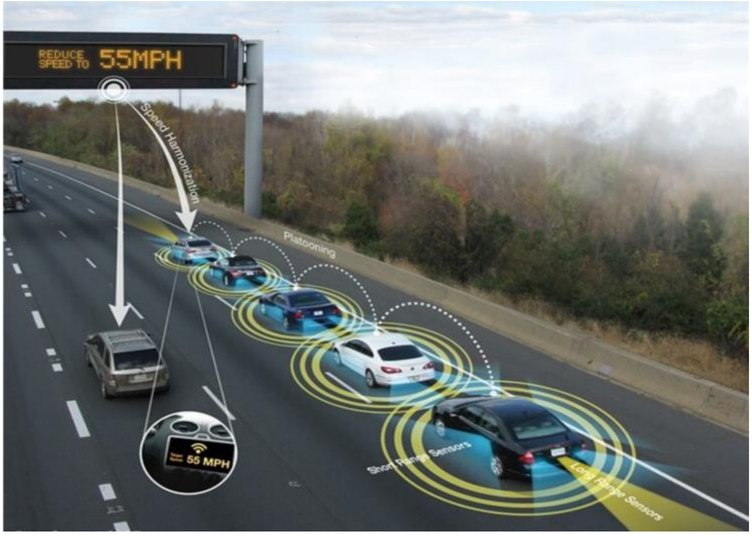
Impact of Exclusive Lanes for Autonomous Vehicles

A Cost-benefit Analysis of Exclusive AV Lanes in Eastern China



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Executive Summary

These days, autonomous driving has become a popular topic in different fields and showed its unavoidable developing tendency. With the increasing application of autonomous vehicles, a mixed period of autonomous vehicles (AVs) and conventional vehicles (CVs) is inevitable. Therefore, some traffic management was proposed. Exclusive lanes for AVs are a new way to improve the mixed road environment's traffic capacity. However, the effect of exclusive AV lanes was rarely studied. Therefore, the decision-makers could not clearly understand this new policy's impact. Besides, the existing research content did not provide a detailed quantitative analysis of this new policy, which is very important for decision-makers. Thus, this thesis focused on the exclusive AV lanes and proposed the following research question: *Under which conditions are exclusive autonomous vehicle lanes societally beneficial?*

First, I did a literature review of more than 30 papers. According to the previous research, AVs' performance in 100% AV penetration is better than that in lower penetration. Besides, the penetration of exclusive AV lanes is 100%. Therefore, AVs could have better behaviour in exclusive lanes. In other words, the exclusive AV lane could magnify the advantage of AVs. However, this kind of new lane management cannot work during the whole period. Also, the exclusive lane for AVs only benefits in specific market penetration rates. Therefore, it is necessary to understand the impact of exclusive AVs lanes to help decision-makers develop this new road space design and make adjustments during the implementation process. However, currently, a quantitative analysis lacks.

Then, I did a case study in the Eastern area of China and used cost-benefit analysis to figure out the impact of exclusive AV lanes from different aspects in several scenarios. The following steps were carried out in the case study: Building the conceptual model, cost-benefit analysis and sensitivity analysis. In the case study, various methods were used, including observation and interview, to collect local data for the calculation. In the case study, this research designed a new road policy which contains CV lanes and AV lanes in different AV penetration. In this design, the lanes were re-allocated for AVs and CVs. CVs and AVs should run in their own lanes and cannot change to each other's exclusive lanes. To manage the order of exclusive lanes, traffic cameras were used in this design to regulate the order on both CV lanes and AV lanes. This research also considered four different scenarios for the new policy: 20% AVs with one exclusive lane, 50% AVs with one exclusive lane, 50% AVs with 2 exclusive lanes and 80% AVs with 2 exclusive lanes respectively.

The NPV of each scenario was calculated to determine if this exclusive lane policy is beneficial to society. Additionally, the impact of exclusive lanes consisted of traffic flow, safety, emission, noise, equipment cost and fuel consumption. The value of each factor was monetized, and thereby the NPV of each scenario was calculated.

The following table shows the results of CBA. According to the table, in scenarios 1 and 3, the exclusive AV lanes had negative NPV, which means this policy would not benefit society. On the contrary, this new road policy is societally beneficial in scenario 2 and 4. And in all four scenarios, change in fuel consumption, time cost, and safety cost played a significant role in impacting the NPV.

	S1 (20% with 1 AV lane)	**S2 (50% with 1 AV lane)**	**S3 (50% with 2 AV lanes)**	**S4(80% with 2 AV lanes)**
Change in fuel consumption	-3.4	-104.5	-42.3	-114.0
Change in Time cost	-13.6	227.4	-20.1	203.7
Change in Safety cost	-13.5	-36.1	-55.0	-16.4
Change in Emission Cost	-0.09	-3.44	-0.89	-3.68
Equipment Cost	-0.51	-0.51	-0.51	-0.51
NPV	-31.2	82.8	-118.1	69.2

In addition, the penetration of 0 NPV was calculated. Therefore, the research question could be answered: for one AV lane, when the real penetration exceeds 15.5%, the exclusive AV lanes are beneficial; for two exclusive AV lanes, this policy is useful when the real penetration is more than 46.1%.

To verify the reliability of CBA results, I also conducted a sensitivity analysis. According to the sensitivity analysis, the change in fuel price, wage and safety lead to the apparent change in B/C ratio and NPV in these four scenarios.

Although this thesis considered the effects of various societal aspects and provided a quantitative analysis of exclusive AV lanes, some weak points still existed. Due to the limitation of CBA, the analysis of the effects did not consider the ethic aspects such as fairness, privacy and risk distribution. And this analysis made several assumptions and overlooked some impact of other technology, which might lead to inaccuracies. Therefore, they could improve calculations' accuracy and include more impacts from different aspects such as moral effects for further studies. Moreover, they could use data from other areas to accurately calculate the NPV of these areas and compare the outcomes.

Acknowledgement

In front of you is the thesis of Master Management of Technology at the faculty of Technology, Policy and Management at Delft University of Technology. When looking back to this project, there are many people I want to thank.

First, I would like to thank my team, thanks to my great supervisors Bert van Wee, Jan Anne Annema and Filippo Santoni De Sio, to support and guide me through this project. We were unable to meet because of the epidemic, but we still met online to maintain the project’s steady progress. It cannot be possible for me to finish the project without your great help and encouragement in this particular period when we are all troubled by COVID-19. I especially want to thank my mentor Jan Anne. He not only gave me academic help, guiding me on the direction of the project, providing suggestions for revision of the paper; but also encourage me in job searching.

Then I would like to thank my participant in the interviews. This project could not be done without their enthusiastic participation. They told me all the details they knew without being paid and provided me with the project's inspiration and strength. It is a great pleasure to chat and exchange ideas with them.

Last but not least, I would like to thank my lovely family and girlfriend, thanks to my family to give me unconditional support during these years and thanks to my girlfriend for helping me in life and study.

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1 Introduction

This introductory chapter discusses the underlying motivation for this research proposal, on the impact of the exclusive lane for autonomous vehicles in the transition period. Also, it discusses the problem that it aims to solve.

1.1 Background

Autonomous vehicles (AVs) are defined as cars that can sense its environment and navigation without human operations (Maurer et al., 2016). These new vehicles can sense their surroundings with radar, optical radar, global positioning systems (GPS), and computer vision. In addition, AVs' forward-looking control systems can convert sensing data into appropriate navigation paths, as well as obstacles and related signs. AVs update their map information through sensing input data, allowing vehicles to track their location continuously, even if the conditions have changed or in an unknown environment (Reschka, 2016). The benefits of autonomous cars are obvious: the driver will become a passenger who can participate in other activities during the journey, and self-driving robot also makes the journey safer (Wachenfeld et al., 2016). Moreover, AVs improve mobility, which will accordingly increase the capacity for existing traffic infrastructure. Traffic jams and lost time are reduced, which improves the quality of traffic flow (Friedrich, 2016). However, in recent research, the defects of AVs have been proposed. For example, Litman thought that a comfortable alternative travel experience might increase total urban vehicle traffic. And to avoid paying for parking, autonomous vehicles may circle city blocks, increasing traffic congestion (Litman, 2017).

The story of the autonomous vehicles started in the USA during the 1920s. The first driverless car was introduced on 5 August 1921 by the engineers of the Radio Air Service (Kröger, 2016). After 2000, AVs developed rapidly. In 2007, DARPA made the publics realize the possibility of self-driving cars through its urban challenge (DARPA, 2007). In the following years, different firms, such as Google, VisLab and Audi, had successfully finished the examination of autonomous vehicles (Lam et al., 2014). By the end of 2013, some states in the USA had given the legal rights to the research institutes which allowed them to test AVs on public roads (B. W. Smith, 2013). In the same year, the National Highway Traffic Sty Administration (NHTSA) introduced 5 levels of self-driving cars (NHTSA, 2013). All this policy and history illustrate that autonomous driving is a promising technology supported by high-tech firms and administrations (Lam et al., 2014).

These days, autonomous driving has become a popular topic in different fields and showed its prosperous developing tendency. To follow the application of autonomous vehicles, several leading global firms are using their research sources to develop this advanced technology (Maurer et al., 2016). The technology of autonomous vehicles is becoming mature, and many AVs will appear on roads in the foreseeable future. According to IHS Markit, a global market research agency, global self-driving car sales will reach 600,000 in 2025 and 21 million in 2035, and the penetration rate for level 4 and level 5 AVs will reach to 5% in 2025 (IHS Markit, 2018). Figure 1.1 shows the expected trend of autonomous vehicles sales in 20 years. The time needed to shift the existing stock of CVs into AVs will last several years during which mixed traffic is expected, which means the traffic stream will be likely mixed with Autonomous vehicle (AVs) and conventional vehicles (CVs) during the transition period. However, this estimation is extraordinarily uncertain and may people thought that the AVs would firstly be launched in motorways.

