reader 2+Tags 2	216013568 Yuan	350832322 Yuan	506592282 Yuan
Reader 2+Tags 3	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 4	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 5	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 6	215967011 Yuan	350759124 Yuan	506491641 Yuan
Reader 2+Tags 7	216050815 Yuan	350890880 Yuan	506672794 Yuan
Reader 2+Tags 8	215943732 Yuan	350722525 Yuan	506441321 Yuan
Reader 2+Tags 9	215943732 Yuan	350722525 Yuan	506441321 Yuan
Reader 2+Tags 10	215990290 Yuan	350795723 Yuan	506541961 Yuan
Reader 2+Tags 11	215873895 Yuan	350612729 Yuan	506290360 Yuan
Reader 2+Tags 12	215641107 Yuan	350246740 Yuan	505787158 Yuan
Reader 3+Tags 1	216023887 Yuan	350855961 Yuan	506629642 Yuan
Reader 3+Tags 2	216000608 Yuan	350819362 Yuan	506579322 Yuan
Reader 3+Tags 3	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 4	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 5	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 6	215954051 Yuan	350746164 Yuan	506478681 Yuan
Reader 3+Tags 7	216037855 Yuan	350877920 Yuan	506659834 Yuan
Reader 3+Tags 8	215930772 Yuan	350709565 Yuan	506428361 Yuan
Reader 3+Tags 9	215930772 Yuan	350709565 Yuan	506428361 Yuan
Reader 3+Tags 10	215977330 Yuan	350782763 Yuan	506529001 Yuan
Reader 3+Tags 11	215860935 Yuan	350599769 Yuan	506277400 Yuan
Reader 3+Tags 12	215628147 Yuan	350233780 Yuan	505774198 Yuan
Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506074079 Yuan
Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506376001 Yuan
Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506174720 Yuan

5.2.3.3 Reliability evaluation

For the reliability requirements of Road Department administrations, the performance evaluation first determined whether the design of ETC tags met the moisture proof standards. The requirement of tag volume is also an important factor to be considered in this performance evaluation activity, which needs to be controlled under the size $100 \times 60 \times 10$ mm. According to the description in **Section 5.1.4** "*classification outcome*", when both two criteria (moisture proof deign and size) was limited in

$100 \times 60 \times 10$ mm were satisfied, the tags were committed to meet the Road Department administration's requirement.

Taking tag 1 as an example, this tag has been moisture proof designed, that is, material requirements can be marked as "qualified"; in terms of volume, its size is not controlled within $100 \times 60 \times 10$ mm, so it is marked as "unqualified". Since section 5.1.4 stipulated that only the performance evaluation result belongs to the set {qualified, qualified}, it can be considered to meet the requirements of the Road Department administration, and tag 1 was clearly not within this scope. Using the same method the performance evaluation results of all tags are shown in following table.

Table 5.2.3i Performance evaluation result of reliability evaluation in G40

	Moisture -proof design	Volume	Result
Tag 1	qualified	unqualified	unqualified
Tag 2	unqualified	qualified	unqualified
Tag 3	qualified	qualified	qualified
Tag 4	unqualified	qualified	unqualified
Tag 5	qualified	qualified	qualified
Tag 6	qualified	qualified	qualified
Tag 7	unqualified	qualified	qualified
Tag 8	qualified	qualified	qualified
Tag 9	qualified	qualified	qualified
Tag 10	qualified	qualified	qualified
Tag 11	qualified	unqualified	unqualified
Tag 12	qualified	unqualified	unqualified
Tag 13	qualified	qualified	qualified
Tag 14	qualified	qualified	unqualified
Tag 15	qualified	qualified	qualified

5.2.3.4 Compatibility evaluation

For Road Department administrations' safety requirements, the anti-collision mechanism required that ETC systems should be working under ISO/IEC 18000-6C protocol (**section 5.1.1.8 assumption** "Traffic statues"). It also required a delay when vehicles pass through the toll gate (**section 5.1.1.8 assumption** "*Traffic statues*"). For the transmission signal encryption settings, the tags must conform to support the EPC Class 1 Gen 2 protocol (**section 5.1.1.8 assumption** "*Traffic statues*"). Therefore, this pre-decision also affected ETC readers and tag closures. It was pointed out that the anti-collision mechanism brings delays depending on their frequency of "Query", which means that it affects the capacity of toll stations. Therefore, it is necessary to satisfy the relationship as follows.

$$T_a + T_v + T_d \geq \frac{1}{f_{query}} \quad (5.2.3e)$$

Like equation 5.2.3a, T_d represents the time required for deceleration of ordinary vehicles; T_a represents the time required for normal vehicle acceleration; T_v indicates the speed the vehicle travels when trading in ETC lanes. In addition, f_{query} represents the frequency of “Query”.

Expression 5.2.3e indicated that delays due to anti-collision must involve the time of vehicles transaction. Here, it must be pointed out that **section 5.1.1.8 assumption** “Traffic status” stated: “*The average transaction time for ETC vehicles is 2.76s, many of tags anti-collusion frequency is 100times/s*” (Zhang,2017), which means all tags from the sample database were satisfied under the relationship of expression 5.2.3e.

For the performance evaluation of compatibility, using the same method as section 5.2.3.3 to select tags, the details are shown in the following table.

Table 5.2.3j Performance evaluation of compatibility selection in G40

	ISO/IEC 18000-6C	EPC Class 1 Gen 2	$\frac{1}{f_{query}}$ is involved in transaction time	Output
Tag 1	qualified	qualified	qualified	qualified
Tag 2	unqualified	qualified	qualified	unqualified
Tag 3	unqualified	qualified	qualified	unqualified
Tag 4	unqualified	qualified	qualified	unqualified
Tag 5	qualified	unqualified	qualified	unqualified
Tag 6	qualified	qualified	qualified	qualified
Tag 7	qualified	qualified	qualified	qualified
Tag 8	unqualified	qualified	qualified	unqualified
Tag 9	unqualified	qualified	qualified	unqualified
Tag 10	qualified	qualified	qualified	qualified
Tag 11	qualified	qualified	qualified	qualified
Tag 12	qualified	qualified	qualified	qualified
Tag 13	qualified	qualified	qualified	qualified
Tag 14	qualified	qualified	qualified	qualified
Tag 15	qualified	qualified	qualified	qualified

5.2.3.5 Tag life

Chapter 4 found that the power consumption of ETC tags follows the regulation as below:

$$W = 365 \times (W_{work} + W_{static}) \quad (5.2.3f)$$

When vehicles pass through toll stations frequently, the ETC systems are activated, and the ETC tags interact with the readers to generate signals. This behaviour brings a certain amount of power consumption to the battery in the ETC tags. I called this part of the loss of energy W_{work}. Compared with the working status, the static power consumption was marked as W_{static} . Chapter 4's research stated the work power consumption can be expressed as follows:

$$W_{work} = U \times I_2 \times 10^{-3} \times N \times (T + T_1 + T_2) \qquad (5.2.3g)$$

From the above equation, it was assumed that the time from wake-up to transmission is T_1, from end of transaction to sleep mode is T_2, and the time for completing a transaction is T; the tag voltage is U; the working current and static current are I_1 and I_2, respectively; and the number of transactions per day is N.

According to equations 5.2.3f and 5.2.3g, the power loss under static conditions can be deduced as:

$$W_{static} = U \times I_1 \times 10^{-6} \times \left(86400 - N(T + T_1 + T_2)\right) \qquad (5.2.3h)$$

Section 5.1.1.9 assumption "*Tags life*" pointed out that ETC manufacturers in China ensured that T is 0.25 s, according to the national standard, wake-up time is less than 5 ms; and according to this threshold, the values of T_1 and T_2 are 5 ms. At the same time, ETC drivers have an average daily usage limit of 10 transactions, the static current is 5 μA and the working current is 100 mA. The working voltage of lithium batteries for ETC tags is 3.6 V. By introducing these parameters into equations 5.2.3f, 5.2.3g and 5.2.3h, I calculated the power consumption of ETC tags as follows.

$$W = 365 \times (W_{work} + W_{static}) = 36v \times 95mA$$

Liu and Ba (2018) provided an example of an active tag integrated with a battery with energy of 3.6v 1200mA. Therefore, this battery should be worked as $\frac{1200mA \times 3.6v}{95mA \times 3.6v} = 12.65$ years.

Due to the protection of patent rights, many OBUs are designed as non-removable, which lead to frequent replacement and higher costs. In addition, ETC manufacturers also provided power supply modules besides batteries. In the sample database that was provided in Table 5.2.3k, tag 13 had been integrated into the solar panels in the appropriate space of OBUs. I followed the steps of Liu and Ba (2018) and used the information in table 5.1.2a to calculate the tag life of those samples. The performance evaluation results are listed in the following table.

Table 5.2.3k Decision output of tag service life requirements in G40

	Tags life
Tag 1	none
Tag 2	none
Tag 3	0.7 years
Tag 4	none
Tag 5	none
Tag 6	1.1 years
Tag 7	none
Tag 8	none
Tag 9	none
Tag 10	2.2 years
Tag 11	7.4 years
Tag 12	12.65 years
Tag 13	Battery for 12.65 years, extra solar panel design for power charging.
Tag 14	7 years
Tag 15	9.65 years

5.2.4 Decision outcome classification

The previous section generated the decision outputs based on five performance evaluation environments, and the measurement of these outputs was not uniform. According to the outcome classification method which was provided in **section 5.1.4** "*classification outcome*", I classified those outcomes into two presentation formations: constraint and optimization.

For constraint, performance evaluation of reliability and compatibility was discussed in sections 5.2.3.3 and 5.2.3.4, and their results had been listed in tables 5.2.3j and 5.2.3k. In addition, the thresholds of some outputs under criteria that was generated by those performance evaluations were also considered. As the assumption of **section 5.1.1.8** "Traffic status" stated: "The size of the whole vehicle OBU is controlled in the space of $100 \times 60 \times 10$ mm and the service life of the vehicle tag (OBU) power supply must be no less than 5 years (Wang, 2019)", only tags that satisfied a volume under $100 \times 60 \times 10$mm and a tag life longer than 5 years, can be set as "qualified" under these constraints. Like tag volume and tag life, the assumption of **section 5.1.1.4** "Toll station traffic lane configurations" stated: "When more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes" (Guangdong Transportation Group, 2016), which means only the capability of ETC lanes greater than those traffic volumes can be set as "qualified". For all readers and tags of the sample database in table 5.1.2a, the results of constraints in this case study were generated by the concepts of tables 5.2.3j and 5.2.3k and listed in the following table.

Table 5.2.4 Value under the constraints of G40 road project

Samples	Reliability	Compatibility	Tags life	Capability
Reader 1+Tags 1	unqualified	unqualified	unqualified	unqualified
Reader 1+Tags 2	unqualified	unqualified	unqualified	unqualified
Reader 1+Tags 3	qualified	qualified	unqualified	unqualified
Reader 1+Tags 4	unqualified	unqualified	unqualified	unqualified
Reader 1+Tags 5	qualified	qualified	unqualified	unqualified
Reader 1+Tags 6	qualified	qualified	unqualified	unqualified
Reader 1+Tags 7	qualified	qualified	unqualified	unqualified
Reader 1+Tags 8	qualified	qualified	unqualified	unqualified
Reader 1+Tags 9	qualified	qualified	unqualified	unqualified
Reader 1+Tags 10	qualified	qualified	unqualified	unqualified
Reader 1+Tags 11	unqualified	unqualified	qualified	unqualified
Reader 1+Tags 12	unqualified	unqualified	qualified	unqualified
Reader 2+Tags 1	unqualified	unqualified	unqualified	qualified
Reader 2+Tags 2	unqualified	unqualified	unqualified	qualified
Reader 2+Tags 3	qualified	qualified	unqualified	qualified
Reader 2+Tags 4	unqualified	unqualified	unqualified	qualified
Reader 2+Tags 5	qualified	qualified	unqualified	qualified
Reader 2+Tags 6	qualified	qualified	unqualified	qualified
Reader 2+Tags 7	qualified	qualified	unqualified	qualified
Reader 2+Tags 8	qualified	qualified	unqualified	qualified
Reader 2+Tags 9	qualified	qualified	unqualified	qualified
Reader 2+Tags 10	qualified	qualified	unqualified	qualified
Reader 2+Tags 11	unqualified	unqualified	qualified	qualified
Reader 2+Tags 12	unqualified	unqualified	qualified	qualified
Reader 3+Tags 1	unqualified	unqualified	unqualified	qualified
Reader 3+Tags 2	unqualified	unqualified	unqualified	qualified
Reader 3+Tags 3	qualified	qualified	unqualified	qualified
Reader 3+Tags 4	unqualified	unqualified	unqualified	qualified
Reader 3+Tags 5	qualified	qualified	unqualified	qualified
Reader 3+Tags 6	qualified	qualified	unqualified	qualified
Reader 3+Tags 7	qualified	qualified	unqualified	qualified
Reader 3+Tags 8	qualified	qualified	unqualified	qualified
Reader 3+Tags 9	qualified	qualified	unqualified	qualified
Reader 3+Tags 10	qualified	qualified	unqualified	qualified
Reader 3+Tags 11	unqualified	unqualified	qualified	qualified
Reader 3+Tags 12	unqualified	unqualified	qualified	qualified
Reader 4+Tags 13	qualified	qualified	qualified	qualified
Reader 4+Tags 14	qualified	qualified	qualified	qualified
Reader 4+Tags 15	qualified	qualified	qualified	qualified

The above table show that the three ETC systems ("reader 4+Tags 13", "reader 4+Tags 14" and "reader 4+Tags 15") meet the expectations of Road Department administrations, this is because those samples were satisfied (were set as "qualified") under all constraint criteria.

According to the description of section 5.1.4, maximum satisfaction value should be calculated for optimization selection of Road Department administrations as the following steps.

Step 1. I set the normalization for the data under each criterion (discussed in section 3.2.4). For the first criterion, "Profit", the candidate ETC system for optimization is listed in the following table.

Table 5.2.4a Candidate ETC system under profit criterion (G40 - scheme 1)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506068579 Yuan
ETC B: Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506370501 Yuan
ETC C: Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506169220 Yuan

Table 5.2.4b Candidate ETC system under profit criterion (G40 - scheme 2)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	215765780 Yuan	350453373 Yuan	506074079 Yuan
ETC B: Reader 4+Tags 14	215905453 Yuan	350672967 Yuan	506376001 Yuan
ETC C: Reader 4+Tags 15	215812338 Yuan	350526571 Yuan	506174720 Yuan

By using 2020's data as the example, in table 5.2.4, ETC B has a max profit of 215905453 Yuan, and a minimum profit of ETC A (215765780 Yuan). To convert those data as uniform value, I introduced the data into the normalization equation 3.2.3, and generated a rank score for ETC C as $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{215812338-215765780}{215905453-215765780} = \frac{46558}{139673} = 0.33$. I used same method (equation 3.2.3), and calculated that the rank score of ETC B is $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 1$ and ETC A is $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 0$. Therefore, the rank scores in both schemes were represented in the following tables.