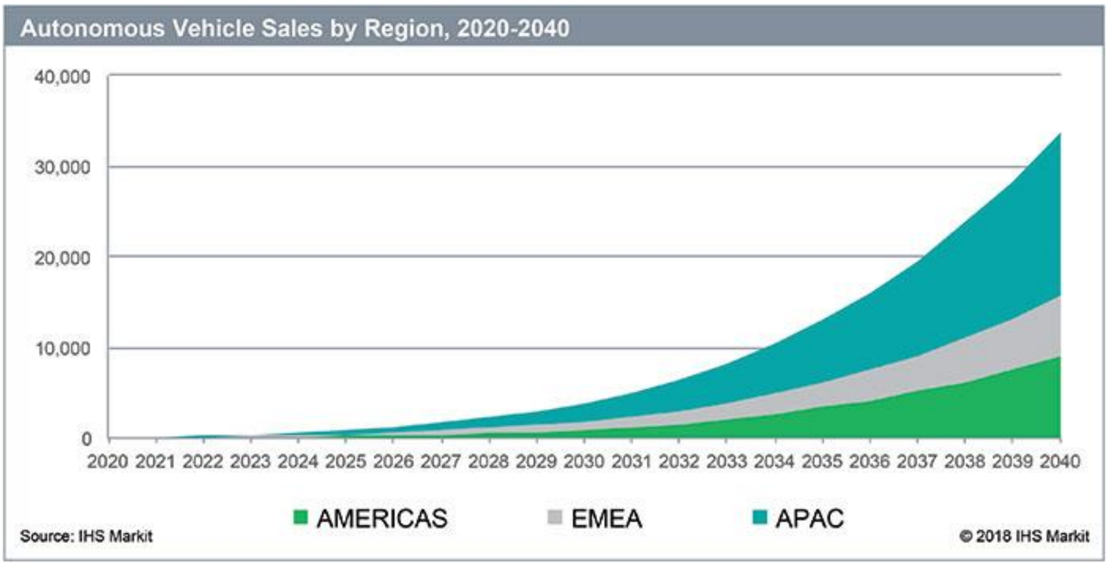


Figure 1.1: Autonomous Vehicle Sales Forecast by Region (HIS Markit, 2018)

Due to communication and self-driving technologies, AVs can improve road traffic capacity by reducing time headways between consecutive vehicles. However, in the mixed traffic environment, when following a CV, due to the lack of vehicle-to-vehicle communications, it may take a longer time for an AV to sense and react than a human driver, which results in a longer time headway and the loss of highway throughput (Li et al., 2020). If long headway is required to ensure AVs' safety, it degrades the traffic capacity and traffic efficiency (Seo & Asakura, 2017). Therefore, plenty of research studies the exclusive lane for autonomous vehicles, a new road management method to fix the problem between conventional vehicles and autonomous vehicles. Much research has been done (see chapter 3). Still, the literature gap lacks quantitative analysis of exclusive lane for AVs and a clearer analysis of whether exclusive lanes have a positive societal benefit to cost ratio. A positive impact on the traffic flow would help with the development of autonomous vehicles and traffic improvement. Therefore, it is meaningful to have a conceptual model explaining the influence of exclusive AV lanes and furthermore, a quantitative analysis such as cost-benefit analysis.

1.2 Practical Problem

The actual problem that is described in the previous paragraph is as follow:
During the early develop period, the traffic environment involves both AVs and CVs, and the mixed environment will influence the traffic capacity and traffic efficiency. The exclusive lane for AVs may foreseeably be a valid way to improve the traffic capacity in a mixed environment. However, the result of the application of the exclusive lane for autonomous vehicles is unknown.

To be more specific, employing vehicle communication and self-driving technologies, autonomous vehicles (AVs) can safely drive closer together than conventional vehicles (CVs), thereby potentially improving traffic efficiency. On the other hand, during the early stage of the transition period, the low autonomous vehicles flow rate may lead to the lower traffic efficiency in a mixed traffic environment (Liu & Song, 2019). The separation between AVs and CVs through the exclusive lanes is foreseen as an effective way to use AVs' advantage. However, it is essential to consider the transportation network mixed with CVs. Therefore, a clear understanding of the exclusive AV lanes would be helpful for different stakeholders, including drivers, policymakers and automakers etc., to the developing AVs market and making strategies in the transition period. Also, well applied exclusive lanes will give passengers a better travel experience.

1.3 Research Objective

With the increase of autonomous vehicles sales and the improvement of self-driving technologies, AVs will be a significant part of traffic flow. When the traffic environment contains autonomous vehicles and conventional vehicles, there will be conflicts between these two kinds of cars due to their different driving abilities. So, the exclusive lane for autonomous vehicles is proposed to be a method to improve the traffic capacity in mixed road conditions. However, the impact of the exclusive lane for AVs is uncertain and varying during the transition period. Thus, the research objective is to analyze the different effect of exclusive AV lanes and find if the benefits of this policy overweight its cost. In addition, this research tested different road design to find out which one has the highest net present value. After the analysis, a conceptual model and framework could be concluded and be used in analyzing different situations of exclusive AV lanes in later study. By researching this objective, the transport department can better understand AVs' exclusive lane's pros and cons and make sense during the decision-making process of AVs policies. The new design for road space could also increase traffic efficiency and improve the acceptability and demand for the public, thereby improving the development of autonomous vehicles. Exclusive AV lanes is a good practice for managing new technology in the future and bringing the most benefit to society.

1.4 Research Question

A main research question is essential to be able to realize the research objective of this thesis. In addition, the main research question included several sub-questions to form the whole research process. The answers to the sub-question are the important part to answer the main research question and reach the research objective.

1.4.1 Main research question

The research question of this thesis is:

Under which conditions are exclusive autonomous vehicle lanes societally beneficial?

The impact of exclusive lane for AVs is relative to various aspects such as traffic flow (travel time), safety and emissions etc. Therefore, to answer the main research question, this research considered different aspects, and the sub-question thereby contains these factors. Also, the difference between different period was concerned as well to form the answer.

1.4.2 Sub-questions

- *What kind of design for exclusive AV lanes are possible?*
- *What are the positive and negative effects to traffic flow of these design?*
- *What are the positive and negative effects to other factors (such as safety, emission and noise)?*
- *What are the monetized values of each effects?*
- *How robust are the outcomes?*
- *What are the managerial implications?*

The answer to the first question illustrates the possible redesign of exclusive AV lanes. And the second and third sub-questions answers the benefit and cost of the exclusive lane mentioned in the first sub-question, consisting of different fields such as traffic efficiency, fuel cost and some other external cost. The first three questions are also the most crucial part of this research because positive and negative effects are the basic cost-benefit analysis components. The fourth research question then answers the different monetized value of various effects mentioned in the first sub-question, which needs to be calculated by data. The next sub-question refers to the verification and validation part. To answer this question, sensitivity analysis would be done for the case study to confirm the outcomes and see if it could be used in other areas.

1.4.3 Premise and Limitation

There are some premise and limitation of this research question. The definition of autonomous vehicle should be clear because AVs have several levels representing different capacity. This paper only discusses the current AVs level, which is level 3-4. If the condition is level 5, the penetration will relatively higher than the current situation, which has less value to discuss the application of exclusive AV lanes. The road redesign mentioned in this paper is a reallocation of lanes rather than adding lanes because the monetary cost of adding lanes is too high. Therefore, this paper only discussed the reallocation of lanes. Thus, to regulate the order of the exclusive lanes, some traffic cameras are installed, and some regulations are introduced to manage the new policy. Moreover, referring to the limitation, the application of exclusive lanes has other further effects such as the impact on sales and inducing demand and moral effects. People are more willing to buy AVs due to the exclusive AV lanes. These impacts was excluded from this paper. In the future study, these effects can also be under consideration.

1.5 Thesis Outline

Following the introduction in this chapter, this thesis develops according to the following structure: Chapter 2 illustrates the methodology used in this research. In Chapter 3, a literature review is given to show the previous study about exclusive AV lanes. Chapter 4 focuses on the case study and the cost-benefit analysis. Chapter 5 focus on the variants and risks of the case study, and a sensitivity analysis is given in this chapter. Chapter 6 discusses the weakness and strong points of this research. Chapter 7 focuses on the conclusion and recommendations.

2 Research Methodology

This chapter discusses the research methodology used to meet the research objective of this thesis. In 2.1, all the research strategies used in this research is introduced. Section 2.2 to section 2.4 describe the methodology used in data collection. Section 2.4 gives the approach of the case study. Section 2.5 introduce the cost-benefit analysis.

2.1 Research Strategies

In order for this research to have certain scientific contributions and innovations, and to allow readers to become familiar with related topics quickly, the first research strategy of this paper is the literature review. Then, to make the research more reliable, the whole analysis process consists of two stages. In the first stage, desk research is the main research strategy. In this early stage, a great many data and information are required to understand the positive and negative impact of the exclusive lanes for AVs. Thus, desk research plays an essential role in collecting existing data and information in many ways, such as the internet, report and literature. It makes sense to see what people have done before, which is related to the exclusive lane. By using desk research, information and data about the autonomous vehicles and transport can quickly form the basic answer of the research question. For example, some items such as travel time reduction and emission reduction can be identified as one of the items of the cost-benefit analysis. During the desk research, the stakeholders was categorized into different groups; for instance, the beneficiary and the aggrieved. Also, the impact of exclusive AVs lanes that reached by desk research was divided into two categories: traffic flow and other factors. After the first stage, this research formed a general structure of analysis. In addition, desk research does, however, also have some disadvantages. For example, the quality of the previous research cannot be assured, and the information may incomplete and not timely. Therefore, it should be noted that although desk research can quickly and cheaply collect data and information, there are some disadvantages which should be considered.

In the next stage, the cost-benefit analysis was done based on a specific case. Using a specific case, the cost-benefit analysis was more clear and reliable. The data was close to reality, making the CBA more reliable and meaningful. The case was chosen from motorways or roads around the city, and the general structure obtained from the first stage was applied in the analysis in this stage. After creating the general structure, a conceptual model was created to guide the case study and further analyze exclusive AV lanes. After this stage, the CBA was finished according to the conceptual model, and a clear picture of our research question would be shown consequently.

Except for desk research and case study, some other methods was also used in this thesis. After desk research, it is important to get some insights to form experts to make the general structure more reliable and comprehensive. Besides, some data could also be collected by interviewing relevant employees. Thus, the survey is another research strategy to support this research. For some data that is difficult to be collected by the above ways, observation is a good method to collect the data.