Table 5.2.4c Rank score under profit criteria (G40 - scheme 1)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	0	0	0
ETC B: Reader 4+Tags 14	1	1	1
ETC C: Reader 4+Tags 15	0.33	0.33	0.33

Table 5.2.4d Rank score under profit criteria (G40 - scheme 2)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	0	0	0

ETC B: Reader 4+Tags 14	1	1	1
ETC C: Reader 4+Tags 15	0.33	0.33	0.33

Step 2. I used normalization (equation 3.2.3) to calculate the rank score of the second criterion "capability", the candidate ETC system of capability performance was listed in tables 5.2.3b and 5.2.3c. The total capability of an ETC system includes both drive in and drive out traffic volume. From the constraint discussion in this section, only reader 4 satisfied the requirements of Road Department administrations. Therefore, I set this rank score as 1.

Step 3. I used normalization (equation 3.2.3) to calculate the rank score of the third criterion "volume", the candidate tag volume was provided in table 5.1.2a. Limited under the constraints of table 5.2.4, I listed useful information in following table.

Table 5.2.4e Tags volume of candidate ETC system

ETC systems	Volume (mm^3)
ETC A: Reader 4+Tags 13	85.5×54×4
ETC B: Reader 4+Tags 14	90×31×10
ETC C: Reader 4+Tags 15	86×54×4.5

From the above table, ETC B has a max tag volume of $90\times31\times10mm^3$, and a minimum tag volume of ETC A ($85.5\times54\times4mm^3$). Therefore, I introduced these data into equation 3.2.3, and calculated the rank score of ETC C as $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{86\times54\times4.5-85.5\times54\times4}{90\times31\times10-85.5\times54\times4} = \frac{2422}{7010} = 0.33$. I used same method (equation 3.2.3), and calculated rank score of ETC A as $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 0$ and ETC B as $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 1$.

Step 4. I used normalization to calculate the rank score of the third criterion "tag life", the candidate tag volume was provided in table 5.2.3k. Limited under the constraints of table 5.2.4, I listed useful information in following table.

Table 5.2.4f Tag life of candidate ETC system

ETC systems	Tags life
ETC A: Reader 4+Tags 13	12.65 years
ETC B: Reader 4+Tags 14	7 years
ETC C: Reader 4+Tags 15	9.65 years

From the above table, ETC A has the longest tag life of 12.65 years, and a minimum tag life of ETC B (7 years). Therefore, I introduced these data into equation 3.2.3, and calculated the rank score of ETC C as $\frac{Value-min}{max-min}=\frac{C_{etc}-B_{etc}}{A_{etc}-B_{etc}}=\frac{9.65-7}{12.65-7}=\frac{2.65}{5.65}=0.47$. I used same method (equation 3.2.3), and calculated the rank score of ETC A as $\frac{Value-min}{max-min}=\frac{A_{etc}-B_{etc}}{A_{etc}-B_{etc}}=1$ and ETC B as $\frac{Value-min}{max-min}=\frac{B_{etc}-B_{etc}}{A_{etc}-B_{etc}}=0$.

Step 5. I introduced the calculated rank scores into equation 5.1.4 in section 5.1.4.2 and generated a satisfaction value for each candidate ETC system. Here, using ETC A as an example in 2020 (scheme 1), the satisfaction value is $0+0.2+0.13+0=0.33$. I used same method and calculated the satisfaction value with the other situations as in the following table.

Table 5.2.4g Satisfaction value (G40 - scheme 1)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	0.33	0.33	0.33
ETC B: Reader 4+Tags 14	0.93	0.93	0.93
ETC C: Reader 4+Tags 15	0.42	0.42	0.42

Table 5.2.4h Satisfaction value (G40 - scheme 2)

ETC systems	2020	2027	2035
ETC A: Reader 4+Tags 13	0.33	0.33	0.33
ETC B: Reader 4+Tags 14	0.93	0.93	0.93
ETC C: Reader 4+Tags 15	0.42	0.42	0.42

The above tables indicate that ETC B is the best solution of equipment arrangement in both installation schemes.

5.3 Case analysis: Qixian-Lishi highway

The Qixian-Lishi highway in Shanxi Province is an important part of the seventh horizontal traffic lane of a key highway construction project of "thirteen vertical and fifteen horizontal traffic lines". Its east section connects the Yuqi highway (S60) and the Beijing-Kunming highway (G5), and the west section connects to the Luliang Huancheng intersection with the Qingyin highway(G20). After the completion of the project, it can not only effectively shorten the operating distance from Lvliang to Taiyuan, but also effectively alleviate the traffic pressure and improve the driving conditions of the Lishi-Fenyang section of the Qingyin highway and the Lishi-Fenyang section of the G307 Line. It is also helpful to improve the highway network of Shanxi Province, establishing a perfect comprehensive transportation system. It is of great significance to enhance the capacity of cargo transportation and tourist attractions, and to improve the capacity and accessibility of the regional highway network.

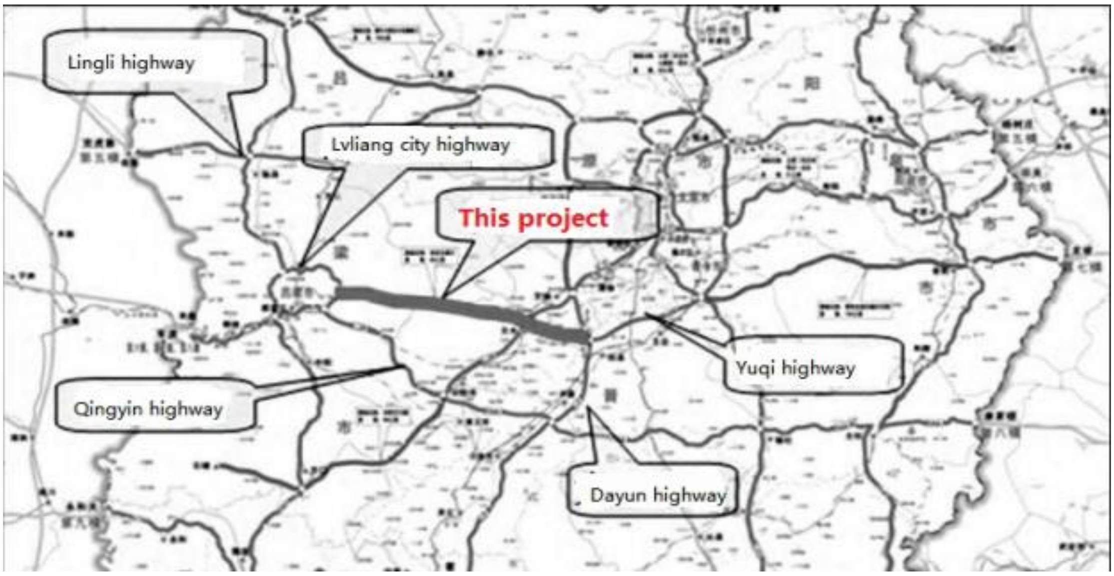

Figure 5.3 Qixian-Lishi highway

The project planned in this case covers a total length of 53 kilometres of highway. The design speed is 120 km/h, and there is a traffic interchange. Based on this interchange, there will be a toll station. The feasibility analysis of this project was carried out in the early planning, and the PCU value of the highway was predicted after the completion of the project. The forecast shows that the traffic volume will increase dramatically within 20 years after the road is opened to traffic in the section covered by this project.

5.3.1 Direct data

Since the toll station is located at one end of the highway, the PCU information is shown in the following table.

Table 5.3.1.PCU value in Qixian-Lishi highway

Road section	Section mileage	2020 prediction	
		West - east	East - west
Qixian to Lishi	53 km	2186 pcu/d	2377 pcu/d

At the same time, this case also gave the PCU value in the toll station of the road interchange. The specific information is shown in the following table.

Table 5.3.1a PCU value of East lishi junction

Toll station	2020 prediction

	Drive in	Drive out
East lishi junction	2241 pcu/d	2208 pcu/d

The width of the traffic lane and isolation zone is same as with the G40 project, and that value can refer to table 5.2.1b.

5.3.2 Decision inputs

Following the steps in case G40, I converted the direct data to the input of performance evaluation, that is the transformed data: revenue, cost of tags, cost of toll station operators' salaries and the number of toll station traffic lanes.

The revenue status of this project in 2020 is shown in following table.

Table 5.3.2 Transformed data- Qixian-Lishi highway revenue

Road section	2020
Qixian to Lishi	56440362 Yuan

The cost of ETC tags is shown in the following table.

Table 5.3.2a Costs of ETC tags (Qixian-Lishi highway)

ETC tags	2020
Tag 1	27563 Yuan
Tag 2	55125 Yuan
Tag 3	11025 Yuan
Tag 4	11025 Yuan
Tag 5	11025 Yuan
Tag 6	110250 Yuan
Tag 7	11025 Yuan
Tag 8	137813 Yuan
Tag 9	137813 Yuan
Tag 10	82688 Yuan
Tag 11	220500 Yuan
Tag 12	496125 Yuan
Tag 13	330750 Yuan
Tag 14	165375 Yuan
Tag 15	275625 Yuan

The cost of toll station operators is shown in the following table.

Table 5.3.2b Salary expenses (operators) in Qixian-Lishi highway

	2020
Salary expense	545472 Yuan

The number of traffic lanes in each toll station (Qixian-Lishi highway) is shown in the following table.

Table 5.3.2c Number of traffic lines in toll station of Qixian-Lishi highway

Toll stations	2020 prediction	
	Drive-in	Drive-out
Qixian to Lishi	MTC: 1 ETC: 1	MTC: 1 ETC: 1

The cost of readers in this road project is listed in the following table.

Table 5.3.2d Costs of readers (Qixian-Lishi highway)

	2020 (C_{reader})
Reader 1	2000 Yuan
Reader 2	3000 Yuan
Reader 3	5160 Yuan
Reader 4	5500 Yuan

5.3.3 Performance evaluation

Profit calculation: For the performance evaluation environment of profit calculation, Table 5.3.2c shows that in 2020, only one ETC toll lane was required for Qixian to Lishi toll station. This indicated that I do not need to set up two reader deployment modes as in Figure 2.2.2a. Here, I can meet the requirements of traffic management by only installing an ETC reader in scheme 1 (Figure 2.2.2). In this way, I used same method as G40 to calculate this performance evaluation output as in the following table.

Table 5.3.3 Performance evaluation output of profit calculation (Qixian-Lishi highway)

ETC systems	2020
Reader 1+Tags 1	55865328 Yuan
Reader 1+Tags 2	55837765 Yuan
Reader 1+Tags 3	55881865 Yuan
Reader 1+Tags 4	55881865 Yuan
Reader 1+Tags 5	55881865 Yuan
Reader 1+Tags 6	55782640 Yuan
Reader 1+Tags 7	55881865 Yuan
Reader 1+Tags 8	55755078 Yuan
Reader 1+Tags 9	55755078 Yuan
Reader 1+Tags 10	55810203 Yuan
Reader 1+Tags 11	55672390 Yuan
Reader 1+Tags 12	55396765 Yuan
Reader 2+Tags 1	55864328 Yuan
Reader 2+Tags 2	55836765 Yuan
Reader 2+Tags 3	55880865 Yuan
Reader 2+Tags 4	55880865 Yuan
Reader 2+Tags 5	55880865 Yuan
Reader 2+Tags 6	55781640 Yuan
Reader 2+Tags 7	55880865 Yuan
Reader 2+Tags 8	55754078 Yuan

Reader 2+Tags 9	55754078 Yuan
Reader 2+Tags 10	55809203 Yuan
Reader 2+Tags 11	55671390 Yuan
Reader 2+Tags 12	55395765 Yuan
Reader 3+Tags 1	55862168 Yuan
Reader 3+Tags 2	55834605 Yuan
Reader 3+Tags 3	55878705 Yuan
Reader 3+Tags 4	55878705 Yuan
Reader 3+Tags 5	55878705 Yuan
Reader 3+Tags 6	55779480 Yuan
Reader 3+Tags 7	55878705 Yuan
Reader 3+Tags 8	55751918 Yuan
Reader 3+Tags 9	55751918 Yuan
Reader 3+Tags 10	55807043 Yuan
Reader 3+Tags 11	55669230 Yuan
Reader 3+Tags 12	55393605 Yuan
Reader 4+Tags 13	55558640 Yuan
Reader 4+Tags 14	55724015 Yuan
Reader 4+Tags 15	55613765 Yuan

Traffic management evaluation: For the performance evaluation environment of traffic management, the traffic volume of toll lanes is the decision output. Based on the actual environment of this case, Table 5.3.2c shows that each direction toll station only needs one ETC lane in 2020. This means that reader deployment in this case is simpler than in G40. I deployed the reader in scheme 1 which was provided by the G40 case and produced the same results as in Table 5.2.3b.

Table 5.3.3a. Output of traffic management in the Qixian-Lishi highway toll station

	Drive out	Drive in	Speed limit
Reader 1	306 ve/h	289 ve/h	15.62km/h
Reader 2	417 ve/h	331 ve/h	39.13km/h
Reader 3	534 ve/h	389 ve/h	52.17km/h
Reader 4	464 ve/h	390 ve/h	80km/h

In this case, I did not need to deploy the reader in scheme 2 as in G40, which shows that reader 1 had been avoided in the consideration. Therefore, in this case, all readers had their performance evaluation outputs.

Reliability evaluation: Similar to G40, the input of this performance evaluation environment was not changed. For the reliability requirements of Road Department administrations, the performance evaluation process first determined whether the design materials of ETC tags met the moisture-proof standards, then the requirement of tag volume was also an important factor to be considered in this performance evaluation activity, which needed to limit the size to under $100 \times 60 \times 10\ mm^3$. According to the description in section 5.1.4, when both criteria (moisture-proof deign and tags size) meet the requirements of Road Department administrations, this candidate ETC system can be considered for optimization. Therefore, the decision output shows the same result as Table 5.2.3i.

Compatibility evaluation: For the compatibility requirements of Road Department administrations, an anti-collision mechanism was required and the ETC system should be operated under ISO/IEC 18000-6C protocol (**Section 5.1.1.8 assumption** "*Traffic statues*"). It also spends time when vehicles travel in toll stations (**Section 5.1.1.8 assumption** "*Traffic statues*"). For the transmission signal encryption, tags must conform to the EPC Class 1 Gen 2 protocol (**Section 5.1.1.8 assumption** "T*raffic statues*"). Therefore, the decision output of tags is same as with Table 5.2.3j.

Tag life evaluation: I used same method with G40 and the performance evaluation output is same as Table 5.2.3k.

5.3.4 Decision outcome

The previous section provided the output of five performance evaluation environments, and the measurement of these results is not uniform. According to the outcome classification method which was provided in **section 5.1.4** "*classification outcome*", I classified those outcomes into two types of formation: constraint and optimization.

1. The constraints of this road project are similar to G40. As the same policies, and the same sample database was used in this research, I believe that the constraints of this case are the same as G40.
2. I used the same steps as G40 to calculate the satisfaction value of candidate ETC systems.

Step 1. I set the normalization for the data under each criterion (discussed in section 3.2.4). For the first criterion "Profit", the candidate ETC system for optimization is listed in the following table.

Table 5.3.4 Candidate ETC system under profit criterion (Qixian-Lishi highway)

ETC systems	2020
ETC A: Reader 4+Tags 13	55558640 Yuan
ETC B: Reader 4+Tags 14	55724015 Yuan
ETC C: Reader 4+Tags 15	55613765 Yuan

In table 5.3.4, ETC B has a max profit of 55724015 Yuan and the minimum profit is ETC A (55558640 Yuan). I introduced these data into the normalization equation 3.2.3 (described in Chapter 3) and generated a rank score for ETC C of $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{55613765-55558640}{55724015-55558640} = \frac{55125}{165375} = 0.33$. I used same method (equation 3.2.3), and calculated rank score of ETC B as $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 1$ and ETC A as $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 0$. Therefore, the rank scores in both schemes are represented in the following table.

Table 5.3.4a Rank score under profit criterion (Qixian-Lishi highway)

ETC systems	2020
ETC A: Reader 4+Tags 13	0
ETC B: Reader 4+Tags 14	1
ETC C: Reader 4+Tags 15	0.33

Step 2. I used normalization to calculate the rank score of second criterion, “capability”, the candidate ETC system of capability performance was listed in table 5.3.3a. Like the demonstration work in G40 project, only reader 4 can satisfy the requirement of the Road Department administrations. Therefore, I set this rank score as 1.

Step 3. I used normalization to calculate the rank score of the third criterion, “volume”, the candidate tags of volume had been provided in table 5.1.2a. And I listed useful information in following table.

Table 5.3.4b Tags volume of candidate ETC system (Same as table 5.2.4e)

ETC systems	Volume (mm^3)
ETC A: Reader 4+Tags 13	85.5×54×4
ETC B: Reader 4+Tags 14	90×31×10
ETC C: Reader 4+Tags 15	86×54×4.5

The situation was the same as the G40 project: ETC B has a max tag volume of 90×31×10mm^3, and a minimum tag volume of ETC A (85.5×54×4mm^3). Then, I calculated the rank score of ETC C as $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{86\times54\times4.5-85.5\times54\times4}{90\times31\times10-85.5\times54\times4} = \frac{2422}{7010} = 0.35$ (equation 3.2.3); Then, I used same method to calculate the rank score of ETC A as $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 0$and ETC B as $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 1$(equation 3.2.3).

Step 4. I also used the method of the G40 project to calculate the rank score of the third criterion, “tag life”, and listed useful information in following table.

Table 5.3.4c Tag life of candidate ETC system (Qixian-Lishi highway)

ETC systems	Tag life
ETC A: Reader 4+Tags 13	12.65 years
ETC B: Reader 4+Tags 14	7 years
ETC C: Reader 4+Tags 15	9.65 years

From above table, ETC A has the longest tag life of 12.65 years, and a minimum tag life is ETC B (7 years); The rank score of ETC C is $\frac{Value-min}{max-min}=\frac{C_{etc}-B_{etc}}{A_{etc}-B_{etc}}=\frac{9.65-7}{12.65-7}=\frac{2.65}{5.65}=0.47$ (equation 3.2.3). Finally, I used the same method to calculate the rank score of ETC A as $\frac{Value-min}{max-min}=\frac{A_{etc}-B_{etc}}{A_{etc}-B_{etc}}=1$ and ETC B as $\frac{Value-min}{max-min}=\frac{B_{etc}-B_{etc}}{A_{etc}-B_{etc}}=0$ (equation 3.2.3).

5). Using the same method as in the G40 project, I introduced the calculated rank scores to the equation 5.1.4 and generated the satisfaction value of each candidate ETC system. Here, using ETC A as an example, the satisfaction value is $0+0.2+0.13+0=0.33$. I used same method and calculated the satisfaction value of the other situations as in the following table.

Table 5.3.4d Satisfaction value (Qixian-Lishi highway)

ETC systems	2020
ETC A: Reader 4+Tags 13	0.33
ETC B: Reader 4+Tags 14	0.93
ETC C: Reader 4+Tags 15	0.42

The above tables indicate that ETC B is the best solution of this case.

5.4 Case analysis: Sutong bridge

The Sutong Yangtze River Highway Bridge, in the southeast of Jiangsu Province, connects Nantong city and Suzhou city. The recommended scheme is about 82 km from the Jiangyin Yangtze River Highway Bridge in the west and 108 km from the Yangtze River estuary in the east. The total length of this project is 32.18 km. The total length of the bridge spanning the Yangtze River is 7,649 metres and the main span is a double-tower cable-stayed bridge with a span of 1,088 metres. It ranks first in the world in span length of the same type of bridge with a total cost of 6 billion yuan.

The main part of the Sutong Bridge is arranged in 100m+100m+300m+1088m+300m+100m+100m+100m spans. The total length of the bridge is 8206 metres, the total length of the north bank connection project is 15.1 km, the total length of the south bank connection project is 9.1 km and the bridge deck is a standard two-way six-lane highway. The calculation speed of the south and north sides of the bridge is 120 km/h and, for the river-crossing bridge, 100 km/hr. The navigation clearance of the main bridge is 62 metres high and 891 metres wide, which meets the navigation requirements of 50,000-ton container freighters and 48,000-ton fleet. There are two interchanges in the north bank wiring project, one in the main toll station and one in the service area, and the south bank also has an interchange.

Figure 5.4 Sutong bridge

Unlike case G40 and the Qixian-Lishi highway, this case adopts an open charging mode. That is, vehicles do not need to enter the bridge road through the ramp. Instead, toll stations are set up on the highway to collect the payments of vehicles. This kind of toll collection is rare in China, mainly due to the inconsistency between the bridge management department and the highway management department. The rate of vehicles passing through the Sutong Bridge is also different from that of the general highway, which leads to the charging of vehicles passing through the bridge by two different management departments.

5.4.1 Direct data

The PCU per day of Sutong Bridge in 2020 was predicted as follows:

Table 5.4.1 PCU value in Sutong bridge

Road section	Section mileage	2020 prediction
Sutong Bridge	32.18 km	67478 pcu/d

Because the main toll station is in the north of the Sutong Bridge and is used to monitor the vehicles entering the bridge, it can be found from the top view that the toll station is one-way service, and the number of traffic lanes is set by the real-time traffic flow. The top view of the toll station is shown as follows:

Figure 5.7 Top view of Sutong north toll station

From the top view, I found that the Sutongbei toll station is the main one-way toll station. I calculated that the PCU per day of this toll station is half of Table 5.4.1. The PCU value of Sutongbei toll station is shown in the following table.

Table 5.4.1.PCU value in Sutong north toll station

Road section	2020 prediction
Sutong North	33739 pcu/d

5.4.2 Decision inputs

According to the description of the **assumption** "*Data prepare*" (**section 5.1.3**), I converted the direct data to the input of performance evaluation, that is the transformed data: revenue, cost of tags, cost of toll station operators' salaries and the number of toll station traffic lanes. The revenue status of this project in 2020, is shown in the following table.

Table 5.4.1a Transformed data- Sutong Bridge revenue

Road section	2020
Sutong Bridge	834644471 Yuan

The cost of ETC tags is shown in the following table.

Table 5.4.1b Cost of ETC tags (Sutong Bridge)

ETC tags	2020
Tag 1	16992 Yuan
Tag 2	33984 Yuan
Tag 3	6797 Yuan
Tag 4	6797 Yuan
Tag 5	6797 Yuan
Tag 6	67968 Yuan
Tag 7	6797 Yuan
Tag 8	84960 Yuan
Tag 9	84960 Yuan
Tag 10	50976 Yuan
Tag 11	135936 Yuan
Tag 12	305856 Yuan
Tag 13	203904 Yuan
Tag 14	101952 Yuan
Tag 15	169920 Yuan

The cost of toll station operators is shown in following table.

Table 5.4.1c. Salary expenses (operators) in Sutong Bridge

	2020
Salary expense	1295496 Yuan

The number of traffic lanes in each toll station (Qixian-Lishi highway) is shown in the following table.

Table 5.4.1d Number of traffic lanes in toll station of Qixian-Lishi highway

Toll stations	2020 prediction	
	Drive-in	
Sutong North	MTC: 7	ETC: 3

5.4.3 Performance evaluation

1. Table 5.41 shows that the PCU value of the Sutong north toll station is larger than that any toll station in the previous two cases. In 2020, three ETC lanes will be set in this toll station, which required us to adopt the same G40 scheme and set the ETC installation mode as two schemes. For scheme 1, each ETC lane is equipped with a reader, so the profit of each type of reader in the sample database is shown in the following table.

Table 5.4.3 Output of performance evaluation of profit calculation (Sutong Bridge - scheme 1)

ETC systems	2020
Reader 1+Tags 1	833328983 Yuan
Reader 1+Tags 2	833311991 Yuan
Reader 1+Tags 3	833339178 Yuan
Reader 1+Tags 4	833339178 Yuan
Reader 1+Tags 5	833339178 Yuan
Reader 1+Tags 6	833278007 Yuan
Reader 1+Tags 7	833339178 Yuan
Reader 1+Tags 8	833261015 Yuan
Reader 1+Tags 9	833261015 Yuan
Reader 1+Tags 10	833294999 Yuan
Reader 1+Tags 11	833210039 Yuan
Reader 1+Tags 12	833040119 Yuan
Reader 2+Tags 1	833327483 Yuan
Reader 2+Tags 2	833310491 Yuan
Reader 2+Tags 3	833337678 Yuan
Reader 2+Tags 4	833337678 Yuan
Reader 2+Tags 5	833337678 Yuan
Reader 2+Tags 6	833276507 Yuan
Reader 2+Tags 7	833337678 Yuan
Reader 2+Tags 8	833259515 Yuan
Reader 2+Tags 9	833259515 Yuan
Reader 2+Tags 10	833293499 Yuan
Reader 2+Tags 11	833208539 Yuan
Reader 2+Tags 12	833038619 Yuan
Reader 3+Tags 1	833324243 Yuan
Reader 3+Tags 2	833307251 Yuan
Reader 3+Tags 3	833334438 Yuan
Reader 3+Tags 4	833334438 Yuan
Reader 3+Tags 5	833334438 Yuan
Reader 3+Tags 6	833273267 Yuan
Reader 3+Tags 7	833334438 Yuan
Reader 3+Tags 8	833256275 Yuan
Reader 3+Tags 9	833256275 Yuan
Reader 3+Tags 10	833290259 Yuan
Reader 3+Tags 11	833205299 Yuan
Reader 3+Tags 12	833035379 Yuan
Reader 4+Tags 13	833136821 Yuan
Reader 4+Tags 14	833238773 Yuan
Reader 4+Tags 15	833170805 Yuan

I adopted the same scheme as G40. It should be emphasized that the reader signal in this case needs to cover three traffic lanes. The signal coverage of reader 1 does not reach the width of the three ETC lanes. Therefore, in scheme 2, I excluded reader 1 and used the same method as in G40 to calculate the expected profit of readers 2, 3 and 4. The performance evaluation outputs are shown in the following table.

Table 5.4.3a Decision output of profit calculation (Sutong Bridge - scheme 2)

ETC systems	2020
Reader 2+Tags 1	833330483 Yuan
Reader 2+Tags 2	833313491 Yuan
Reader 2+Tags 3	833340678 Yuan
Reader 2+Tags 4	833340678 Yuan
Reader 2+Tags 5	833340678 Yuan
Reader 2+Tags 6	833279507 Yuan
Reader 2+Tags 7	833340678 Yuan
Reader 2+Tags 8	833262515 Yuan
Reader 2+Tags 9	833262515 Yuan
Reader 2+Tags 10	833296499 Yuan
Reader 2+Tags 11	833211539 Yuan
Reader 2+Tags 12	833041619 Yuan
Reader 3+Tags 1	833329403 Yuan
Reader 3+Tags 2	833312411 Yuan
Reader 3+Tags 3	833339598 Yuan
Reader 3+Tags 4	833339598 Yuan
Reader 3+Tags 5	833339598 Yuan
Reader 3+Tags 6	833278427 Yuan
Reader 3+Tags 7	833339598 Yuan
Reader 3+Tags 8	833261435 Yuan
Reader 3+Tags 9	833261435 Yuan
Reader 3+Tags 10	833295419 Yuan
Reader 3+Tags 11	833210459 Yuan
Reader 3+Tags 12	833040539 Yuan
Reader 4+Tags 13	833142321 Yuan
Reader 4+Tags 14	833244273 Yuan
Reader 4+Tags 15	833176305 Yuan

2. According to the reader deployment scheme provided by the profit calculation, the performance evaluation output of the road management evaluation is divided into two situations. In this case, the Sutong North toll station adopts the mode of an open toll road, so the vehicles do not enter the freeway when they leave the toll station, but continue to accelerate to the highway. According to the analysis of the vehicle speed changing at toll stations in Chapter 4, I believed that the output of this performance evaluation was different from the previous two cases. For scheme 1, the ETC lane traffic entity information of the toll station is shown in the following table.

Table 5.4.3b. Decision output of traffic management in Sutong Bridge toll station (scheme 1)

	Drive out	Drive in	Speed limit
Reader 1	306 ve/h	289 ve/h	15.62km/h
Reader 2	417 ve/h	331 ve/h	39.13km/h
Reader 3	534 ve/h	389 ve/h	52.17km/h
Reader 4	464 ve/h	390 ve/h	80km/h

The ETC lanes in this project were set as three (Table 5.4.1b), which means one reader should have enough signal coverage to cover three traffic lanes. For this reason, I recalculated the traffic capability in each ETC lane for scheme 2. The following table lists the decision outputs in this scheme.

Table 5.4.3c Decision output of traffic management in Sutong Bridge toll station (scheme 2)

	Drive out	Drive in	Speed limit
Reader 2	296 ve/h	429 ve/h	18.6 km/h
Reader 3	312 ve/h	449 ve/h	25.4 km/h
Reader 4	557 ve/h	722 ve/h	80 km/h

3. Similar to the previous two cases, the performance evaluation input of the reliability performance evaluation environment was not changed. For the reliability requirements of Road Department administrations, the performance evaluation behaviour first determined whether the design materials of ETC tags achieved the moisture-proof standards. The requirement of tag volume is also an important factor to be considered in the performance evaluation process, which needs to limit the tag size to under $100 \times 60 \times 10\ mm^3$. According to the description in Section 5.1.4, when both two criteria (moisture-proof deign and limited size limit of $100 \times 60 \times 10\ mm^3$) were satisfied, these tags will be selected for optimization. Therefore, this performance evaluation output is the same as section 2.3.3.3.

4. For the compatibility requirement of Road Department administrations, the anti-collision mechanism was required and the ETC system should be operated under ISO/IEC 18000-6C protocol (**Section 5.1.1.8 assumption** "*Traffic statues*"). It also spends time when vehicles travel in toll stations (**Section 5.1.1.8 assumption** "*Traffic statues*"). For the transmission signal encryption, tags must conform to the EPC Class 1 Gen 2 protocol (**Section 5.1.1.8 assumption** "*Traffic statues*"). Therefore, the decision output of tags is the same as Table 5.2.3j.

5. For tag life calculation, I used same method as in the G40 analysis, and this performance evaluation output is same as Table 5.2.3k.

5.4.4 Decision outcome

The previous section provided the output of five performance evaluation environments in this Sutong bridge project, and then simulated these results by different measurements. According to the outcome classification method which was provided in **section 5.1.4** "*classification outcome*", I classified those outcomes into constraint and optimization.

1. The compatibility and reliability evaluation of this road project is similar to previous cases. As the same policies, and the same parameters were from the sample database, I believe that the constraints of this case are the same as the previous two case.

2. I used the same steps as for the previous cases to calculate the satisfaction value of the candidate ETC systems.

Step 1. I set the normalization (equation 3.2.3) for the data under each criterion (discussed in section 3.2.4). For the first criterion, "Profit", the useful information which was calculated from section 5.4.3 is listed in following tables.