2.2 Desk research

During the initial stage of this research, desk research was needed to collect the information about the research topic: exclusive AV lanes, and understand the current research situation of exclusive AV lanes. Based on the initial information form desk research, this study could build on its outline to carry out the analysis.

As secondary research, desk research collects data and information from various sources such as newspapers, reports, and the internet. This thesis's desk research was mainly focused on literature and statistic agency to ensure the quality of the data and the information. The information and the data collection of this research are various because the impact of exclusive AV lanes is related to many aspects. Thus, to make the analysis clearer, both the stakeholders and the impacts was categorized in the desk research stage. The impacts was divided into two categories: traffic flow and other factors, which is the two main parts of the cost-benefit analysis. Other factors would include noise, emission and safety etc. As mentioned in chapter 1, some other further impact of exclusive AV lanes, such as the impact on sales and demand, is excluded in this research. A literature review is given in chapter 3 to show the previous study about autonomous vehicles and exclusive AV lanes.

One crucial aspect that was not forgotten is the information and data changes in different stages during the transition period. The impact of the exclusive lane in different stages is not always the same due to AVs' penetration rate. And according to the review (see chapter 3), the penetration significantly influences AVs' performance. Thus, this part of the information also plays a vital role in forming the general structure.

According to the literature study, some negative and positive effects of exclusive AV lanes and AVs were understood. Therefore, the following to research question could be initially answered:

- What are the positive and negative effects to traffic flow of these design?

- What are the positive and negative effects to other factors (such as safety, emission and noise)?

2.3 Interview

As mentioned in chapter 1, the exclusive lane for AVs should consist of many aspects. And to collect the view from stakeholders, experts, except desk research, interviews were carried out.

To gather the initial view and information for the design of the lanes from stakeholders and experts can help form the general analysis outline. An interview is a guided, purposeful conversation between two or more people. There are many different types of interviews. Individual or group interviews may be unstructured or structured and conducted face-to-face, telephone, or online (Sakaran & Bougie, 2016). The result of desk research may have some omission, so that interview with stakeholders and experts can get insight and information to make the analysis more comprehensive and thereby remedy the omission. In this research, the interview was semi-structured. Some interview questions based on the desk research was prepared before the conversation. There should also be some space for interviewees to express their opinions about the impact of exclusive lanes. According to the interview, a more general conclusion of the impact of the exclusive lane for AVs was concluded and used in the case study.

An interview is an important method to collect data which is difficult to find through other ways. In this study, the cost of equipment and maintenance is unknown. Thus, interview with some engineers is a good way to gather the relevant data.

2.3.1 Interview structure

The interview in this study aims to collect some information about the equipment and maintenance cost and the camera's installation density. The initial step is gathering some relevant information to prepare the interview. Thus, some basic information about the traffic camera was collected in the first step. Secondly, the interview question was prepared based on the information collected in step 1 and the aim of the interview. The third step is to select the candidates. The interview's main purpose was to collect the data on equipment cost; therefore, the candidates are mainly production engineers and solution engineers who work for a camera company. These candidates are familiar with traffic cameras setting, and traffic cameras cost. They could also provide opinions about traffic cameras' effectiveness on exclusive AV lanes. As a result, ten candidates were selected to have an interview.

The next step is sending emails or message to the candidates and make appointments with them to have an interview. There were eight candidates replied the email or message and accepted the interview. Then, the interviews with 8 participants were finished through phone call video call. During the interview, all the information was collected in Chinese. After the interview, the Chinses notes were sent back to the participants to confirm if the content is right. Next, all the information was sorted out and be used in the analysis process. In addition, all the Chinses notes were translated into English and were given in the Appendix-C. Also, for more detail, see Appendix-C.

2.4 Observation

Observation is a useful and natural method to collect data on action and behaviour (Sakaran & Bougie, 2016). In this research, observation was needed to collect some data which was difficult to search through other ways. To be more specific, the average passenger quantity for one car in China was unknown. Thus, the observation is a good and easy way to collect these data.

Observation is divided into several variety such as controlled observation, uncontrolled observation, participant observation, nonparticipant observation and so on. In addition, there is some advantage and disadvantages of observation. For advantages:

1.It can obtain information directly through observation, without other intermediate links. Therefore, the observed information is more real;

2. Observation under natural conditions can obtain vivid information;

3. Observation has the advantage of timeliness, and it can capture what is happening;

4. Observation can collect some unspeakable materials (Sakaran & Bougie, 2016).

And for the disadvantages:

1. Limited by time, certain events have a certain time limit, and after this period of time they will not happen again;

2. Restricted by the object of observation;

3. Restricted by the observer. On the one hand, human senses have physiological limitations, beyond which it is difficult to observe directly. On the other hand, the observation results will also be affected by subjective consciousness;

4. Observers can only observe appearance phenomena and certain material structures, and

cannot directly observe the essence of things and people's ideology;

5. The observation method is not suitable for large-scale surveys (Sakaran & Bougie, 2016).

In this research, the observation is uncontrolled and nonparticipant. In the case study, the average passenger quantity in one car needs to be collected. This kind of data is difficult to collect by other methods. Thus, observation is a good method to get these data. The observation is selected in a highway toll-gate, and 200 cars are involved in the observation. The observation collects the passenger quantity of 200 cars and thereby calculated the average passenger quantity in one car used in CBA. More detail is shown in the Appendix-B. Both observation and interview were used to collect certain data to calculate the NPV of exclusive AV lanes. Hence, this tow methodology helps to answer the research question: *What are the monetized values of each effects?*

2.5 Case study

According to Saunders's book, the case study focuses on collecting information about a specific object, event or activity, such as a particular business unit or organization (Saunders et al., 2009). The idea behind a case study is that in order to obtain a clear picture of a problem one must examine the real-life situation from various angles and perspectives using multiple methods of data collection (Sakaran & Bougie, 2016). It is also easier to collect quantitative data in a case study, which makes the analysis more reliable. Due to the different policy and development of autonomous vehicles, it is complicated and unfeasible to do a large-scale analysis for exclusive AV lanes. Thus, case study helps to focus on a specific case and narrows the scope of the project, which make this study more focused and manageable. In addition, AVs and exclusive AV lanes are not fully applied in the real world; thereby, the adoption of case study permits investigation of otherwise impractical situations. Moreover, the aim of this study is to make a cost-benefit analysis which is a quantitative analysis. By using a case study, the specific data can be collected to support the calculation of the cost-benefit analysis for exclusive AV lanes.

In this paper, the case study of exclusive AV lanes considered motorways or roads around the city whose road condition is easier and more suitable for the application of exclusive AV lanes. This research collected some relative information and data about the specific case such as the reallocation cost and traffic capacity influence. The selected case is a stretch of Shengyang-Haikou highway in China. This stretch of road is about 80KM long and located between Shanghai and Zhejiang province which has stable traffic flow and enough space (4 lanes) for reallocation. Using the quantitative data of this particular case, the cost-benefit analysis was done. The net value was calculated to find out the condition that is suitable for applying the exclusive AV lanes. More detailed information about case selection is given in chapter 4. Through the case study, data were used in the cost-benefit analysis. Thereby, the monetized value of effects was calculated to answer the research question: *What are the monetized values of each effect?*

2.6 Analysis

The main analysis method being used in this research is cost-benefit analysis. CBA is a policy assessment method that quantifies in monetary terms, the value of all consequences of a policy to all members of society (Boardman et al., 2017). The cost-benefit analysis of exclusive lane contained different aspects as mentioned above, including traffic flow and other factors, and the basic data of the selected case was collected from literature and statistic report. Followed are some examples of data collecting: the number of trips, the monetary value of statistical life, and the monetary value of average travel time-saving. These data of selected case can be found in the previous study or be obtained by the interview with experts, and directly used in this paper. Besides, some other secondary data, which are not be found in the previous statistic, could be calculated and estimated. This cost-benefit mainly consisted of two parts and finally conclude a quantitative assessment of exclusive lanes for a particular case. Figure 2.1illustrates the general structure of CBA.

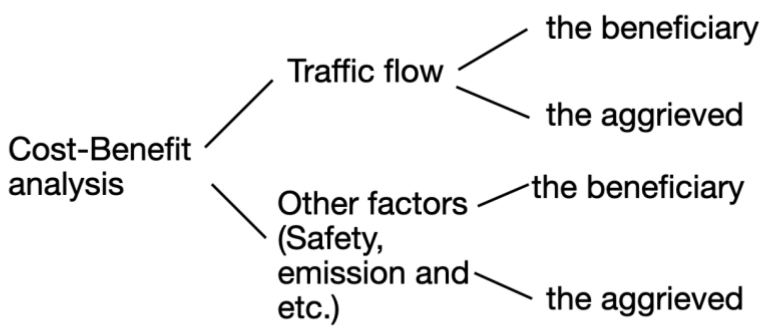


Figure 2.1 The structure of CBA

However, there are some limitations to CBA. Following van Wee and Roeser's research, the CBA scores high for effectiveness and efficiency, but generally ignores equity and other ethically important implications of policies including justice, fairness and autonomy (van Wee & Roeser, 2013). For example, in this case study, the distribution justice of public space (including bike lanes, sidewalks, etc.) was not under consideration in CBA. In addition, according to Hansjürgens's study, CBA has the evaluating-future scarcity and the problem of uncertainty. Thus, CBA is only possible to a very limited extent (Hansjürgens, 2004). Figure 2.2 indicates the model of exclusive AV lanes' effects. In Figure 2.2, risk distribution, fairness, privacy, and public perceived safety belong to exclusive AV lanes' moral impacts, which was not under consideration in this research. For more information about figure 2.2, see section 4.6.