Table 5.4.4 Candidate ETC system under profit criterion (Sutong Bridge-scheme 1)

ETC systems	2020
ETC A: Reader 4+Tags 13	833136821 Yuan
ETC B: Reader 4+Tags 14	833238773 Yuan
ETC C: Reader 4+Tags 15	833170805 Yuan

Table 5.4.4a Candidate ETC system under profit criterion (Sutong Bridge-scheme 2)

ETC systems	2020
ETC A: Reader 4+Tags 13	833142321 Yuan
ETC B: Reader 4+Tags 14	833244273 Yuan
ETC C: Reader 4+Tags 15	833176305 Yuan

In table 5.4.4, ETC B has a max profit of 833238773 Yuan and the minimum profit of ETC A is 833136821 Yuan. Therefore, I introduced these data into equation 3.2.3 (described in Chapter 4) and generated a rank score for ETC C of $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{833170805-833136821}{833238773-833136821} = \frac{33984}{101952} = 0.33$. Similarly, I used the same method (equation 3.2.3), and calculated a rank score for ETC B of $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{833238773-833136821}{833238773-833136821} = \frac{101952}{101952} = 1$ and for ETC A of $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{833136821-833136821}{833238773-833136821} = \frac{0}{101952} = 0$. The rank score in both schemes are represented in the following tables.

Table 5.4.4b Rank score under profit criterion (Sutong Bridge highway-scheme 1)

ETC systems	2020
ETC A: Reader 4+Tags 13	0
ETC B: Reader 4+Tags 14	1

ETC C: Reader 4+Tags 15	0.33

Then, I used same method to calculate the satisfaction value in scheme 2. The results are listed in the following table.

Table 5.4.4b Rank score under profit criterion (Sutong Bridge highway-scheme 2)

ETC systems	2020
ETC A: Reader 4+Tags 13	0
ETC B: Reader 4+Tags 14	1
ETC C: Reader 4+Tags 15	0.33

Step 2. I used normalization to calculate the rank score of the criterion, "capability", the candidate ETC system's capability performance had been listed in tables 5.4.3b and 5.4.3c. Similar to the demonstration work in the G40 project, in both schemes which were discussed in section 5.4.3, only reader 4 satisfies the requirements of the Road Department administrations. Therefore, I set this rank score as 1.

Step 3. I used normalization to calculate the rank score of the criterion, "volume", (the candidate tags of volume had been provided in table 5.1.2a) and listed useful information as following table.

Table 5.4.4c Tags volume of candidate ETC system (Similar to table 5.2.4e)

ETC systems	Volume (mm^3)
ETC A: Reader 4+Tags 13	85.5×54×4
ETC B: Reader 4+Tags 14	90×31×10
ETC C: Reader 4+Tags 15	86×54×4.5

The situation was the same as with the G40 project (equation 3.2.3). ETC B has the max tag volume as 90×31×10 mm^3, and the minimum tag volume is ETC A (85.5×54×4mm^3). Then, I calculated the rank score of ETC C as $\frac{Value-min}{max-min} = \frac{C_{etc}-A_{etc}}{B_{etc}-A_{etc}} = \frac{86\times54\times4.5-85.5\times54\times4}{90\times31\times10-85.5\times54\times4} = \frac{2422}{7010} = 0.35$ (equation 3.2.3), the rank score of ETC A as $\frac{Value-min}{max-min} = \frac{A_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 0$ and ETC B as $\frac{Value-min}{max-min} = \frac{B_{etc}-A_{etc}}{B_{etc}-A_{etc}} = 1$.

Step 4. I also used the method of the previous projects to calculate the rank score of the third criterion, "tag life", and listed useful information in the following table.

Table 5.4.4d Tag life of candidate ETC systems (Sutong Bridge highway)

ETC systems	Tags life
ETC A: Reader 4+Tags 13	12.65 years

ETC B: Reader 4+Tags 14	7 years
ETC C: Reader 4+Tags 15	9.65 years

From the above table, ETC A has the longest tag life of 12.65 years, and a minimum tag life is ETC B (7 years). The rank score of ETC C is $\frac{Value-min}{max-min}=\frac{C_{etc}-B_{etc}}{A_{etc}-B_{etc}}=\frac{9.65-7}{12.65-7}=\frac{2.65}{5.65}=0.47$ (equation 3.2.3). Finally, I calculated the rank score of ETC A as $\frac{Value-min}{max-min}=\frac{A_{etc}-B_{etc}}{A_{etc}-B_{etc}}=1$ and ETC B as $\frac{Value-min}{max-min}=\frac{B_{etc}-B_{etc}}{A_{etc}-B_{etc}}=0$ (equation 3.2.3).

5). I used the same method as in the previous projects, and introduced the calculated rank scores into equation 5.1.4 and generated a satisfaction value of each candidate ETC system. Here, I used ETC A as an example, the satisfaction value is.$0+0.2+0.13+0=0.33$. I used the same method and calculated the satisfaction value in both two reader installation schemes as per the following table.

Table 5.4.4e Satisfaction value (Sutong Bridge highway)

ETC systems	2020
ETC A: Reader 4+Tags 13	0.33
ETC B: Reader 4+Tags 14	0.93
ETC C: Reader 4+Tags 15	0.42

The above tables indicate that ETC B is the best solution of this case.

5.5 Demonstration conclusion

Three cases were used in this study: the G40 (Pingchao-Guangling Section) reconstruction and extension project, the Sutong bridge highway project and the Qixian-Lishi highway project in Shanxi Province. I also used feasibility reports which were provided by those projects to obtain the direct data for the demonstration work. These data include the PCU values of each road section, the PCU values of the toll stations, the width of the traffic lanes and the width of the isolation zones between traffic lanes. Since the data provided by these feasibility reports are not for Road Department administrations selections, their attention is focused on the road environment of their projects. This impels us to provide the data preparation plan in section 5.1.3, that is, only if those original data provided by the feasibility report were transformed into input information that can be identified by the decision-making behaviour, can the decision-making model be implemented, and the decision output can be issued.

The factors that influence decision making were mentioned in Chapter 3, including

ETC attributes, road environments and road policies. This information is the effective input of the decision model, that is, when the decision model obtains the input information that meets the requirements of the Road Department administration, then the decision model can be implemented. In this chapter, ETC attributes were provided by the sample database which was mentioned in section 5.1.2; road policies were provided by the data assumption which was proposed in section 5.1.1 and road environments were provided by the feasibility reports which came from the case studies in sections 5.2, 5.3 and 5.4. Therefore, the direct data provided by the feasibility report is considered closely related to the road environment of the decision-making model.

In the process of demonstrating the three cases, according to the discussion in section 5.1.3, I transformed the direct data into decision inputs, which is also road environment data. Then, I imported those transformed environmental data, ETC attributes which were provided in the sample database and the road policies which were mentioned in section 5.1.1 into the performance evaluation environments which were developed in Chapter 4, to meet the five requirements of the Road Department administrations. These five performance evaluation environments are profit calculation, traffic management assessment, reliability assessment, compatibility assessment and tag life assessment. After performance evaluation in advance, I obtained the performance data of the ETC systems under each decision criterion. Due to the conflict between these criteria, I finally introduced these performance data into the decision model which was developed in section 4.5.4 and generated the optimized ETC system which was expected by the Road Department administrations.

After decision activities in the three case studies, each project generated its own optimized ETC systems with constraints. I compared these decision outputs from our developed DS model with the real-world ETC system which was provided by the Road Department administrations after I talked in one-hour interviews, and that comparison information is shown in the following table.

Table 5.5 Comparison information between decision output and real-world system

Technique characteristics	Realistic system	G40 2020 ETC B	G40 2027 ETC B	G40 2035 ETC B	Qixian - Lishi ETC B	Sutong bridge ETC B
Frequency	2.4G or higher	√	√	√	√	√
Signal range of	More than 20 metres	√	√	√	√	√

readers						
Speed limit	Approximately 80km/h	√	√	√	√	√
Moisture-proof design	Yes	√	√	√	√	√
Volume	Under 100 x 60 x 10 mm	√	√	√	√	√
Protocols	ISO/IEC 18000-6C and EPC Class 1 Gen 2	√	√	√	√	√
Tag life	More than 5 years	√	√	√	√	√

Information in the above table shows that the output of the decision model is consistent with the parameters of ETC systems in the real world, which means that the decision model developed in Chapter 4 effectively imitated the decision-making activities of the Road Department administrations and can assist the Road Department administrations to do reasonable ETC system planning. One of the advantages of the decision model is that, compared with the manual decision making of the Road Department administrations, the model refines the decision-making activities, divides the behaviour into five performance evaluation scenarios, and can produce its own decision-making results by the comprehensive multi-criteria model. This approach is to help the Road Department administrations to set specific decision goals to obtain decision results corresponding to the requirements of different types of positions. Another advantage of this model is limiting the scope of decision making and limiting the selected objects to the conceptual scope of ETC system. This makes the decision making more specialized and the data acquisition based on ETC systems more accurate.

Table 5.5 also indirectly indicates that decision activities have the following characteristics:

1. Generality: the performance value (after the performance evaluation behaviour) of the optimized ETC system which was generated by the three cases is consistent with the parameters of the real world ETC system. This means, under the decision-making environment, ETC attributes, road environment and road policies as factors that made the decision-making model produced consistent results. This proved the wide application use of this decision model, and I believed that the decision model can also be applied to other road project scenarios in China.

2. Priority of constraints: the real-world data came from the criteria under constraint, which further verified the priority of constraints in the decision-making environment. At the same time, those three case studies show that the constraint criteria mainly achieved the reliability and compatibility requirements of Road Department administrations, that is, these requirements come from the specifications of road policies. Due to the wide

applicability of road policies in China, the data it produced and pointed out are not changeable. For example, the data proposed in **section 5.1.1** "**assumption**" is applicable to national road projects for a long time, to meet the reliability and compatibility requirements of national traffic networks.

3. The optimization decision is determined by the road environment, for example, the ETC system generated in Chapters 5.2, 5.3 and 5.4 produced different profit values under the road environment proposed in each case, which was determined by the different traffic volumes. This indicated that the optimal decision making depended on the Road Department administration's judgment, according to the characteristics of the road environment.

5.6 Sensitivity Analysis for optimization

Sensitivity analysis was used in this study to find the influence of decision factors on the optimization results, which were not solved by the demonstration work. The sensitivity analysis of this study mainly discussed the following two aspects:

1. The influence of decision criteria on satisfaction values.
2. The impact of thresholds (discussed in section 4.5.2) in the decision-making process.

It should be emphasized that the demonstration work (sections 5.2, 5.3 and 5.4) and the decision-making model proposed in Chapter 4 indicated that satisfying the constraints is the premise of optimal decision-making behaviour. That is, only if the candidate ETC systems that meet the reliability and compatibility requirements of the Road Department administration, can the optimization decision be executed and the satisfaction value of the ETC system be calculated. Therefore, as a feature of the Yes/No criterion (discussed in section 4.5.2), constraint decision-making behaviour does not meet the requirements of the sensitivity analysis. This research only focus on the optimization of the decision-making process, trying to discuss and find the influence of the decision-making factors.

5.6.1 Impact of criterion

Theoretically, when I change a fixed value under a specific criterion, with the implementation of decision-making behaviour, the change will be reflected in satisfaction, I can then judge the importance of that criterion from the change of the satisfaction value. Therefore, this research extracted the optimization decision results of sections 5.2, 5.3 and 5.4, and listed the useful data in the following table.

Table 5.6.1 Rank score of each criterion

ETC systems	Profit	Capability	Volume	Tags life	Satisfaction
ETC A: Reader 4+Tags 13	0	1	0	1	0.33
ETC B: Reader 4+Tags 14	1	1	1	0	0.93
ETC C: Reader 4+Tags 15	0.33	1	0.35	0.47	0.42

In this work, sensitivity analysis was used to find the most critical and least critical decision criteria of each candidate ETC system in the above table. That is, for all candidate ETC systems, A, B and C, the rating of each criterion was increased by 10%, and the corresponding change of satisfaction value was listed in the following table.

Table 5.6.1a Sensitivity analysis for change 10% of each criterion

Criterion	Change in criterion (%)	Change in satisfaction of Candidate ETC system (%)		
		A	B	C
Profit	+10%	0	5.8	1.914
Capability	+10%	2	2	2
Volume	+10%	0	0.9	0.315
Tags life	+10%	1.3	0	0.611

The information provided in the above table clearly pointed out the most critical and least critical decision criteria. In the criterion named "Profit", the sum of the satisfaction value was changed as 7.714, which shows this criterion is the most important indicator in the process of optimization decision making; for the criterion named "volume", I calculated the sum of the satisfaction change as 1.215, which shows that criterion is the least critical criterion in optimization decision making. Through the above analysis, I found that the results of sensitivity analysis are consistent with the influence of weights.

5.6.2 Impact of threshold

Although the discussion in the previous section helps to prove the impact of fixed changes in each decision criterion on the satisfaction value of Road Department administrations, it was not helpful to represent the data that Road Department administrations input for decision-making behaviour in the decision-making meeting. For example, it may happen that the value of a particular ETC attribute is out of the range of constraints, so that the optimization decision cannot be made from the beginning, which is completely reasonable. This may occur in the absence of real-world data to support the input of this decision model. An example of this is trying to use the optimal decision model to output the decision results when only the information of the sample database is available. On the contrary, some of the data under the criteria are involved in the way of road policies (**section 5.1.1 "assumptions"** was discussed), so there is a high understanding of this value.

Sensitivity analysis can be carried out by changing each decision criterion to the highest and lowest possible value. The definition of "possible" varied with road policies (discussed in **section 5.1.1 "assumptions"**), but it was generally reasonable to change the criteria based on the range of changes in the data. Finally, a more detailed method for sensitivity analysis of a specific decision criteria is to evaluate the impact of a series of numerical values on the model output. In this analysis, a series of tables can be generated to draw the comprehensive model results according to each possible input value. This demonstrated the relationship between input values and model output. This kind of analysis can also be used to determine the threshold of possible changes in the conclusions of the model.

5.6.2.1 Lists of thresholds

According to the research in section 4.5 and the discussion of "assumption" in section 5.1.1, I believed that in the optimization process of decision making, the following criteria have the characteristics of threshold value:

1. Traffic capacity of ETC lane: as described in section 5.1.1.4, "*When more than 300 vehicles enter the highway in each hour, the toll station should set up a new traffic line for pass through. Similarly, when more than 160 vehicles leave the highway in each hour, toll stations should also open new lanes.*", that is, I took the sum of 300ve/h of drive-in traffic volume and 160ve/h of drive-out traffic as the threshold. I believe that the ETC system can participate in the optimal decision making only when the vehicle capacity exceeds this threshold.

2. Tag volume: as described in section 5.1.1.8, "*The size of the whole vehicle on board unit (OBU) is controlled in the space of 100×60×10mm*", that is, I took tag volume of $100 \times 60 \times 10\ mm^3$ as the threshold. I believe that only when the volume of the tag does not exceed this size, the RFID module of the ETC tag can be installed into the OBU

system. At the same time, according to the research in section 4.4.3, the volume of tags determined the stability of signal transmission, which made the larger volume tags more acceptable to the Road Department administrations.

3. Tag life: as described in section 5.1.1.8, "*The service life of vehicle tags (OBU) power supply must be no less than 5 years* (Wang, 2019)", I took the tag life of 5 years as the threshold. I believe that ETC tags can only be accepted by the Road Department administrations if their lifetime exceeded this threshold.

In addition, the decision criterion, "profit", does not have a threshold, but this does not mean that there is no limit to the change of the value under this criterion. I believe that when the profit is negative, the ETC system is in a loss state, and once this situation occurred, the system will not be accepted by the Road Department administrations.

5.6.2.2 Re-normalization for sensitivity analysis

Section 5.6.1 discussed the impact of fixed changes under the criteria on satisfaction and indicated the most critical and least critical decision criteria. When I introduced threshold into sensitivity analysis, the values of the criteria needed to be redefined. Sections 5.2, 5.3, and 5.4 discussed the outputs of the performance evaluation, and I standardized these outputs according to the methods provided in section 3.2.2 and translated them into satisfaction scores. Here, thresholds limited the range of these outputs, so I was recalculating the ranking score. In the process of re-normalization, I defined the following transformation rules.

1. Unlike section 5.6.1, the change of fixed value will not be reflected in the ranking score. Instead, I used the result of performance evaluation to reflect that fixed value for sensitivity changes.

2. Due to the limitations of the threshold, when the changes reached the boundary of the threshold, I believed that changes will be stopped to ensure the output of the decision is effective. For example, when I increased the tag volume of the specific candidate ETC system to reach the size of $100 \times 60 \times 10\ mm^3$, changes on that system will not continue, but this termination will not affect the change of other candidate ETC systems.

3. Based on meeting the second point, I normalize the performance evaluation output with

adding the threshold to re-score the ranking, according to section 4.5.5.

5.6.2.3 Sensitivity analysis by adding threshold

The following table shows that the satisfaction value for each candidate ETC system in decision criteria vary from -100% to the maximum possible in steps of 10%. Unlike with section 5.6.1, the ranking score of each decision criterion is obtained on a scale of 0-1, that is, the maximum value is limited to 1.

Table 5.6.2 Sensitivity analysis for ETC A

Change	Satisfaction value for variation in decision criterion			
(10%)	Profit	Capability	Volume	Tags life
-100 %	0.33	0.13	0.33	0.2
-90 %	0.33	0.13	0.33	0.2
-80 %	0.33	0.13	0.33	0.2
-70 %	0.33	0.13	0.33	0.2
-60 %	0.33	0.13	0.33	0.2
-50 %	0.33	0.13	0.33	0.33
-40 %	0.33	0.13	0.33	0.33
-30 %	0.33	0.13	0.33	0.33
-23 %	0.33	0.33	0.33	0.33
-20 %	0.33	0.33	0.33	0.33
-10 %	0.33	0.33	0.33	0.33
0	0.33	0.33	0.33	0.33
10 %	0.33	0.33	0.33	0.33
20 %	0.33	0.33	0.33	0.33
30 %	0.33	0.33	0.33	0.33
40 %	0.33	0.33	0.33	0.33
50 %	0.33	0.33	0.33	0.33
60 %	0.33	0.33	0.33	0.33
70 %	0.33	0.33	0.33	0.33
80 %	0.33	0.33	0.33	0.33
90 %	0.33	0.33	0.33	0.33
100 %	0.33	0.33	0.33	0.33

Table 5.6.2a Sensitivity analysis for ETC B

Change	Satisfaction value for variation in decision criterion			
(10%)	Profit	Capability	Volume	Tags life
-100 %	0.35	0.73	0.84	0.93
-90 %	0.93	0.73	0.93	0.93
-80 %	0.93	0.73	0.93	0.93
-70 %	0.93	0.73	0.93	0.93
-60 %	0.93	0.73	0.93	0.93
-50 %	0.93	0.73	0.93	0.93
-40 %	0.93	0.73	0.93	0.93
-30 %	0.93	0.73	0.93	0.93
-23 %	0.93	0.93	0.93	0.93
-20 %	0.93	0.93	0.93	0.93
-10 %	0.93	0.93	0.93	0.93
0	0.93	0.93	0.93	0.93
10 %	0.93	0.93	0.93	0.93
20 %	0.93	0.93	0.93	0.93
30 %	0.93	0.93	0.93	0.93
40 %	0.93	0.93	0.93	0.93

50 %	0.93	0.93	0.93	0.93
60 %	0.93	0.93	0.93	0.93
70 %	0.93	0.93	0.93	0.93
80 %	0.93	0.93	0.93	0.93
90 %	0.93	0.93	0.93	0.93
100 %	0.93	0.93	0.93	0.93
110 %	0.93	0.93	0.93	0.93
115 %	0.93	0.93	0.84	0.93

Table 5.6.2b Sensitivity analysis for ETC C

Change	Satisfaction value for variation in decision criterion			
(10%)	Profit	Capability	Volume	Tags life
-100 %	0.1764	0.22	0.3885	0.3589
-90 %	0.42	0.22	0.42	0.3589
-80 %	0.42	0.22	0.42	0.3589
-70 %	0.42	0.22	0.42	0.3589
-60 %	0.42	0.22	0.42	0.3589
-50 %	0.42	0.22	0.42	0.3589
-48 %	0.42	0.22	0.42	0.3589
-40 %	0.42	0.22	0.42	0.42
-30 %	0.42	0.22	0.42	0.42
-23 %	0.42	0.42	0.42	0.42
-20 %	0.42	0.42	0.42	0.42
-10 %	0.42	0.42	0.42	0.42
0	0.42	0.42	0.42	0.42
10 %	0.42	0.42	0.42	0.42
20 %	0.42	0.42	0.42	0.42
30 %	0.42	0.42	0.42	0.42
40 %	0.42	0.42	0.42	0.42
50 %	0.42	0.42	0.42	0.42
60 %	0.42	0.42	0.42	0.42
70 %	0.42	0.42	0.42	0.42
80 %	0.42	0.42	0.42	0.42
90 %	0.42	0.42	0.42	0.42
100 %	0.42	0.42	0.42	0.42
187 %	0.42	0.42	0.3885	0.42

The information provided by the above three tables revealed the impact of threshold on the satisfaction of the Road Department administrations, and further verified the role of the most critical and least critical criteria in decision-making behaviour. Tables 6.5.2a and 6.5.2b show the psychological impact of "profit" on the Road Department administrations in decision making. When the value under the criterion changes to - 100%, it means that the operation of the candidate ETC will turn into a loss state. The corresponding satisfaction change shows the huge psychological gap of the Road Department administrations. On the contrary, under the criterion called "volume", the satisfaction does not change much.

It should be noted that the values under the "capacity" criterion vary in all three tables, which means that the criterion has a wide range of functions. According to the research results in sections 5.2, 5.3 and 5.4, the candidate ETC systems used the same type of readers, which made their influence on the traffic capacity of ETC lanes consistent.

CHAPTER SIX: SUMMARY AND IMPLICATIONS

6 Overview

This thesis made a deep research into the decisions of ETC selection and its influencing factors under the traffic background of China's highways. The central research question of this paper was: how do the RFID technical parameters affect the performance of the ETC system, and how do they affect the decisions of decision makers? The basic goal of this study was to establish a conceptual framework to illustrate the possible impact of RFID technical parameters on the selection of ETC systems. To solve this research problem and achieve the research goal, a comprehensive review of the potential theoretical and theoretical literature was carried out. In Chapter 2, some relevant directions for determining the factors affecting the performance of ETC systems were studied. In Chapter 3, a design method for decision model development was proposed, and an interview protocol was issued to better understand the decision-making process of Road Department administrations. In addition, a 6-point semantics method was established to define the respondents' evaluation of ETC attributes to determine the degree of support for decision-making schemes. Because this research was devoted to the study of the decision-making process, Chapter 4 built a decision support model based on the third chapter. The decision support model is based on a multi-criteria decision support framework, which weighted each criterion after the performance evaluation. This finding was concluded in this chapter and proposed theoretical and practical significance as well as the contribution of research. At the end of this chapter, the limitations of the study and future research directions are discussed.

6.1 Summary from answering research questions

To answer the research questions which were listed in Chapter 1, I studied the ideological activities of Road Department administrations in ETC systems selection and the evaluation of various decision-making factors from the concept, process and results of decision activities. At the same time, the concerns mentioned in the research questions were explored and discussed one by one, and the following findings are elaborated.

For the first research question, "*What factors influence the choice of ETC systems? How do they affect ETC systems?*", this study listed three factors: ETC attributes, road environment and road policies.

Limited by the research scope in Chapter 1, I focused on the influence of ETC attributes, and found in the performance evaluation process:

1) The profits of ETC systems depend on road revenue and cost (O'Sullivan, 2003); Cost calculation comes from planned, unplanned and persistent costs; The theory and calculation of this work were introduced in Section 4.4.1.

2) The performance of ETC in traffic management depends on the capacity of ETC lanes; Chapter 4 found that the speed of vehicles in toll stations and the installation procedure of readers on ETC traffic lanes determined the ETC capacity.

3) In the aspect of ETC compatibility of safety design, this research focused on anti-collision design and data encryption design; This mainly depends on the protocol of information transmission; Meanwhile, this limitation also narrows the scope of selection to a sample database.

4) The DSS design work in Chapter 4 also found that the reliability of ETC tags depended on the tag material and volume, and there was a priority between these two elements; It should pointed out that the volume of tags is lower priority, its value should as large as possible but must meet the standards proposed by the Ministry of Transportation (ITS China, 2014); This evidence also supported in the demonstration work of Chapter 5.

5) The tag life mainly depends on the power supply of the on-board equipment. The demonstration work in Chapter 5 found that the power supply design of lithium batteries on Tag 14 will bring the most acceptable performance.

These five performance evaluations generated the performance value by ruling of criteria under road administrations' requirements. ETC attributes of cost of tags, vehicle speed limit in toll stations, ETC reader installation, material design of the ETC tag, ETC tag volume, anti-collision protocol, data encryption protocol and power supply design of the ETC tag, are driving performance evaluation in five situations.

In addition, other factors are road environment and road policies. They were frequently mentioned in this research but are not within the research scope because the Road Department administrations are not able to change their values. All those non-ETC factors (road environment and road policies) provided important support information to influence the decision making and can bring changes on performance evaluation outcomes.

1. Chapter 4 provided a detailed answer to the second research question, "How can we create a DSS model to establish the relationship between those factors, and to address Road Department administrations' requirements?".

I found that Road Department administrations have multiple goals when selecting the appropriate ETC system. These sub-objectives are independent and incommensurable, and will produce the final comprehensive results, thus they have formed independent performance evaluation. In this study, I divide those objectives of decision making into five types: profits, traffic management, reliability, compatibility and tag life. After performance evaluation, criteria under the Road Department administrations' requirement were generated as constraint and optimization. Constraint criteria are marked as "Yes or No" features, and optimization criteria are weighted by the entropy method for decision outcome calculation.

Many methods and technologies were used in the model creation approaches:

Through expert-based interviews, I obtained information from the participants about the objectives of decision making and the main factors affecting decision activities. In Chapter 3, I gave a detailed description and analysis of these objectives and factors. In response to the requirements (sub-objectives) of the Road Department administrations, I organically combined the ETC attributes affecting decision making and the relationship between requirements. These combinations show that performance evaluation met the sub-objectives of decision making. Road Department administrations need to consider the impact of ETC attributes on performance evaluation in response to these requirements.

Based on this study, I set five performance evaluations, and each performance evaluation accomplished a sub-objective. The final decision result merged all decision objectives to produce an ETC system that had maximum satisfaction of Road Department administrations.

In the process of building the decision support model, I used 6-point semantics in interviews to determine the importance of ETC attributes in performance evaluations through participants' tone intensity in order to determine whether the ETC attribute was involved in a performance evaluation. 6-point semantics were also used to determine the importance of criteria in criteria weighting.

The decision support model was created in this study by using a muti-criteria decision method. The development of the model was implemented in Chapter 4, and a detailed description of each performance evaluation was provided. The performance evaluation included the evaluation based on profit, the evaluation based on traffic management, the evaluation based on reliability evaluation, the evaluation based on compatibility and the evaluation based on ETC tag life. The outcomes from those performance evaluations determined the characteristics of the criteria. I followed the decision-making approach in section 3.2, using the entropy method to calculate the criterion weights from collected 6-point semantics data.

Normalization (discussed in section 3.2.4) was used to structure the results of performance evaluation and provided a unified sense to the performance value of decision-making.

Chapter 5 provided a detailed answer to the third research question, "How can we assess the proposed decision support system and how do we determine whether the results of its implementation meet the user's expectations?". The decision-making model created in Chapter 4 was demonstrated and evaluated in that section, to judge whether the decision-making model met the expectations of the Road Department administrations. These works first used assumptions to the stated road environment and road policies, to scope the data range of performance evaluation. Then, I transformed direct data from the road environment as the decision inputs. By using the regulations provided in the assumptions, the performance evaluation outputs were issued in five aspects. The Road Department administrations’ final demonstration was used to obtain constraint and optimization from the perspective of decision support, to determine whether the model met its expectations. The main purpose of sensitivity analysis was to determine the relationship between criteria issued by the demonstration and the satisfaction of Road Department administrations, to analysis the influence of criteria and thresholds.

In the demonstration work, I extracted three cases from real world projects. There are different road environments among these cases, but road policies are the same. I tried to find the possible deviations in the demonstration results through these differences. In the analysis of these cases, some traffic information was entered into the decision-making model which was created in Chapter 4. These data include traffic volume, conversion coefficient and other data assumptions. Meanwhile, ETC attributes in the decision-making model were also introduced into these cases in the form of variables. When I had completed the data that I needed, the decision model was introduced into these cases in the form of formulas and produced consistent results. The demonstration results show that all cases can produce consistent decision-making results, which are like the ETC parameters used in real practice. Demonstration results proved that the decision model has features in generality, high priority constraints and the road environment drives optimization.

Sensitivity analysis comes from changing the value of a criterion, which mainly obtains the Road Department administrations' satisfaction value from five aspects: profits, traffic management, reliability evaluation, compatibility evaluation and tag life. The results of changes show how a single criterion affected the satisfaction value of the Road Department administrations. The obtained ratings were normalized and simplified as the data of percentage and the final results show that the decision model has features of high sensitivity, limited by threshold and weights of criteria.

6.2 Theoretical and practical implications

Findings used to answer the research question have theoretical and practical significance.

Theoretical implications: Essentially, the literature review described the basic elements of decision making: decision factors and decision methods. ETC selections usually took place in the procurement activities, which made it easier for the researcher to determine the decision-making process and definition of decision makers. In China, the decision makers are the Road Department administrations. A Road Department administration is a type of organization which includes the local transportation department and road administration and is responsible for road equipment procurement. Thus it was easily to clarify the source of the decision information. The literature review provided three types of information about the factors that influence decision making: ETC attributes, road environments and road policies. This means that any decision-making activities in this study must depend on the road environments and current policies in China, and then evaluate whether the ETC attributes meet the requirements of the Road Department administrations. Obviously, the road environments and road policies can affect the decision making but cannot be changed by the Road Department administrations, this was proven in Chapter 5. Chapter 4 is based on the decision-making framework which was created in the Chapter 3, and proposed five performance evaluations as the related requirements of the Road Department administrations: profit calculation, traffic management evaluation, reliability evaluation, compatibility evaluation and tag life evaluation.