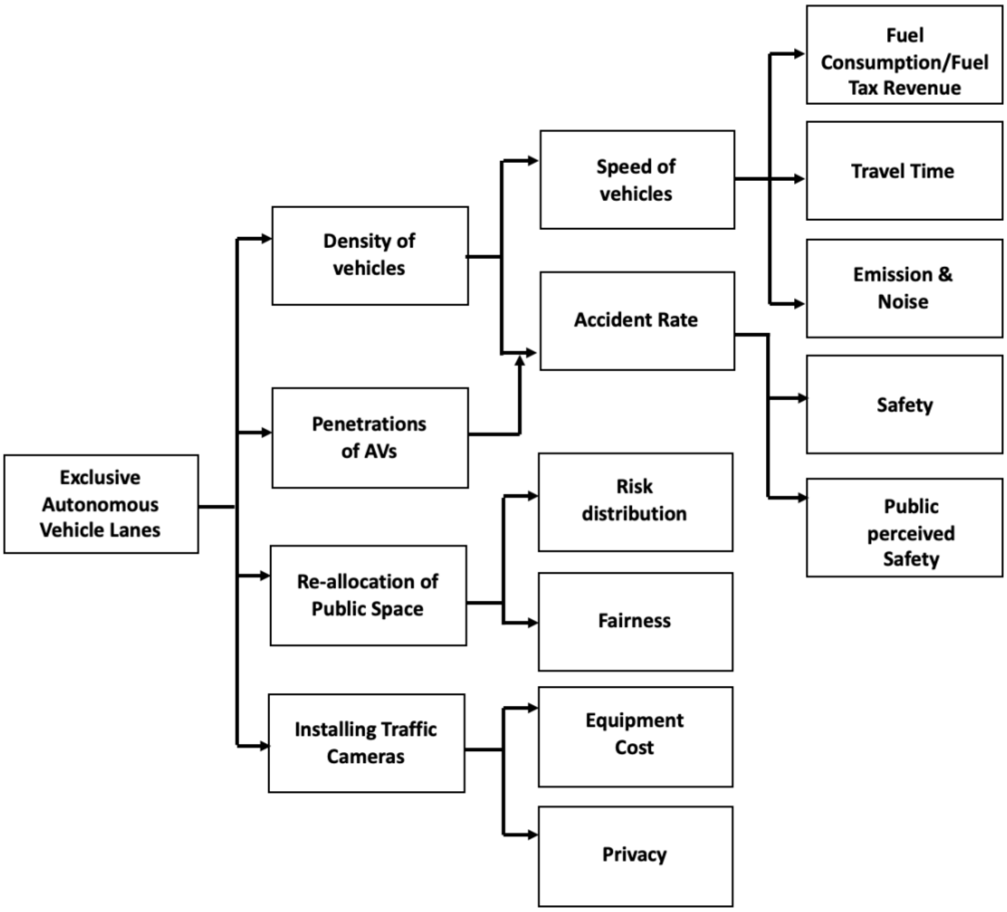


Figure 2.2 Model of Exclusive AV Lanes' Effects

Models are an abstraction of reality, and case study is not suitable for all situation in reality. Hence, verification and validation are necessary to ensure if the conceptual model is accurate and represent reality and if the result of the case study is robust. Verification and validation can be achieved through sensitivity analysis. Sensitivity analysis is one of the commonly used methods to analyze uncertainty in the economic evaluation of investment projects. In this study, sensitivity analysis changed some factor to check how sensitive the results were if the assumptions have been changed. More detailed information about CBA is introduced in chapter 4, and more detailed content about sensitivity analysis is given in chapter 5. Therefore, the following research questions were answered after the analysis:

- *What are the monetized values of each effect?*
- *How robust are the outcomes?*
- *What are the managerial implications?*

3 Literature Review

Before the search, it is necessary to know the current condition of the topic. Thus, this chapter illustrates the current development of autonomous vehicles and the discussion about the exclusive lane for autonomous vehicles. Hence, a literature review will lead to many useful insights on your research topics; it allows you to work as an expert, make informed decisions, and benefit from existing knowledge in many different ways (Sakaran & Bougie, 2016). In this research, the purpose of literature review was to collect some initial information about AVs and exclusive AV lanes. Through these initial information, the advantages and disadvantages of AVs and exclusive AV lanes could be clear understand. Then, some effects could be defined after literature review, which can help to build the outline of CBA.

The literature review of AVs and exclusive AV lanes consists of 3 different parts. Firstly, this section 3.1 discusses the increased driving ability of autonomous vehicles, which is an important part of the exclusive AV lanes' advantage. Then, according to the previous study, the advantage and the disadvantage is demonstrated in section 3.2. In addition, some other relative design about exclusive lane is introduced in section 3.3. According to the review, plenty of researches have been done. However, there is a little article written about a comprehensive analysis of exclusive lane for AVs, and thereby in this research, this gap was made up.

The search for relevant literature begins with a relatively broad scale. Google Scholar has been used in the early stage of searching the literature. The terms "autonomous vehicles transport" and "autonomous vehicles traffic" were used at the beginning. And 617,000 and 718,000 results have been provided respectively. It is clear that the scope was too broad to find closely relevant literature. However, there still 4 papers were selected after reading the abstracts and keywords.

To narrow the scale of the search, the following keywords has been used: "exclusive lane for autonomous vehicles" and "individual lane for autonomous vehicles". 27,100 and 18,400 results were given in Google Scholar. Apparently, after changing the search terms, the scope became narrower. As a result, 9 papers were chosen. After narrowing the scale of literature topics, Scopus was used to replace Google Scholar. Firstly, "autonomous AND vehicles AND exclusive AND lanes" were used in the search. Some results of Scopus are the same as the results being chosen in Google Scholar. This time 8353 results were found, and 19 of them were selected in the end. The search items “cost-benefit AND analysis” were used, and no literature was found, which means there is a scientific gap in this topic. Besides, during the search in Scopus, published time is another factor that was concerned. Autonomous vehicle becomes a hot topic in the recent five years. Thus, I mainly selected the literature after 2016. The studies before 2016 may be excluded to ensure the timeliness of the information.

To end up, with the use of Google Scholar and Scopus, finally, 32 pieces of literature have been selected as the reference of this literature review.

3.1 Improved driving ability of AVs

Autonomous vehicles use high-tech devices to sense the road condition and control the car by computer. With the help of different advanced sensors, autonomous vehicles can behave better than the human drivers in both safety and traffic efficiency aspects. Moreover, the safety improvement will simultaneously improve traffic efficiency because the less traffic accident means smoother traffic flow. When a traffic accident occurs on an urban link, the congestion would propagate to and affect adjacent links (Zheng et al., 2020). Vice versa, the increase in safety will leads to a decrease in traffic jams.

The previous study has approved that autonomous driving influences the traffic in many aspects such as traffic safety, traffic capacity and traffic jam. For example, Winkle’s study shows that human failure is the main cause of road accidents, and autonomous driving technology can make a contribution to minimizing the consequences of human failure (Winkle, 2016).
Besides safety aspects, autonomous vehicles directly improve traffic capacity. In Wagner’s study, a time gap is used as a parameter that shows the improvement of autonomous vehicles in traffic capacity. Time gap expresses the distance to the vehicles ahead which autonomous vehicles can achieve times of 0.3-0.5s, while the human drivers are legally required to keep a distance of at least 0.9s (Wagner, 2016). This means that autonomous vehicles can drive relatively short distances and increase the density of traffic flow. Due to the short time gap, autonomous vehicles also contribute to a reduction in green times. Wagner concluded that AVs' introduction has the potential to generate considerable time gain at traffic signals (Wagner, 2016).

Besides, Friedrich demonstrates two factors which are responsible for the increase in traffic capacity. The first factor is the shorter headways between autonomous vehicles, and the second one is the higher speed of the vehicles group (Feriedrich, 2016). Similar conclusion is also shown in Yao et al.'s study. Yao et al.'s researchers conclude that the traffic capacity of the road segment gradually increases with the increase in the penetration rates. And the greater the free flow velocity is, the greater the corresponding traffic capacity will be (Yao et al., 2019). Figure 3.1 shows the increasing capacity for mixed traffic.

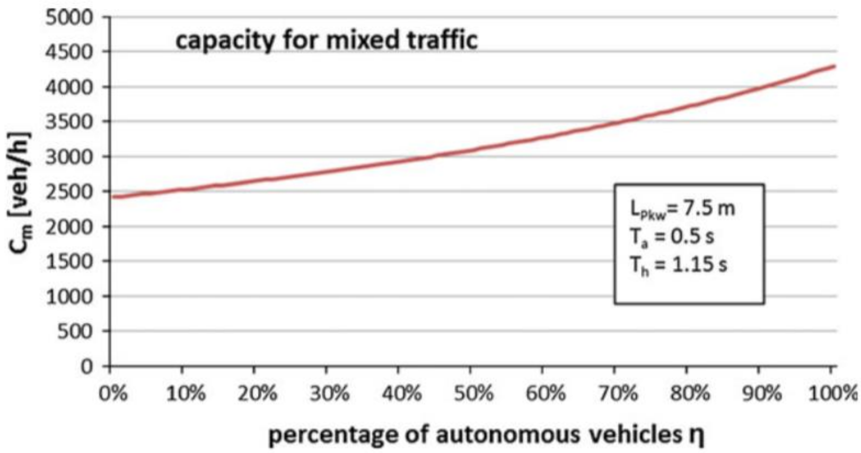


Figure 3.1: Capacity of a lane in proportion to the penetration of AVs (Feriedrich, 2016)

3.2 Impact of exclusive lane for AVs

Although autonomous vehicles bring many benefits to many aspects, there are also some defects in the allocation of autonomous vehicles. The increase in road capacity indicates a smaller average headway, bringing safety issues (Hua et al., 2020). Also, many studies suggest that the system-level effects will be minimal at low market penetration rate. Therefore, the exclusive lane for AVs is one potential approach to address this limitation because these special lanes increase AVs' density, in other words, increase the penetration on the exclusive lane (Talebpour et al., 2017). Additionally, exclusive lanes for AVs may benefit a transport network in two aspects: First, they may benefit the AVs and improve the traffic capacity of individual roads. Second, it could improve the system-wide flow distribution in the transport network (Liu & Song, 2019).

Many studies refer to the exclusive lanes for autonomous vehicles and analyse its impact on traffic capacity. These studies get a similar result that exclusive lanes for AVs only make sense in specific penetration rate. In short, the exclusive lane for AVs will have negative impacts during the low penetration rate and benefit the traffic flow in relatively high market penetration.

Ye and Yamamoto study three kinds of the highway (2 lanes, 3 lanes and 4 lanes highway) to show the changing impact of the exclusive lane for AVs in different penetration rate. Ye and Yamamoto found that exclusive lane will deteriorate the overall throughput in a low penetration rate due to the small autonomous density. In this low penetration situation, the conventional vehicles lanes become crowded, and the exclusive lanes are underused, thereby decreasing the overall performance of traffic capacity. When the penetration rate exceeds 50%, 30% and 30% for 2 lanes, 3 lanes and 4 lanes highway respectively, setting exclusive lanes for AVs is advantageous. In addition, Ye and Yamamoto illustrated that the maximum speed on the exclusive lane is higher than that on normal lanes, which means higher performance on exclusive lanes (Ye & Yamamoto, 2018). Mahmassani reach similar results as well. Mahmassani concluded that the impacts of exclusive lanes for autonomous vehicles are relatively minor on either throughput or stability, but will increase with higher market share. In addition, the exclusive lanes for AVs are good only if its use is optional and when the market share of autonomous vehicles is greater than the percentage of nominal capacity represented by that lane (Mahmassani, 2016).

Moreover, considering the endogenous AV market penetration, it is found that AV exclusive lanes should not be widely deployed until the AV market penetration reaches a relatively high level, for example, 20%. The reason behind is also similar that when the level of the market penetration rate of AVs is low, although deploying exclusive lanes can help to enlarge the gain of AVs, it will lead to tremendous increase in the travel time of conventional vehicles (Chen et al., 2016). Furthermore, by studying a four-lane heterogeneous CA flow model Ma and Wang found that only when the number of AVs is huge, there also should be no exclusive lanes (Ma & Wang, 2019). In their research, the performance of exclusive lanes for AVs is better than normal lanes during the penetration scale from 10% to 90%.

Besides the direct influence on traffic capacity, exclusive lanes for AVs have other impacts on many aspects. For instance, Zhang et al.'s study concluded that the exclusive lanes for AVs could even worsen the longitudinal safety in a low market penetration rates situation, and it could reduce the overall crash risks when the market penetration rates are larger than 15% (Zhang et al., 2020). As Sivak and Schoettle said, "During the transition period when conventional and self-driving vehicles would share the road, safety might actually worsen, at least for the conventional vehicles" (Sivak & Schoettle, 2015). Referring to the speed, roads with exclusive lanes for AVs are more potential to have a greater average speed gap between autonomous vehicles and conventional vehicles, showing the superiority of AVs. This is helpful to increase the market penetration rate of AVs (Hua et al., 2020). However, According to Seo and Akakura, new technology penetrates a market when its advantage is more beneficial than it of conventional products. For autonomous vehicles, one of the most significant merits of AVs is comfortable in-vehicles experience. Thus, the benefit of AVs compared to conventional vehicles would be almost proportional to the in-vehicle travel time (Seo & Akakura, 2017). Hence, the decrease of travel time made by exclusive lanes for AVs will cut down the superiority of AVs and thereby impede the penetration process.

3.3 Optimal Methods of Exclusive AV Lanes

As mentioned in section 2.2, exclusive lanes for autonomous vehicles have some defects in some certain penetration rates. Thus, some researchers studied to improve the overall performance of exclusive lanes for AVs.

Liu and Song design a new form of managed lanes for AVs, designated as autonomous vehicles/toll (AVT), which charging fee to conventional vehicles when they access the lanes and grant free access for AVs. In their study, they considered the user equilibrium between AVs and CVs. They proposed a robust optimal deployment model, and the results show that the system performance can be significantly improved through the AVT lanes (Liu & Song, 2019).

Despite a new form of exclusive lanes, some other strategies are also studied and proposed by researchers. Hua et al. studied the influence of different exclusive lane policies on mixed traffic and provide recommended lane policies under various traffic volumes and CAV penetration rates. In this research, two-lane and three-lane highway were studied, and sixteen exclusive policies were proposed. Figure 3.2 shows some example of 16 exclusive lane policies. The results illustrated that 7 lane policies had better performance than others and significantly improved traffic capacity and efficiency (Hua et al., 2020).

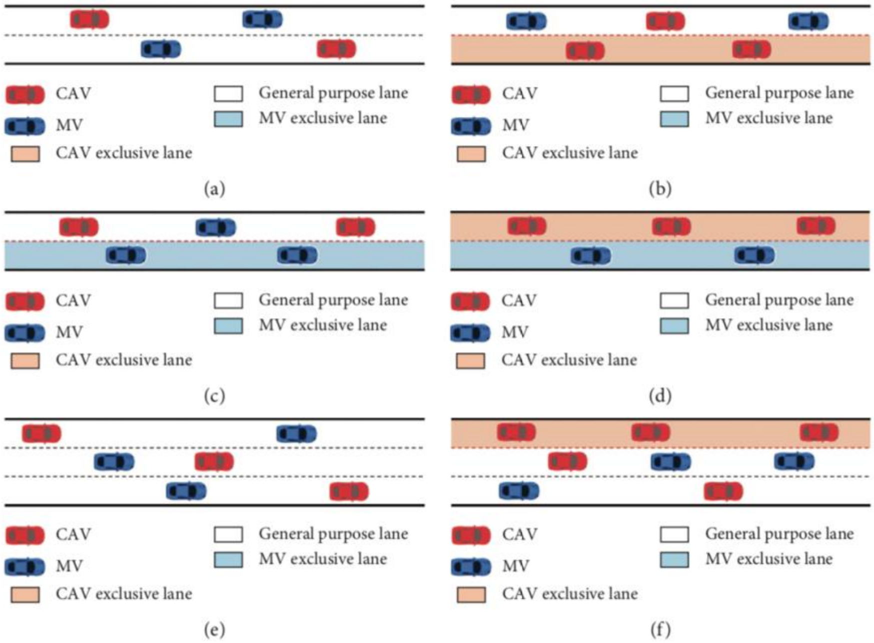


Figure 3.2 Example of some exclusive lane policies (Hua et al., 2020)

Overall, the current studies about exclusive lane consist of many aspects including transport, safety and market penetration and reach different results to show the impact of exclusive AV lanes. And the exclusive AV lanes will magnify the advantage of AVs mentioned above because it creates 100% penetration lanes for AVs. For example, AVs could run faster and safer in exclusive AV lanes, which have 100% AV penetration compared to their normal lanes' performance. But it may lead inconvenience to conventional vehicles. Thus, a quantitative analysis is essential for policymakers to determine if the exclusive AV lanes are societal beneficial. However, there is little research about quantitative analysis for exclusive AV lane considering multiple dimensions such as transport, safety, emission, fuel consumption, etc. Thus, this thesis will take several aspects, including traffic flow (travel time), emission and noise, safety and fuel consumption, into consideration to make a cost-benefit analysis of the exclusive lane for AVs and receive a net present value to judge whether this new road policy is efficient and effective.

4 Cost-Benefit Analysis

In this research, the cost-benefit analysis is based on the selected case in eastern China. Section 4.1 introduce the theory of cost-benefit analysis. Section 4.2 describe the criteria of case selection. Section 4.3 analyse the opportunity and problem of exclusive AV lanes. Section 4.4 and 4.5 describes the basic information of the baseline case and alternative case. Section 4.6 determines the effect, cost and benefit of exclusive AV lanes in this case study. An overview result is given in section 4.7.

4.1 Introduction of CBA

CBA is a policy assessment method that quantifies in monetary terms the value of all consequences of a policy to all members of society. More generally, CBA applies to policies, programs, projects, regulations, demonstrations, and other government interventions. (Boardman et al., 2017). It is an essential tool for evaluating policy options in advance. It is a system information tool that can investigate and evaluate the advantages and disadvantages of policy measures from society's perspective. This supports the approach to the proposed measures so that CBA can incorporate various measures in all strategic areas (Romijn & Renes, 2013). But, according to the previous research, CBA ignore some moral aspects and CBA also has evaluating-future scarcity and the problem of uncertainty (van Wee & Roeser, 2013; Hansjürgens, 2004). In this research, CBA is used in the transport sector to inspect the exclusive AV lanes.

There are two major types of CBA. Ex ante CBA, usually standard CBA, is carried out before the project or policy is considered and before the start or implementation. Ex ante CBA helps determine whether the government should allocate resources to specific projects or policies. Therefore, ex-ante CBA could directly make a contribution to the policy-making process. Another type of CBA is ex-post CBA which is conducted at the end of projects. In this study, ex-ante CBA is used because this analysis is done before the implementation of exclusive AV lanes.

4.2 Case selection

In this paper, the case study of exclusive AV lanes considered motorways or roads around the city or between cities, because there is no traffic light and no pedestrians on these roads which means the road condition is less complicated and therefore more suitable for the application of exclusive AV lanes. After choosing the particular road for the case study, relative information and specific data about the selected case was collected to calculate and monetize the impact of exclusive AVs lanes. The exclusive lanes affect the density directly, thereby affect the speed of both CVs and AVs. Accordingly, the change of speed leads to the change of safety, emission and fuel consumption. Thus, the relationship between speed and the different effect was collected to quantify the consequence for relevant information. Also, some specific data about this relative information was collected for the calculation and monetization. The information and date mentioned above were collected from different approaches including official report, previous study and so on.

The first step of this case study was selecting a suitable highway to make a cost-benefit analysis. There are some criteria for the selected motorway:

1. The selected case should have a stable and relatively high traffic flow to ensure that the reallocation will impact every lane's density. If the traffic flow is not sufficient, the traffic capacity will have an inconspicuous impact on a small speed change. Thus, a stable and relatively high flow is essential.
2. There should be enough lanes for reallocation for exclusive AVs lanes. With enough lanes, the administrators could change the number of lanes to meet different AVs penetration.
3. The length of the selected road should be relatively long to ensure that the quantitative value of cost or benefits change is big enough to reflect the influence of the new policy.

According to the above criteria, the selected case is a stretch of Shenyang-Haikou highway in China. This stretch of road is about 80KM long and located between Shanghai and Zhejiang province which has enough lanes (4 lanes for single direction) for reallocation. Additionally, Shanghai and Zhejiang province is located in the Yangtze River delta area, which is one of the areas with the best economic development and the highest population density. Therefore, the traffic flow between these two areas is relatively high. According to the Xinhua News Agency's report, the designed daily average traffic flow is 100,000 (Xinhua News Agency, 2007). In addition, this case study did not consider the freight cars to simplify the analysis and make it clear because there is some regulation about the lane for freight cars. Also, the proportion of freight car in the selected road is low. Thus, the freight is not under consideration in this case study. Moreover, the selected case did not consider the junction of motorways or other complex traffic networks to decline the complexity of case study. If the selected case consists of junction or other complex networks, the design of exclusive AV lanes will become much more complicated. For instance, the design should consider the lane change rule and the its impact to traffic flow, which makes the analysis much more complex and uncertain.