The profits of ETC systems depend on road revenue and cost (O'Sullivan, 2003). Cost calculation comes from planned, unplanned and sustained costs. The theory and calculation of this part of the information were described in detailed analysis. In addition, many early researchers have also done corresponding research. On the other hand, the revenue of highways also depends on traffic capacity. I believed when the road capacity increased, the traffic volume of toll stations increased accordingly and will bring considerable revenue. Chapter 4's research analyzed the possible operating conditions of toll stations and developed a profit calculation equation. The above two aspects are the positive significance of this study, but a single aspect, calculation, cannot assist the generated performance evaluation results (the potential profits of a specific ETC system). Based on this problem, Chapter 4 and Chapter 5 combined two aspects to produce a unified equation which can help the Road Department administrations calculate the approximate profits.

ETC lane capacity is an important criterion to measure the traffic management and environmental benefits. According to the concerns of the Road Department administrations, I believe that it is necessary to classify this evaluation into a separate performance evaluation and to incorporate its outcome into the design of the decision-making model. More accurately, the capacity of the toll station determines the capacity of the highway. After the analysis of the operational characteristics of toll stations, I believed that the deceleration entering the toll station, the speed in the toll gates and the acceleration leaving the toll station determined the toll station's capacity. More importantly, the speed of vehicles also can affect the transaction times, and thus made speed a key attribute affecting the decision making. In Chapter 4, I discussed two possible situations and possible values of this vehicle speed. Similarly, in terms of ETC reader installation, I used signal coverage and ETC lane width to determine the cost-benefits of the ETC equipment and discussed possible limitations of road policies. Chapter 4 explored this performance evaluation in depth and incorporated the performance value of this evaluation into the decision-making model development.

In contrast, the study of reliability depended on the experimental analysis, which is different from the theoretical support provided by the literature (Gu, 2018). The experiment results of reliability have more objectivity. In this study, the initialization settings and environment of the experiment were provided, and the collected samples are explained in Chapter 4. When I converted the experimental results into the output of the test samples, the corresponding decision tree was created. This decision tree can intuitively provide the priority of ETC tag material design from different features. That is, the system is considered meaningful and reliable only if the tags were moisture-proof designed and satisfied for reasonable size.

As with economic benefits, the safety design of ETC tags is also based on existing research. Through research on section 4.4.4, I believe that the safety of an ETC system mainly depended on the compatibility of protocols, which required ETC designers to layout the functions of the system in advance. The anti-collision and data encryption of vehicle tags also affects the safety of the system (He, 2018). The anti-collision scheme proposed by section 4.4.4 determined that the recognition distance and capacity are constant according to the characteristics of the RFID reader. It can be concluded that the recognition period is inversely proportional to the moving speed. When the vehicle moves too fast, the ETC system will fail to respond, because not enough time is allowed for anti-collision. This performance evaluation environment also provided the methods for the compatibility evaluation of safety protocol. That is, for any ETC uses, tags must be able to work under the protocol of ISO/IEC 18000-6C and EPC Class 1 Gen 2.

Performance evaluation provided the tag life evaluation to calculate the annual power consumption. I can use this annual power consumption value to determine the possible tag life. This is the theoretical significance in that performance evaluation.

The above five performance evaluations generated the outputs used to determine the characteristics of criteria. Criteria on decision making are profit, capacity of ETC lane, tag life, tag volume, moisture proof design and compatibility. And all these criteria have value characteristics of Maximum, Threshold, Max order and Yes/No (discussed in **section 4.5.1 and 4.5.2**). Section 4.5.4 pointed out that constraint criteria were used to limit the selection scope and will be first evaluated by decision makers. The other criteria were used to weight for optimization.

Practical implications: Practical implications mainly came from the process of information collection, decision-model creation, demonstration, and sensitivity analysis, that is how I followed the decision framework which was developed in section 3.2. Marakas (2003) indicated that any decision-making system development must follow the design approaches: 1. Identifying and diagnosing decision problems. 2. Targeting decision objectives. 3. Developing alternative solutions. 4. Evaluating alternatives and selecting solutions. 5. Implementing decision making. 6. Evaluating decision results. Then I referred MilenkoviT (2018)'s research and developed the decision-making approach of Figure 3.1. By following this framework, selected technologies and methods (concluded in follow paragraphs) were used in decision-model creation, and this work has practical significance.

Both qualitative and quantitative methods were used to collect information from expert-based interviews. Pilot studies were conducted on a small number of sample participants (1 ETC technical expert, 1 Toll-road manager and 1 Government transportation department expert) to improve the questionnaires. I used semi-structured questions to confirm information of requirements, criteria and ETC attributes. Structured questions were used in following interviews to collect the elements (requirements, criteria ranks and performance) of decision making.

Performance evaluation was developed for transforming the original data from ETC attributes to the performance value per criteria. This process also indicated the characteristics of the criteria. These performance evaluation environments were established for 1. Determining the requirements of the Road Department administrations, which are the objectives of the related performance evaluation; 2. Determining the attributes of ETC systems that participated in this performance evaluation; 3. Determining how performance was evaluated under this requirement. The data generated by each performance evaluation environment are more objective and independent of participants' subjective emotions and preferences. I used normalization to quantify the performance values into a unified standard (discussed in section 3.2.4).

A 6-point semantics method was used in expert-based interviews to determine the importance of a criterion in decision making, divided it into six levels by tone strength. The entropy method was used for analysis work, to calculate the weight of each criterion.

In decision model development, I used a multi-criteria method to develop the decision-making model as this study has characteristics on 1. Road Department administrations have multiple requirements for candidate ETC systems, which determined that decisions have multiple sub-objectives; 2. Each sub-objective has no uniform measurement standard or criteria and is difficult to compare; 3. There are contradictions between decision-making sub-objectives. 4. Quantitative and qualitative methods can be used to obtain weights and ranks in our study.

I demonstrated the decision model as an approach in Chapter 5. After running the model in three real-world projects, the results show that the outputs of the decision model are consistent with the parameters of ETC systems in the real world. This indicated that decision activities have characteristics of generality, priority of constraints and road environment limited optimization decisions.

Sensitivity analysis was used in this study to find the influence of decision factors on the optimization results, to 1) discuss the influence of decision criteria on satisfaction value and 2) discuss the impact of threshold (discussed in section 5.6.2) after demonstration work. Results show that the decision model has characteristics of 1) sensitivity by criteria drive. 2) sensitivity by threshold influence. 3) Weights are important to the sensitivity of both most critical and least critical decision criteria.

6.3 Overall contributions

This research has contributed in many ways to the application of transportation. Most importantly, in the research of a decision support system, the decision-making model was developed according to the existing theories to achieve the expectations of the Road Department administrations. This confirms various contributions. There is a consistent detailed description of the validation of the main findings.

In theory, this study summarizes the requirements of the Road Department administrations for ETC systems, and better understands the expectations and objectives of selecting an ETC system. As mentioned earlier, profit, traffic management, reliability, compatibility and ETC tag life explain the behaviour of Road Department administrations in the decision-making environment through performance evaluation. These decision-making behaviours need to participate in ETC attributes, and this study also clearly described the characteristics of these ETC attributes and how they join in the performance evaluation. However, starting with performance evaluation, this study subdivides the scope of the ETC attributes and finds the relationship between decision objectives and these ETC attributes in a variable way. Therefore, this study is helpful to understand the general nature of these theories and extend their RFID technical characteristics to the application of the decision support system.

A review of the literature (as summarized in Chapter 2) shows the consistency of information, and I reached a consensus with the interviewees on the requirements of the decision-making environment and ETC attributes. In the literature review, I consulted a lot of information about the impact of ETC attributes on decision making, but most did not provide an intuitive definition, for example, which ETC attributes participate in the performance evaluation, and which are ignored. Therefore, this study used a 6-point semantics method to screen the information provided by the participants of the expert-based interviews. In addition, in the second chapter, a few studies confirm the role of ETC attributes and are included in the development of the decision support model. These are new and solid contributions to the development method of decision model.

Essentially, since most of the existing decision-making studies have investigated the opinions of the Road Department administrations, they have contributed to the literature by comparing the evaluation of ETC attribute participation in decision making, especially in a variety of decision-making environments.

Most importantly, structured interview data helps to understand the details of ETC attributes participating in decision making. These attributes are subdivided and enhanced in the actual decision-making process, and sometimes further studied in the context of similar cost analysis. However, although these data are professional and helpful to verify detailed concepts, in the decision-making process, they are only part of the reverse study through literature review.

When the details of each performance evaluation and the ETC attributes which were involved in these evaluations were studied extensively, it is particularly important to develop an overall and generalized decision support model. In particular, although individual performance evaluation has been used in other studies to measure the performance of some ETC systems, a multi-criteria structure decision support model has been developed in this research. Referring to the research of MilenkoviT (2018), this model combined the decision support model of Chapter 4 and provides a new method of researching the decision theory of the transportation industry through constraint and optimization expression. The demonstration is carried out by extracting relevant product information from the market, introducing it into the formula of the decision-making model for simulation calculation, and generating the optimal results for discussion by the Road Department administrations to obtain their approval. The results of demonstration work show that decision-making activities achieved the expectations of the Road Department administrations and can be adapted to most road projects. After taking these measures, this study ran a sensitive test, evaluating the variables in the optimization equation by changing a fixed value under a criterion, to determine the changes of the Road Department administrations' satisfaction. All measures and developments in the decision model are contribution discoveries, which provide convenience for future decision making of decision makers.

It can be said that the research and application of the related RFID technology knowledge in ETC system and the related methodology in DSS belong to the two main theoretical directions of this study. Systematic studies of academic contributions show that up to now, no other literature has conducted a comprehensive discussion and research in this field. Therefore, this study is helpful to fill in the gaps in this field as far as possible. The following table briefly summarizes these contributions.

Table 6.1 Contribution of this research

A. Theoretical Contribution	
Decision factors and decision makers	This study defined the decision factors which are ETC attributes, road environment and road policies. Road Department administrations are decision makers in ETC selection, who (1) decide what ETC system is appropriate, that is, they put forward the requirements for decision making; (2) are responsible for taking expert-meetings and determining suitable evaluation criteria.
Performance evaluation for profit calculation	The profits of ETC systems depend on road revenue and cost. Cost calculation comes from predictable, unpredictable and sustained costs; Traffic volume determines the road revenue. As this research only focused on the profit of ETC systems, this is different with other research.
Performance evaluation processes for traffic management	This study identified the factors that affect toll station capacity, including the deceleration of vehicles entering the toll station, the speed of vehicles trading at the toll station and the acceleration of vehicles leaving the toll station. At the same time, this study discussed several schemes of ETC reader installation. Under these schemes, toll station capacity can be switched as different performance. Other similar research has not been discussed with this performance evaluation.
Performance evaluation processes for reliability evaluation	According to the advantages of the decision tree, this research designed a model to evaluate the reliability of ETC systems. According to our queries on mainstream literature databases and search engines, there is no literature focusing on this area at present.
Performance evaluation processes for compatibility evaluation	Under the ISO/IEC 18000-6C and EPC Class 1 Gen 2 protocols, anti-collision design and data encryption protocols are discussed in Chapter 4. Reference to the existing research was summarized and formulated. The results of these performance evaluation process are generated as Yes/No criteria. This is not discussed in other research
Performance evaluation processes for battery usage for ETC tags	A large amount of literature has explained the relationship between ETC tag battery life and daily power consumption, and the formulaic expressions of this relationships are consistent. However, these operations are not included in decision making, but rather as an unavailable part of technical analysis. In this study, it is introduced into the decision-making model, that is, the impact of weights for criteria. This is the first time in this area.
Multi-criteria decision-making model development	Five performance evaluations generated by the outputs have been used to determine the performance value and the characteristic of criteria: Profit，Capacity of ETC lane，Tag life，Tag volume，Moisture proof design and Compatibility. And all these criteria have value characteristics of Maximum, Threshold, Max order and Yes/No. Section 4.5.4 pointed out that constraint criteria were used to limit the selection scope, and will be first evaluated by decision makers. The other criteria were used to weight for optimization. This is the first time in this research area.
Methodological Contributions	
Collected data from expert-based interviews	A large amount of literature provided ETC attributes that may affect the Road Department administrations in making decisions. Although this information is extensive, it is too fragmented due to its different research objectives. In this study, through in-depth interviews with experts, the expectations of the respondents on ETC systems and the ETC attributes affecting their decision making were determined. These attributes acted on their respective performance evaluations and achieved optimal results. As a pioneer, this study presents detailed information about these ETC attributes, and describes how they affect

	the decision making of the Road Department administrations under specific requirements.
Semantic Method	Semantic ratings of respondents and degree of importance are used in many studies. However, this kind of research is the first to obtain ETC attributes and participate in performance evaluation of the Road Department administrations.
Entropy method	The entropy method was used to determine the weight of each criterion in decision model development because 1.The differences suggested by experts will attract more attention from the Road Department administrations; 2. Experts come from a wide range of positions, and there are many kinds of decision-making suggestions; 3. The entropy method is suited for displaying these differences in weights calculation.
Experiment & C4.5	In Chapter 4, I used experiment to obtain the running state of the ETC samples. These running states were introduced into the C4.5 algorithm, and finally a decision tree was created to guide the Road Department administrations to pay attention to ETC tag material design and volume. I released this part of work in an international conference.
Model creation: multi-criteria method	I used a multi-criteria method to develop the decision-making model as this study has characteristics on 1. Road Department administrations have multiple requirements for candidate ETC systems, which determined that decisions have multiple sub-objectives; 2. Each sub-objective has no uniform measurement standard or criteria and is difficult to compare; 3. There are contradictions between decision-making sub-objectives. 4. Quantitative and qualitative methods can be used to obtain weights and ranks in our study.
Normalization	The data generated by each performance evaluation environment are more objective and independent of participants' subjective emotions and preferences. I used normalization to quantify these two types of data into a unified standard.
Contribution to real world applications	
Generality, Priority of constraints and road environment limited optimization decision.	I demonstrated a decision model in Chapter 5. After running the model in three real-world projects, the results showed that the output of the decision model is consistent with the parameters of ETC systems in the real world. This indicated that decision activities have characteristics of generality, priority of constraints and road environment limited optimization decisions.
Sensitivity	Sensitivity analysis was used in this study to find the influence of decision factors on the optimization results, to 1) discuss the influence of decision criteria on satisfaction value, 2) discuss the impact of thresholds (discussed in section 5.6.2) in the decision-making process. Results show that the decision model has characteristics of 1) sensitivity by criteria drive, 2) sensitivity by threshold influence, 3) weights are important to the sensitivity of both most critical and least critical decision criteria.

6.4 Limitations

This study investigated the impact of ETC attributes on the decision making of the Road Department administrations and established a decision support model. Although effective, the contribution of this study must be carefully considered, as this attempt based on Road Department administration evaluation is rare and unique in the current research environment. However, in the field of ETC system application in China, the extensiveness of research fields and various external factors may potentially influence the research results. Future research is required to focus on how to incorporate it into the development of decision-making models and consider it. In addition, interviews in this study also discussed the impact of regional and economic factors not involved in the decision-making environment. Therefore, the existing problems arise as to what areas should be included in the research and what areas should be excluded. In view of these problems, the following important issues need to be carefully verified when attempting in-depth study:

The information obtained in the interview mainly comes from the subjective data of the respondents, not from vertical data with depth. This may not be an effective response to changes in the Road Department administrations' perceptions of existing ETC systems and a range of related situations over time. Subjective data may be influenced by the respondents' experience in using ETC systems in the past and their mental state.