Due to the changing market of autonomous vehicles, this case study considered different penetrations to represent different stages of AVs development. According to Litman's study, there was three typical stages for AVs: 20%, 50% and 80%, which represent Commercial release, expansion and maturation, respectively (Litman, 2020). And for a different stage, the number of exclusive lanes should change to meet the requirement of variable penetration. Besides, the proportion of exclusive lanes could be lower than the penetration of AVs, which means AVs could be denser in exclusive lanes due to the better driving capacity. Thus, this case study consists of 4 different situations: 20% AVs with one exclusive lane, 50% AVs with one exclusive lane, 50% AVs with 2 exclusive lanes and 80% AVs with 2 exclusive lanes respectively.

Using the quantitative data of this particular case, the cost-benefit analysis was finished. The net present value in different scenarios was calculated to determine the condition suitable for applying the exclusive AV lanes. Furthermore, a conceptual model has been established before the analysis to determine the societal impacts are of the exclusive lanes. After that, during the analyzing process, the cost-benefit analysis is divided into several steps which including problem/opportunity analysis, establish the baseline alternative, define policy alternatives, determine effects and benefits, determine costs analyse variants and risk, an overview of cost and benefits and presentation of results (Romijn & Renes, 2013). By using these steps, the impact of exclusive AV lanes can be clearly illustrated, and the valuation of cost and benefit can be presented in a distinct way.

4.3 Opportunity/problem analysis

The problem analysis illustrates the problem which is seeking for solutions, the origin of the problem and also the future development of this problem. With the improvement of self-driving technology, more autonomous vehicles will show on the road in the near future. Base on Maurer's book, autonomous vehicles bring many benefits to safety and traffic capacity (Maurer et al., 2016). According to WHO, 1.24 million people worldwide died in road accidents in 2010. Thus, vehicles' autonomous capability to drive provides a new opportunity for drivers' safety. Also, AV offers the greatest potential for optimizing traffic flow autonomous (Maurer et al., 2016). Besides, Calvert's study shows that some automated vehicles in mixed traffic will initially have a small negative effect on traffic flow and road capacities (Calvert et al., 2017). In order to play AVs' role in a more efficient way and solve the problem, exclusive lanes for AVs are proposed to increase the penetration in these exclusive lanes, therefore, improve the traffic capacity in these lanes. In short, the application of

AVs will bring benefits to many aspects, but the exclusive lanes for AVs could magnify these benefits and fix some negative impact of AVs in low penetration. Thus, the opportunity is that with the application of exclusive AV lanes, AVs' advantage could be magnified, which brings more benefit to society. And without the exclusive AV lanes, the traffic flow will have negative impacts in low penetration.

4.4 Establish the baseline alternative

The baseline alternative shows the most likely scenario without any introduction of new policies. In this case study, the baseline alternative is that there is no exclusive lane on the selected motorway which means the traffic flow on motorways is mixed by AVs and CVs. This study includes three penetrations of AVs (20%, 50% and 80% respectively), which shows three different stage of AVs market and the results of three penetration was used as a reference to measure the impact of exclusive lanes. In addition, this analysis introduces a value named willingness to use AVs on motorways, which shows AVs owners' willingness to use self-driving technology on highways.

Real penetration is shown in the following formula:

$$NP * WTU$$

In which:

NP: Nominal penetration

WTU: Willingness to use AVs on motorways

Using this formula, a new real penetration was calculated based on the nominal penetration and used in cost-benefit analysis. According to the study made by Bjørner, about 60% of the participants felt comfortable to use self-driving cars in highway driving (Bjørner, 2015). With the development of autonomous vehicles, the willingness of using AVs will also increase in the future.

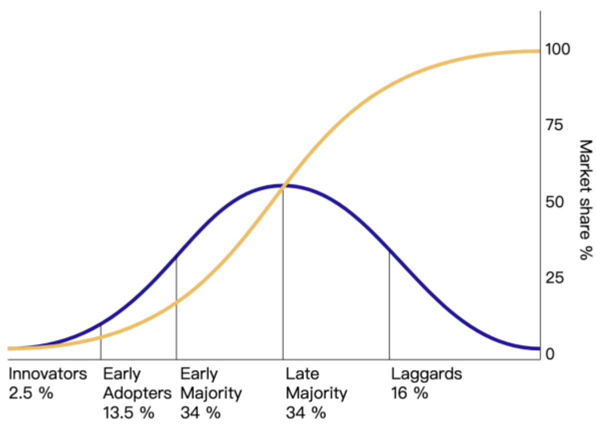


Figure 4.1: Diffusion of Innovation

Figure 4.1 Diffusion of Innovation according to Rogers (Blue: adoption; Yellow: Market share)

According to the diffusion of innovation theory created by Everett Rogers, new technology adoptions in different market share are shown in Figure 4.1. Thus, this calculation assumed that the WTU was 70% in 50% penetration and 90% in 80% penetration. Thereby, the real penetration of 20%, 50% and 80% could be calculated (12%, 35% and 72% respectively). Table 4.1 shows the distribution of cars in different baseline cases. In the baseline case, the density of every single lane is the same (25%). Also, the number of AVs in each lane are illustrated separately in Table 4.1.

Distribution of Cars for Baseline Case				
20% AVs (12% real penetration)	1	2	3	4
Car Proportion in Every Lane	25%	25%	25%	25%
Car Amount	25000	25000	25000	25000
AVs Amount	3000	3000	3000	3000
50% AVs (35% real penetration)	1	2	3	4
Car Proportion in Every Lane	25%	25%	25%	25%
Car Amount	25000	25000	25000	25000
AVs Amount	8750	8750	8750	8750
80% AVs (64% real penetration)	1	2	3	4
Car Proportion in Every Lane	25%	25%	25%	25%
Car Amount	25000	25000	25000	25000
AVs Amount	18000	18000	18000	18000

Table 4.1: Distribution of Cars in Baseline Case

4.5 Define policy alternative

The policy alternative describes a potential measure which can help to solve the problem. In this study, the exclusive AVs lanes are the policy alternative. This case study contains three penetrations, and for different penetrations, the number of exclusive lanes is not the same. Thus, this analysis includes four situations for three penetrations (20% with 1 exclusive lane, 50% with 1 exclusive lane, 50% with 2 exclusive lanes and 80% with 2 exclusive lanes respectively). Due to the introduction of real penetration, AVs and CVs' real distribution is different from nominal penetration, which is 12% with 1 exclusive lane, 35% with 1 exclusive lane, 35% with 2 exclusive lanes and 72% with 2 exclusive lanes respectively. By using the data of daily average traffic flow (100,000), Table 4.2 shows the distribution of every single lane in mentioned four scenarios and the difference between project case and baseline case. The density represents the proportion of car quantity in every lane, and car amount means the daily average traffic flow for a single lane. In scenario 1 and 3 the car density in CV lanes increased and that in AV lanes decreased.

On the contrary, the density in CV lanes decreased, and that in AV lanes increased in scenario 2 and 4. This is because the proportion of AV lanes is higher than the AV penetration in scenario 1 and 3. And the proportion of AV lanes is lower than the AV penetration in scenario 2 and 4 vice versa.

Distribution of Cars (Green for CVs, Red for AVs)				
20% with 1 exclusive lane (12% for real penetration)	1	2	3	4
Car Proportion in Every Lane	29.3%	29.3%	29.3%	12%
Car Amount	29333	29333	29333	12000
Car Amount for Baseline case	25000	25000	25000	25000
Car Proportion in Every Lane	+4333	+4333	+4333	-13000
50% with 1 exclusive lane (35% for real penetration)	1	2	3	4
Car Proportion in Every Lane	21.67%	21.67%	21.67%	35%
Car Amount	21666	21666	21666	35000
Car Amount for Baseline case	25000	25000	25000	25000
Difference	-3334	-3334	-3334	+10000
50% with 2 exclusive lanes (35% for real penetration)	1	2	3	4
Car Proportion in Every Lane	32.5%	32.5%	17.5%	17.5%
Car Amount	32500	32500	17500	17500
Car Amount for Baseline case	25000	25000	25000	25000
Difference	+7500	+7500	-7500	-7500
80% with 2 exclusive lanes (72% for real penetration)	1	2	3	4
Car Proportion in Every Lane	14%	14 %	36%	36%
Car Amount	14000	14000	36000	36000
Car Amount for Baseline case	25000	25000	25000	25000
Difference	-11000	-11000	+11000	+11000

Table 4.2: Distribution of CVs and AVs for 4 scenarios

4.6 Determine effects, benefits and cost

According to previous studies, the advantage of autonomous vehicles has been illustrated. For example, AVs could reduce the human fail to increase travel safety, and AVs could also improve the traffic capacity by decreasing the headway (Winkle, 2016; Wagner, 2016). Moreover, AVs could have better driving performance in higher penetration (Talebpour et al., 2017). Thus, exclusive lanes will impact on AVs, and therefore the CVs will also be influenced because of the change of penetration in a single lane. In a short conclusion, the exclusive AV lanes will magnify AVs' benefit due to the change of penetration in exclusive lanes.

The effect consists of several aspects, including direct effect and indirect effect. Firstly, as shown in Table 4.2, the introduction of exclusive lanes will change the density and car amount of every single lane so that vehicles' speed will be changed, which means the travel time will be impacted. To be more specific, the increase in travel time means that drivers will cost more value of time (VoT) on the road. And vice versa, the decrease in travel time makes drivers spend less VoT. Secondly, the safety was also considered into the effect because AVs' driving performance is variable with the different penetration (Talebpour et al., 2017). Therefore, the exclusive lanes for AVs are proposed to increase the penetration on exclusive lanes for better performance of AVs, and thereby, the accident rate of AVs will decrease. This means AVs are beneficial, referring to the safety aspect. However, CVs will have higher accident rate due to the zero penetration of AVs, which means they will cost more on the safety part because of the increase in the accident rate. These two aspects are the direct impact of exclusive AV lanes, and the following aspects are the indirect one which is affected by the change of speed.

Thirdly, according to previous studies, cars running at different speeds have different fuel consumption (Ahn et al., 2002). Thus, the introduction of exclusive lanes will affect fuel consumption for both CVs and AVs. Whether drivers are beneficial or not depends on the change in fuel consumption. Moreover, the government will also be influenced because the fuel tax is related to fuel consumption. Lastly, to study if the new policy is societal beneficial, the environment is also an essential part that was considered to calculate the external cost. To be more specific, the emission cost consists of air pollution cost and climate change cost. Air pollutants' emission can lead to different types of damages, such as health effects and crop losses. And The emission of greenhouse gases into the atmosphere leads to global warming and climate change (Essen et al., 2019). Based on earlier studies, there exists some relationship between speed and emission and noise (Oneyama et al., 2001; Shridhar Bokare, 2013; et al.). Therefore, the emission and noise will change because of the variable speed. If the emission and noise decrease, these external costs will decline. To the contrary, when emissions and noise increase, the cost of these problems will raise. Besides, the equipment cost cannot be ignored referring to the cost part. This analysis assumes that the transport department will introduce some traffic rule to manage the exclusive AV lanes. However, only the rule is not sufficient to regulate the exclusive lanes; thus, some enforcement should be involved in the management of exclusive lanes which means more cost for this policy. In analogy with vehicle speed monitoring, this case study assumed that the traffic administration would use traffic monitoring to regulate the exclusive lanes. Therefore, the cost of camera and maintenance was considered in the calculation.

Figure 4.2 illustrated the conceptual model of cost-benefit analysis for exclusive AV lanes, including the societal impact in different aspects. The upper left part of this model shows that the normal lanes are changed to exclusive autonomous vehicles lanes by using some enforcement, including traffic camera and regulation. By these ways, the drivers could follow the traffic rules and drive in their lanes. And the societal impact is showed in the upper right part, including change in safety, change in travel time, change in emission & noise and change in fuel consumption. Additionally, the change in fuel consumption consists of changes in fuel cost and changes in fuel tax. To be more specific, for different stakeholders, the costs are defined as equipment cost, increase of travel time, increase of fuel consumption, increase of accident rate for CVs and increase of emission and noise. And the benefits are defined as increase of fuel tax revenue, decreased travel time, decreased fuel consumption, and decreased accident rate for AVs. After the comparison between cost and benefit, the net value would be calculated to show if the exclusive AV lane is beneficial.

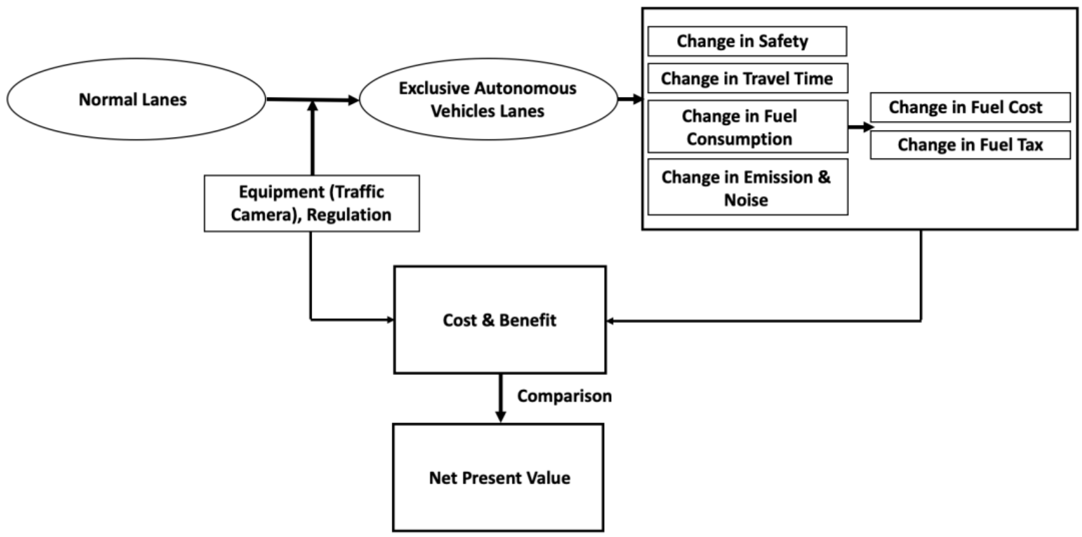


Figure 4.2: Conceptual Model of Cost-benefit Analysis in This Case

Figure 4.3 (a) and (b) reflect the relation between different AV lanes and CV lanes parameters. The exclusive lanes will change the density and the AVs penetration in AV lanes and CV lanes, thereby impacting the speed and safety. With the change of speed, fuel consumption and fuel tax revenue, travel time, and other environmental factors (emission and noise) will be affected. In Figure 4.3, "+" means positive correlation and "-" represent the negative correlation.

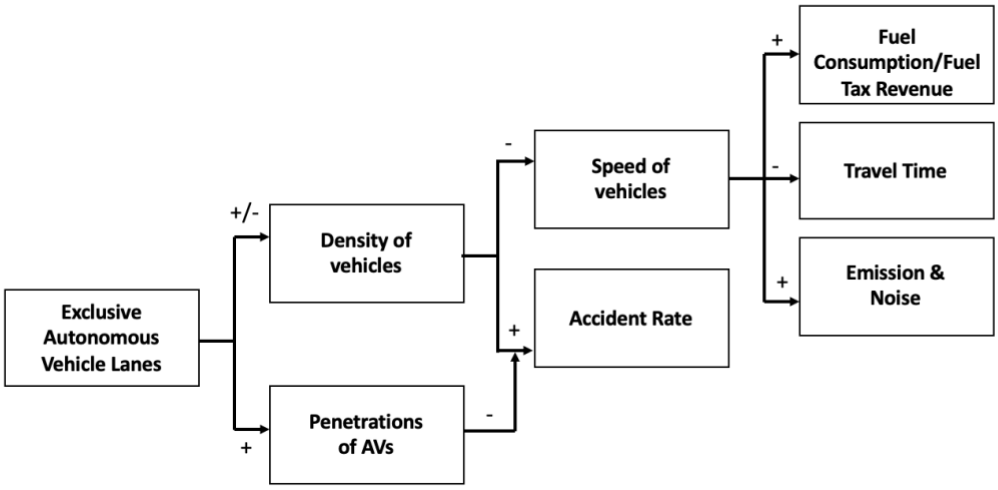


Figure 4.3 (a): Relation between Different Parameters for AV Lanes

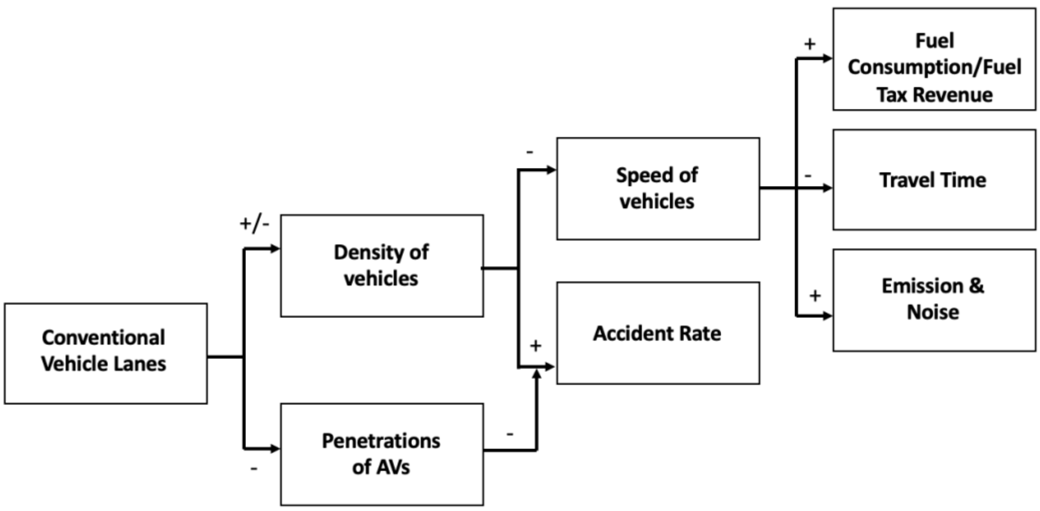


Figure 4.3 (b): Relation between Different Parameters for CV Lanes

Besides, due to the limitation of CBA mentioned above, there were some moral effect which was not considered into the analysis. Firstly, the effect to public perceived safety and risk distribution. The exclusive AV lanes will change traffic condition, and thereby impact to the public perceived safety, especially in urban situation. And this new road policy will re-distribute the risk to different people including CV drivers, AV drivers, bike rider and pedestrians. Secondly, this CBA did not consider the effect to privacy and fairness. The fairness of lanes re-allocation could be considered as the fairness of distribute the public space. It might cause unfairness to some certain stakeholders such as pedestrians and bike riders. In addition, the application of traffic cameras leads to privacy protection problem. All these mentioned effects were considered form ethics aspects (also shown in Figure 2.2). It is difficult to evaluate the cost and benefit about this aspect. Therefore, this case study did not take these effects into account. Figure 4.4 shows how the exclusive AV lanes impacts to different aspects including both moral and normal effects.