This research discussed applications of ETC systems in China. The interviewees' evaluation of the use of ETC systems was also subject to existing traffic conditions in China. This helped to broaden the data, but it must also have been constrained by the limitations of China's traffic regulations. Due to the rapid development of China's economy, the corresponding traffic regulations are also changing, and research in this field needs to adapt to this situation.

This study is based on the RFID technology of ETC systems and combines the feedback of experts as the research data. This may not have been able to explore the overall ETC systems from other aspects. For example, the level of regional economic development may affect the road traffic flow, leading to a gap of road revenue in different regions. Regional economic factors may be important in assessing the economic benefits of ETC systems.

Data on ETC attribute participation of the Road Department administrations in decision making were collected, which may not reflect the evaluations of persons who were not invited into this research.

Information was collected from face-to-face interviews independently. Due to resource and time limitations, it was difficult to organize group discussions to collect information. This made it impossible for respondents to communicate with each other and may lead to differences of understanding.

While acknowledging these limitations, this study shows an effective understanding of Road Department administration decision making. This study demonstrated a decision-making model. It also highlighted how the Road Department administrations strive to choose a suitable ETC system.

6.5 Future research directions

Because research has regarded the choice of ETC systems in China as a neglected field in current academic research, some insights and directions are provided for the research field of DSS. More specifically, this study attempts 1) to study the technical attributes of RFID in ETC systems and the impact of these attributes on the decision making of the Road Department administrations, 2) to quantify some quantitative and qualitative data on the subjective views of some experts in decision meeting, 3) and to develop a comprehensive decision-making model combined with existing technical literature. This provides a solid foundation for many research approaches, so some suggestions for further research are put forward.

Firstly, from the perspective of ETC technical attributes, this study envisages an ideal decision environment. That is to say, the planning of road construction conforms to the economic development of a region. This means that the capacity of the road meets the expected traffic flow. This also shows that government transportation department experts involved in road planning regard the upper limit of road capacity as an indicator of the expected value of traffic flow. However, feedback from some Road Department administrations yielded the opposite result. In particular, toll road managers from the expert-based interviews believed that traffic flow is constrained by local economic development, and government transportation department experts involved in the road often neglect this problem, resulting in waste of resources. Therefore, in the economic context of different regions, detailed research can be further promoted. In addition, the change of traffic volume with time cannot be ignored. Changing road conditions often lead to a gap between expected income and reality. Detailed studies in this area need to refer to relevant data of economics and statistics.

Secondly, it is more important to consider the importance of ETC attributes affecting the Road Department administration's decision making by incorporating a variety of views of respondents into the study. Therefore, in the future research direction, introducing comparison and contrast into the questionnaire survey would be very attractive. In addition, the longitudinal data may be more authentic to verify the results of the study.

Thirdly, because the factors affecting the reliability of ETC systems have been emphasized in the existing literature, this study proposed for the first time an experimental measurement method and, combined with the running state of samples, introduced the C4.5 operation, and generated a decision tree This can be included in any future research model, more specifically extracting samples from various factors of the external environment, and classifying ETC tag design. From the perspective of decision support theory, this may be interesting.

Finally, this study incorporates general traffic conditions and existing traffic regulations to examine the precedents of Road Department administration decision making. More representative, however, it has been found that some findings have been affected by road environments and road policies. Therefore, these also affect the decision making. In other words, considering traffic regulation and policy changes should be included in further research.

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Appendix

Appendices include the documents used in expert-based interviews, while I was following the approaches in Figure 3.1.

Those documents are:

- Invitation letter.
- Participant information sheet.
- Consent form.
- Expert-based questionnaire.

It should be ed out that every document has a related Chinese translation, and there was no difficulty communicating with those experts.

Appendix 1 Invitation letter

Dear Colleagues

I would like to thank you sincerely for volunteering your kind assistance with research being undertaken at your toll collection station. I would like to conduct my research project at your working place. My research topic is "**A useful decision model for ETC selection**"

This research project will involve a face to face interview with road administrators. The information obtained will be treated with the strictest confidentiality and will be used solely for this research purposes only.

Before commencing with any data collection exercise I will first come to your station and explain the research and what participant's role will be.

I will explain how I will go about the interviews and how information recordings will be done. I would like to thank you in assisting me in this research. I hope that the information obtained from this research will benefit you most in identifying different strategies and decision making in future ETC selections.

Yours sincerely

If you are willing to participate in this study, please sign this letter as a declaration of your consent, i.e. that you participate in this project willingly and that you understand that you may withdraw from the research project at any time. Under no circumstances will the identity of interview participants be made known to any parties/organizations that may be involved in the research process.

Researcher's signature ....:
Date: ....

Participant's signature..:
Date: ....

Yours Sincerely

Appendix 2 Participant information sheet

Participant Information Sheet

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Date Information Sheet Produced:

23/01/2017

Project Title

A useful decision - support model for ETC selection

An Invitation

Hello, my name is Yu Gu and I am current studying for a PhD in computer and information sciences at AUT

What is the purpose of this research?

We would like to develop a useful decision support model for road owners to select electronic toll collection (ETC) systems. We would also like to investigate factors that affect road owners selecting Electronic toll collection (ETC) systems.

How was I identified and why am I being invited to participate in this research?

You have been chosen because you are an ETC designers or other staffs who have background and experience to develop the electronic toll collection (ETC) system.

What will happen in this research?

You will be invited to participate based on when the sessions can be organised, I will send a quick welcome and information about the interview, and an explanation of what will happen. I will then come to your working place (highway toll collection station) and go through a short interview - based around your electronic toll collection (ETC) system's performance and your requirements and advice with this system.

You shall be under no pressure throughout the entire session as this research is focusing on your experience of using the software and device, not your individual performance. All data collected will be only accessible for the researcher and his supervisor. Your identity will be anonymous in the written report.

Your participation is fully voluntary. You may withdraw yourself at any time during data collection and all data will be destroyed.

How do I agree to participate in this research?

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What are the discomforts and risks?

None, this study designed a face to face interview that will take around 1 hours total. Participants only need to answer questions which were provided by researchers. There is no any discomforts and risks.

How will these discomforts and risks be alleviated?

N/A

What are the benefits?

- To identify what road owners' requirements in future electronic toll collection (ETC) system selection.
- To identify what issues that affect Electronic toll collection (ETC) systems' performance.
- To explore suitable decision support methods associated with the ETC selection in a specific working environment
- This project will assist researcher to obtain the PhD degree.

How will my privacy be protected?

The researcher and teacher/lecturer will assure the confidentiality of the participants. All participants' names will not be mentioned in the report. There will be no video recording or audio recordings of interviews. They will be referred to as, e.g. as A, B or C and the toll collection station will be referred to as station A, B, C etc. There is no information will be obtained from third parties. All the data collected will be securely stored and is only accessible for the researcher and his supervisor.

What are the costs of participating in this research?

A session of interview will take around 1 hours total.

How do I agree to participate in this research?

Please complete the consent form and return it within a week. .

Will I receive feedback on the results of this research?

The results and discussion sections will be sent to you either electronically or by post upon request. Summary of findings will be shared and disseminated with the participants as they are produced during the research in form of scholarly articles (conference or journal papers and thesis) to the participants wishing to receive such feedback.

What do I do if I have concerns about this research?

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 0064 921 9999 ext 6038.

Whom do I contact for further information about this research?

Project researcher and supervisor contact details:

Researcher: Yu Gu Email <Yudepassport@msn.com>	Supervisor: Dave Parry dparry@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on *type the date final ethics approval was granted*, **AUTEC Reference number** *type the reference number*.

Appendix 3 Consent form

CONSENT FORM

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Project title: **A useful decision - support model for ETC selection**

Project Supervisor: ***Dave Parry***

Researchers: *Yu Gu*

- ○ I have read and understood the information provided about this research project in the Information Sheet dated ______________________
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that notes will be taken during the interviews.
- ○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ○ If I withdraw, I understand that all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- ○ I agree to take part in this research.
- ○ I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant Signature : ....

Participant Name : ....

Date :

Appendix 4 Questions for Pilot interviews

This questionnaire was prepared for improve question items in later interviews.

Q1. In your experience, what requirements were often put forward by Road Department administrations?

Q2. In your experience, what ETC attributes were often put forward by ETC manufacturers?

Q3. When you make decisions to select suitable ETC systems, which criteria are usually considered?

Appendix 5 Questionnaire

Aim: This questionnaire will collect information from experts who have experience in decision making, to complete following sub-goals：

- Determine the participation of ETC attributes
- Determine the importance of each criterion

Part 1： Key information Confirmation

Q1a. What is the category of your work?

A. ETC technical expert

B. Toll-road manager.

C. Government transportation department expert.

Q1b. In your experience, what requirements were often put forward by Road Department administrations?

A. Profits,

B. Efficient traffic management,

C. Reliability,

D. Compatibility of safety design

E. Long tags life.

Specify other requirements.________________________________

Q1c. In your experience, what ETC attributes were often put forward by ETC manufacturers?

A Costs

B Working frequency

C Vehicle speed limits

D Installation procedures

E Material

F Size of tags

G Battery design of ETC tags

H. Anti-collusion configuration

I. Encryption Protocol constraint

Specify other ETC attribute.________________________________

Q1d. When you made decision to select suitable ETC systems, which criteria were usually considered?

A. Profit

B. Capability

C. Moisture-proof design

D. Compatibility

E. Tag volume

F. Tag life

Specify other criteria.________________________________

Q1e. How long have you been doing this job?

A. 1-2 years

B. 2-5 years

C. 5-10 years

D. More than 10 years

Part 2：Participation of each ETC attribute

Q2a. In your experience, if Road Department administrations want a candidate ETC system with good performance of profit, what ETC attributes should be considered in this decision-making environment?

I believe that costs of ETC systems should be considered in profit calculation.	0	1	2	3	4	5
I believe that working frequency of ETC systems should be considered in profit calculation	0	1	2	3	4	5
I believe that vehicle speed limits of ETC systems should be considered in profit calculation	0	1	2	3	4	5
I believe that installation procedure of ETC systems should be considered in profit calculation	0	1	2	3	4	5
I believe that material of ETC tags should be considered in profit calculation.	0	1	2	3	4	5
I believe that size of ETC tags should be considered in profit calculation.	0	1	2	3	4	5
I believe that battery design of ETC tags should be considered in profit calculation.	0	1	2	3	4	5

I believe that anti-collision configuration should be considered in profit calculation	0	1	2	3	4	5
I believe that encryption protocol constraint should be considered in profit calculation.	0	1	2	3	4	5

Q2b. In your experience, if Road Department administrations want a candidate ETC system with efficient traffic management, what ETC attributes should be considered in this decision-making environment?

I believe that costs of ETC systems should be considered in efficient traffic management.	0	1	2	3	4	5
I believe that working frequency of ETC systems should be considered in efficient traffic management	0	1	2	3	4	5
I believe that vehicle speed limits of ETC systems should be considered in efficient traffic management	0	1	2	3	4	5
I believe that installation procedure of ETC systems should be considered in efficient traffic management	0	1	2	3	4	5
I believe that material of ETC tags should be considered in efficient traffic management.	0	1	2	3	4	5
I believe that size of ETC tags should be considered in efficient traffic management.	0	1	2	3	4	5
I believe that battery design of ETC tags should be considered in efficient traffic management.	0	1	2	3	4	5
I believe that anti-collision configuration should be considered in efficient traffic management	0	1	2	3	4	5
I believe that encryption protocol constraint should be considered in efficient traffic management.	0	1	2	3	4	5

Q2c. In your experience, if Road Department administrations want a candidate ETC system with reliability, what ETC attributes should be considered in this decision-making environment?

I believe that costs of ETC systems should be considered in reliability.	0	1	2	3	4	5
I believe that working frequency of ETC systems should be considered in reliability	0	1	2	3	4	5
I believe that vehicle speed limits of ETC systems should be considered in reliability	0	1	2	3	4	5
I believe that installation procedure of ETC systems should be considered in reliability	0	1	2	3	4	5
I believe that material of ETC tags should be considered in reliability	0	1	2	3	4	5
I believe that size of ETC tags should be considered in reliability.	0	1	2	3	4	5
I believe that battery design of ETC tags should be considered in reliability.	0	1	2	3	4	5

I believe that anti-collision configuration should be considered in reliability	0	1	2	3	4	5
I believe that encryption protocol constraint should be considered in reliability.	0	1	2	3	4	5

Q2d. In your experience, if Road Department administrations want a candidate ETC system with compatibility of safety design, what ETC attributes should be considered in this decision-making environment?

I believe that costs of ETC systems should be considered in compatibility of safety design.	0	1	2	3	4	5
I believe that working frequency of ETC systems should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that vehicle speed limits of ETC systems should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that installation procedure of ETC systems should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that material of ETC tags should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that size of ETC tags should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that battery design of ETC tags should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that anti-collision configuration should be considered in compatibility of safety design	0	1	2	3	4	5
I believe that encryption protocol constraint should be considered in compatibility of safety design	0	1	2	3	4	5

Q2e. In your experience, if Road Department administrations want a candidate ETC system with long tag life, what ETC attributes should be considered in this decision-making environment?

I believe that costs of ETC systems should be considered in tag life evaluation.	0	1	2	3	4	5
I believe that working frequency of ETC systems should be considered in tag life evaluation.	0	1	2	3	4	5
I believe that vehicle speed limits of ETC systems should be considered in tag life evaluation.	0	1	2	3	4	5
I believe that installation procedure of ETC systems should be considered in tag life evaluation.	0	1	2	3	4	5
I believe that material of ETC tags should be considered in tags life evaluation.	0	1	2	3	4	5
I believe that size of ETC tags should be considered in tags life evaluation.	0	1	2	3	4	5
I believe that battery design of ETC tags should be considered in tags life evaluation.	0	1	2	3	4	5

I believe that anti-collision configuration should be considered in tag life evaluation.	0	1	2	3	4	5
I believe that encryption protocol constraint should be considered in tag life evaluation.	0	1	2	3	4	5

Part 3：Importance of each criterion

Q3a. In your experience, how importance of each criterion in decision making activities?

Profit	0	1	2	3	4	5
Capability	0	1	2	3	4	5
Moisture-proof design	0	1	2	3	4	5
Compatibility	0	1	2	3	4	5
Tag volume	0	1	2	3	4	5
Tag life	0	1	2	3	4	5

Part 4：Supplementary information from participants

Q4a. For the additional ETC attributes you provided in Part 1, please indicate the extent to which it participates in decision making under each requirement that was requested by Road Department administrations.

Q4b. For the additional Road Department administrations' requirements that you provided in Part 1, please indicate the participation of all listed ETC attributes in decision making under that requirement.

Q4c. For the additional criteria you proposed in Part 1, please rank the importance in comprehensive decision making.

Appendix 6 Ethics approval

Auckland University of Technology Ethics Committee (AUTEC)

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

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22 June 2018

Dave Parry
Faculty of Design and Creative Technologies

Dear Dave

Ethics Application: **17/122 A useful decision - support tool for road owners to select ETC systems**

On 14 June 2017 you were advised that your ethics application was approved.

I would like to remind you, that it was a condition of this approval that you submit to AUTEC the following:

- A brief annual progress report using the EA2 Research Progress Report / Amendment Form, available at http://www.aut.ac.nz/researchethics/forms, or
- A brief Completion Report about the project using the EA3 from, which is available online through http://www.aut.ac.nz/researchethics/forms. This report is to be submitted either when the approval expires on 14 June 2020 or when the project is completed;

It is also a condition of approval that AUTEC is notified if the research did not proceed or any adverse events occurring during the research. If there has been any alteration to the research, (including changes to any documents provided to participants) then AUTEC approval must be sought using the EA2 form.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please contact us at ethics@aut.ac.nz.

Yours sincerely

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: yudepassport@msn.com; Ajit Narayanan; pleong@aut.ac.nz

Appendix 7 Summary of information collection

This part of the content mainly collected feedback from participants in one-hour expert-based interviews. Questionnaires are provided in Appendix 5. Here, I collected the feedback from 28 experts in the form of tables for easy display and used them to support the development of the decision model in Chapter 4.

Part A： Answers to general questions:

Table 7.1 Answers of Q1a and Q1b in questionnaire.

Name	Job focus	Experience
Participant 1	ETC technical expert	5-10
Participant 2	ETC technical expert	2-5
Participant 3	ETC technical expert	1-2
Participant 4	ETC technical expert	1-2
Participant 5	ETC technical expert	1-2
Participant 6	ETC technical expert	1-2
Participant 7	ETC technical expert	1-2
Participant 8	ETC technical expert	1-2
Participant 9	ETC technical expert	2-5
Participant 10	ETC technical expert	1-2
Participant 11	ETC technical expert	2-5
Participant 12	ETC technical expert	1-2
Participant 13	ETC technical expert	1-2
Participant 14	ETC technical expert	1-2
Participant 15	ETC technical expert	1-2
Participant 16	Toll road manger	5-10
Participant 17	Toll road manger	5-10
Participant 18	Toll road manger	5-10
Participant 19	Toll road manger	5-10
Participant 20	Toll road manger	5-10
Participant 21	Toll road manger	5-10
Participant 22	Toll road manger	5-10
Participant 23	Government transportation department expert	More than 10
Participant 24	Toll road manger	5-10
Participant 25	Toll road manger	5-10

Participant 26	Toll road manger	5-10
Participant 27	ETC technical expert	1-2
Participant 28	ETC technical expert	1-2

Part B: Participation of each ETC attribute:

The following tables collected participants' feedback on the questionnaire in parts B and C in the one-hour expert-based interview. This feedback was scored based on the 6-point semantic method (Section 3.2.2, point 1).

Q2a. In your experience, if Road Department administrations want a candidate ETC system with good performance of profit, what ETC attributes should be considered in this performance evaluation?

Table 7.2 shows that all participants believe costs is the only ETC attribute to determine the profit. Other ETC attributes are not concerned.

Table 7.2 Answers of Q2a in questionnaire.

Name	Costs	Working frequency	Moving speed	Installation procedures	Material	Battery design of ETC tags	Anti-collision configuration	Size of tags	Encryption Protocol constraint
Participant 1	5	0	0	0	0	0	0	0	0
Participant 2	5	0	0	0	0	0	0	0	0
Participant 3	5	0	0	0	0	0	0	0	0
Participant 4	5	0	0	0	0	0	0	0	0
Participant 5	5	0	0	0	0	0	0	0	0
Participant 6	5	0	0	0	0	0	0	0	0
Participant 7	5	0	0	0	0	0	0	0	0
Participant 8	5	0	0	0	0	0	0	0	0
Participant 9	5	0	0	0	0	0	0	0	0
Participant 10	5	0	0	0	0	0	0	0	0
Participant 11	5	0	0	0	0	0	0	0	0
Participant 12	5	0	0	0	0	0	0	0	0
Participant 13	5	0	0	0	0	0	0	0	0
Participant 14	5	0	0	0	0	0	0	0	0
Participant 15	5	0	0	0	0	0	0	0	0

Participant 16	5	0	0	0	0	0	0	0	0
Participant 17	5	0	0	0	0	0	0	0	0
Participant 18	5	0	0	0	0	0	0	0	0
Participant 19	5	0	0	0	0	0	0	0	0
Participant 20	5	0	0	0	0	0	0	0	0
Participant 21	5	0	0	0	0	0	0	0	0
Participant 22	5	0	0	0	0	0	0	0	0
Participant 23	5	0	0	0	0	0	0	0	0
Participant 24	5	0	0	0	0	0	0	0	0
Participant 25	5	0	0	0	0	0	0	0	0
Participant 26	5	0	0	0	0	0	0	0	0
Participant 27	5	0	0	0	0	0	0	0	0
Participant 28	5	0	0	0	0	0	0	0	0

Q2b. In your experience, if Road Department administrations want a candidate ETC system with efficient traffic management, what ETC attributes should be considered in this performance evaluation?

Table 7.3 shows that all participants believe moving speed and installation procedures affect the performance of ETC traffic management. Due to ETC technical experts not being responsible to toll station management, they have no strong feelings of moving speed. Unlike ETC technical experts, toll road managers and transportation department experts strongly agree with the impact of these two ETC attributes on road management. Other ETC attributes are not concerned.

Table 7.3. Answers of Q2b in questionnaire.

Name	Costs	Working frequency	Moving speed	Installation procedures	Material	Battery design of ETC tags	Anti-collision configuration	Size of tags	Encryption Protocol constraint
Participant 1	0	0	3	5	0	0	0	0	0
Participant 2	0	0	3	5	0	0	0	0	0
Participant 3	0	0	3	5	0	0	0	0	0
Participant 4	0	0	3	5	0	0	0	0	0
Participant 5	0	0	3	5	0	0	0	0	0
Participant 6	0	0	3	5	0	0	0	0	0

Participant 7	0	0	3	5	0	0	0	0	0
Participant 8	0	0	3	5	0	0	0	0	0
Participant 9	0	0	3	5	0	0	0	0	0
Participant 10	0	0	3	5	0	0	0	0	0
Participant 11	0	0	3	5	0	0	0	0	0
Participant 12	0	0	3	5	0	0	0	0	0
Participant 13	0	0	3	5	0	0	0	0	0
Participant 14	0	0	3	5	0	0	0	0	0
Participant 15	0	0	3	5	0	0	0	0	0
Participant 16	0	0	5	5	0	0	0	0	0
Participant 17	0	0	5	5	0	0	0	0	0
Participant 18	0	0	5	5	0	0	0	0	0
Participant 19	0	0	5	5	0	0	0	0	0
Participant 20	0	0	5	5	0	0	0	0	0
Participant 21	0	0	5	5	0	0	0	0	0
Participant 22	0	0	5	5	0	0	0	0	0
Participant 23	0	0	5	3	0	0	0	0	0
Participant 24	0	0	5	5	0	0	0	0	0
Participant 25	0	0	5	5	0	0	0	0	0
Participant 26	0	0	5	5	0	0	0	0	0
Participant 27	0	0	3	5	0	0	0	0	0
Participant 28	0	0	3	5	0	0	0	0	0

Q2c. In your experience, if Road Department administrations want a candidate ETC system with reliability, what ETC attributes should be considered in this decision-making environment?

Table 7.4 shows that all participants believed working frequency, material and size of tags affect the performance of ETC reliability. ETC technical experts with short experiences are do not strongly realize other impact of working frequency. Unlike ETC technical experts, toll road managers, government transportation department expert and one ETC technical expert (long experience) strongly agreed with the impact of all these three ETC attributes on reliability. Other ETC attributes are not concerned.

Table 7.4 Answers of Q2c in questionnaire.

Name	Costs	Working frequency	Moving speed	Installation procedures	Material	Battery design of ETC tags	Anti-collision configuration	Size of tags	Encryption Protocol constraint
Participant 1	0	5	0	0	5	0	0	5	0
Participant 2	0	3	0	0	5	0	0	5	0
Participant 3	0	3	0	0	5	0	0	5	0
Participant 4	0	3	0	0	5	0	0	5	0
Participant 5	0	3	0	0	5	0	0	5	0
Participant 6	0	3	0	0	5	0	0	5	0
Participant 7	0	3	0	0	5	0	0	5	0
Participant 8	0	3	0	0	5	0	0	5	0
Participant 9	0	3	0	0	5	0	0	5	0
Participant 10	0	3	0	0	5	0	0	5	0
Participant 11	0	3	0	0	5	0	0	5	0
Participant 12	0	3	0	0	5	0	0	5	0
Participant 13	0	3	0	0	5	0	0	5	0
Participant 14	0	3	0	0	5	0	0	5	0
Participant 15	0	3	0	0	5	0	0	5	0
Participant 16	0	5	0	0	5	0	0	5	0
Participant 17	0	5	0	0	5	0	0	5	0
Participant 18	0	5	0	0	5	0	0	5	0
Participant 19	0	5	0	0	5	0	0	5	0
Participant 20	0	5	0	0	5	0	0	5	0
Participant 21	0	5	0	0	5	0	0	5	0
Participant 22	0	5	0	0	5	0	0	5	0
Participant 23	0	5	0	0	5	0	0	5	0
Participant 24	0	5	0	0	5	0	0	5	0
Participant 25	0	5	0	0	5	0	0	5	0
Participant 26	0	5	0	0	5	0	0	5	0
Participant 27	0	3	0	0	5	0	0	5	0
Participant 28	0	3	0	0	5	0	0	5	0

Q2d. In your experience, if Road Department administrations want a candidate ETC system with the compatibility of safety design, what ETC attributes should be considered in this decision-making environment?

Table 7.5 shows that all participants believed anti-collision design and encryption protocol constraints to determine the safety of an ETC system was essential. Other ETC attributes are not concerned.

Table 7.5 Answers of Q2d in questionnaire.

Name	Costs	Working frequency	Moving speed	Installation procedures	Material	Battery design of ETC tags	Anti-collision configuration	Size of tags	Encryption Protocol constraint
Participant 1	0	0	0	0	0	0	5	0	5
Participant 2	0	0	0	0	0	0	5	0	5
Participant 3	0	0	0	0	0	0	5	0	5
Participant 4	0	0	0	0	0	0	5	0	5
Participant 5	0	0	0	0	0	0	5	0	5
Participant 6	0	0	0	0	0	0	5	0	5
Participant 7	0	0	0	0	0	0	5	0	5
Participant 8	0	0	0	0	0	0	5	0	5
Participant 9	0	0	0	0	0	0	5	0	5
Participant 10	0	0	0	0	0	0	5	0	5
Participant 11	0	0	0	0	0	0	5	0	5
Participant 12	0	0	0	0	0	0	5	0	5
Participant 13	0	0	0	0	0	0	5	0	5
Participant 14	0	0	0	0	0	0	5	0	5
Participant 15	0	0	0	0	0	0	5	0	5
Participant 16	0	0	0	0	0	0	5	0	5
Participant 17	0	0	0	0	0	0	5	0	5
Participant 18	0	0	0	0	0	0	5	0	5
Participant 19	0	0	0	0	0	0	5	0	5
Participant 20	0	0	0	0	0	0	5	0	5
Participant 21	0	0	0	0	0	0	5	0	5
Participant 22	0	0	0	0	0	0	5	0	5
Participant 23	0	0	0	0	0	0	5	0	5
Participant 24	0	0	0	0	0	0	5	0	5
Participant 25	0	0	0	0	0	0	5	0	5
Participant 26	0	0	0	0	0	0	5	0	5
Participant 27	0	0	0	0	0	0	5	0	5
Participant 28	0	0	0	0	0	0	5	0	5

Q2e.In your experience, if Road Department administrations want a candidate ETC system with long tag life, what ETC attributes should be considered in this decision-making environment?

Table 7.6 shows that all ETC technical experts and toll road managers believe only battery design determines the performance of tag life. Other ETC attributes are not concerned. The government transportation department expert has not commented on this question, because his job is not concerned with ETC technical design problems.

Table 7.6 Answers of Q2e in questionnaire.

Name	Costs	Working frequency	Moving speed	Installation procedures	Material	Battery design of ETC tags	Anti-collision configuration	Size of tags	Encryption Protocol constraint
Participant 1	0	0	0	0	0	5	0	0	0
Participant 2	0	0	0	0	0	5	0	0	0
Participant 3	0	0	0	0	0	5	0	0	0
Participant 4	0	0	0	0	0	5	0	0	0
Participant 5	0	0	0	0	0	5	0	0	0
Participant 6	0	0	0	0	0	5	0	0	0
Participant 7	0	0	0	0	0	5	0	0	0
Participant 8	0	0	0	0	0	5	0	0	0
Participant 9	0	0	0	0	0	5	0	0	0
Participant 10	0	0	0	0	0	5	0	0	0
Participant 11	0	0	0	0	0	5	0	0	0
Participant 12	0	0	0	0	0	5	0	0	0
Participant 13	0	0	0	0	0	5	0	0	0
Participant 14	0	0	0	0	0	5	0	0	0
Participant 15	0	0	0	0	0	5	0	0	0
Participant 16	0	0	0	0	0	5	0	0	0
Participant 17	0	0	0	0	0	5	0	0	0
Participant 18	0	0	0	0	0	5	0	0	0
Participant 19	0	0	0	0	0	5	0	0	0
Participant 20	0	0	0	0	0	5	0	0	0
Participant 21	0	0	0	0	0	5	0	0	0
Participant 22	0	0	0	0	0	5	0	0	0
Participant 23	0	0	0	0	0	0	0	0	0

Participant 24	0	0	0	0	0	5	0	0	0
Participant 25	0	0	0	0	0	5	0	0	0
Participant 26	0	0	0	0	0	5	0	0	0
Participant 27	0	0	0	0	0	5	0	0	0
Participant 28	0	0	0	0	0	5	0	0	0

Part 3：Importance of each criterion

Q3a. In your experience, how important is each criterion in decision-making activities?

Table 7.7 shows all participants believe all criteria are important, all their ranks were above 3. Among them, moisture-proof design and compatibility have highest ranks of all participants, which is 5. This is same judgment with characteristics of criteria (section 4.5.2). This means moisture-proof design and compatibility are important constraints to satisfaction calculations (equation 4.5.4).

Table 7.7 Answers of Q3a in questionnaire.

Name	Profit	Capability	Moisture-proof design	Compatibility	Tag volume	Tag life
Participant 1	5	4	5	5	5	4
Participant 2	4	4	5	5	5	4
Participant 3	3	4	5	5	5	4
Participant 4	3	4	5	5	5	4
Participant 5	3	4	5	5	4	4
Participant 6	3	4	5	5	4	4
Participant 7	3	4	5	5	4	4
Participant 8	3	4	5	5	4	4
Participant 9	3	4	5	5	4	4
Participant 10	3	4	5	5	4	4
Participant 11	3	4	5	5	4	4
Participant 12	3	4	5	5	4	4
Participant 13	3	4	5	5	4	4
Participant 14	3	4	5	5	4	4
Participant 15	3	3	5	5	4	4
Participant 16	4	5	5	5	5	5
Participant 17	4	5	5	5	5	5
Participant 18	4	5	5	5	5	5
Participant 19	4	5	5	5	5	5

Participant 20	4	5	5	5	4	5
Participant 21	4	5	5	5	4	5
Participant 22	3	5	5	5	4	5
Participant 23	5	4	5	5	5	5
Participant 24	3	5	5	5	4	4
Participant 25	3	5	5	5	4	4
Participant 26	3	5	5	5	4	4
Participant 27	3	4	5	5	4	4
Participant 28	3	3	5	5	4	4