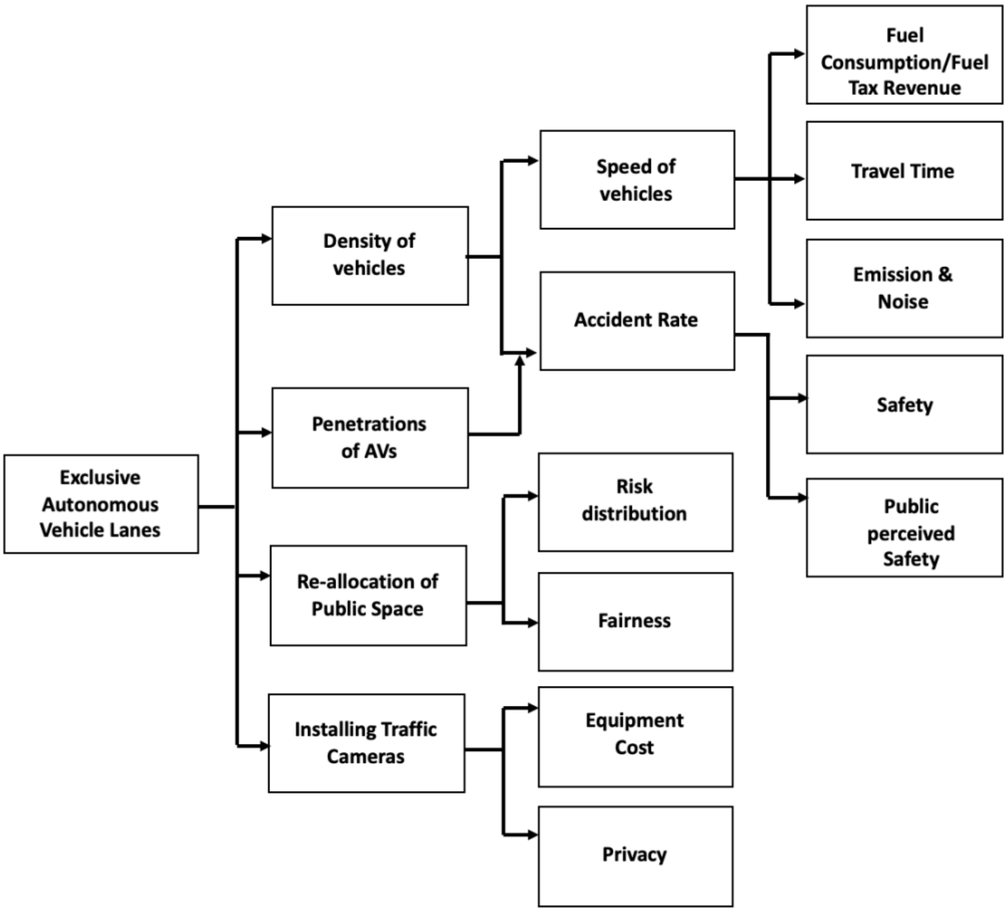


Figure 4.4 Effects of Exclusive AV lanes

In conclusion, this cost-benefit analysis contains three different stakeholders: AVs drivers, CVs drivers and the government based on above analysis. For AVs drivers and CVs drivers, they will be effected in travel time, safety and fuel consumption. The third stakeholder, government, will be influenced in the fuel tax revenue and the budget of emission and noise. However, some ethics effects of exclusive AV lanes were not considered due to the limitation of CBA. This case study will focus on the above-mentioned aspects and stakeholders to calculate their cost and benefit separately.

Moreover, the speed is the most important parameter due to its relationship with different aspects including travel time, fuel consumption, safety, noise and emission.

4.6.1 Travel time

According to the statement above, the travel time of both AVs and CVs will be impacted due to the introduction of exclusive lanes. This study estimated the speed on the selected road based on the Baidu Map, one of the most common-used navigation software in China. After making several estimations at different times (see Appendix-A), the average speed on the selected road was estimated at around 96 km/h. Then, the travel time could be calculated by speed. Table 4.3 shows average speed and the estimation of travel time on the selected highway in 0% AVs penetration.

Route (km)	**velocity (km/h)**	**Travel Time (min)**
80	96	50

Table 4.3: Estimation of Travel Time with 0% AVs penetration

Because there are few previous studies works on the quantitative analysis of AV's impact to traffic flow. Thus, this case study uses the impact of ACC (Adaptive Cruise Control) to represent the influence of self-driving technology to travel time. ACC is a core technology of self-driving therefore this analysis uses the data of ACC to represent the relationship between the AVs penetration and travel time (also the speed). Thus, the travel time and speed of reference case could be calculated based on the different penetration (20%, 50%, 80% for nominal penetration and 13%, 37.5%, 70.6% for real penetration respectively). Similarly, the travel time and speed of AVs in exclusive lanes also could be calculated by using the data of 100% penetration. Figure 4.5 (a) shows that the travel time and the mean speed is related to the penetration of ACC (Calvert et al.,2017). And Figure 4.5 illustrated the travel time for 0%, 20%, 50%, 80% and 100% nominal penetration (1163, 1200, 1213, 1174 and 975 respectively). Therefore, the travel time for different penetration (T_n)could be calculated by following formula:

$$T0 * \frac{t_n}{t_0}$$

In which:

t_n: Travel time of n% penetration in Calvert's study (1200,1213,1174 and 975)

t_0: Travel time for 0% penetration in Calvert's study (1163)

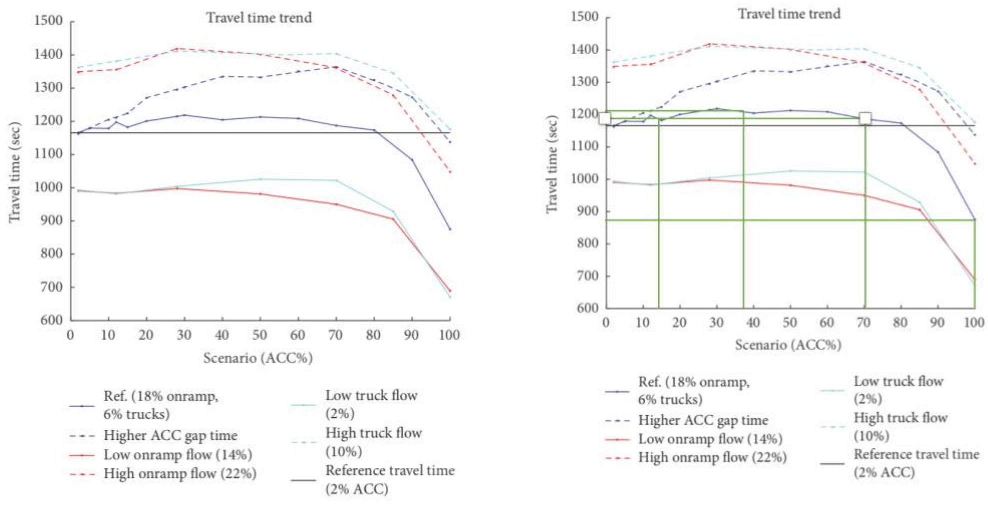
T0: Estimation of Travel Time with 0% Avs penetration (50 mins)

After calculating the travel time, the speed could also be calculated for different penetrations. Table 4.4 demonstrates the travel time and speed in three baseline cases separately. According to the study made by Calvert, the impact to travel time is negative in low penetration. Thus, the travel time of the base case slightly increased comparing with 0% AVs penetration.

Penetration	20%	50%	80%
Time (Min)	51.59	52.15	50.47
Speed (Km/h)	93.04	92.04	95.10

Table 4.4: The Travel Time and Speed of Base Case

According to Wang et al.'s study, there exists some relationship (shown in Figure 4.6) between speed and density (Wang et al., 2011). Therefore, the density of different penetration for baseline case could be found on the fitted curve, combining the speed calculated above: 13 veh/km for 20% and 50%, 12 veh/km for 80%.



(a) (b)

Figure 4.5 (a): Relationship between ACC% and Travel time; (b) Travel time for 0%, 12%, 35%,72% and 100% (Calvert et al.,2017).

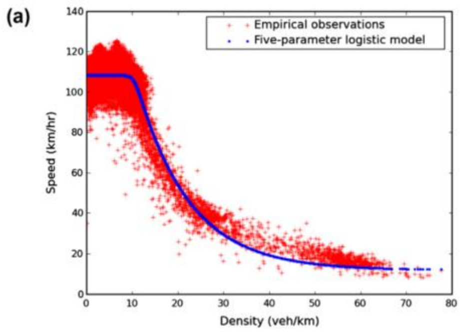


Figure 4.6: Relationship between Speed and Density (Wang et al., 2011)

Speed is a vital parameter to do the analysis as being mentioned above. To obtain the effect of exclusive lanes, CVs and AVs' speed should first be calculated or estimated. This case study uses density to estimate the speed on every single lane. According to Table 4.2, the change in density could be calculated. Combining the density for baseline case, the density for the alternative case could be calculated. Then, the speed of vehicles in the project case could be estimated by the fitted curve in Figure 4.6. In addition, considering the different headway between AVs and CVs, the curve should be changed when estimating AVs' speed. According to the study of Hussain, Ghiasi and Li, the headway of CVs is roughly 2 second while the headway between two AVs is 0.45s (Hussain et al.,2016). This means the density of AVs is around 4 times more than that of CVs at the same speed. Therefore, the abscissa axis of the curve should be scaled down to a quarter. Table 4.5 illustrated every lane's speed in different penetration and its difference compared to the base case. In this table, green grids represent the lanes for CVs, and red grids mean exclusive lanes for AVs. In addition, when AVs reach the highest speed (the left part of the curve in Figure 4.6), the speed changes to 120km/h, which the limitation speed on the motorway in China. In Table 4.5, red numbers meantime increases and speed decreases. On the contrary, the green number represents time-saving and speed improvement. The increase of AVs’ speed is because AVs could run at a fast speed in 100% AV penetration and keep a small headway. Besides, the main reason for CVs’ speed change is the car density in a single lane. Higher density leads to a lower speed for CVs and vice versa.

20% with 1 AVs lane	1	2	3	4
Travel Time (min)	53.3	53.3	53.3	40.0
Time Difference (min)	+1.71	+1.71	+1.71	-11.59
Speed (km/h)	90.0	90.0	90.0	120.0
Speed Difference (km/h)	-3.04	-3.04	-3.04	+26.96
Density (veh/km)	13.9	13.9	13.9	6.2
50% with 1 AVs lane	1	2	3	4
Travel Time (min)	44.4	44.4	44.4	40.0
Time Difference (min)	-7.75	-7.75	-7.75	-12.15
Speed (km/h)	108.0	108.0	108.0	120.0
Speed Difference (km/h)	+15.96	+15.96	+15.96	+27.96
Density (veh/km)	10.0	10.0	10.0	18.0
50% with 2 AVs lanes	1	2	3	4
Travel Time (min)	56.5	56.5	40.0	40.0
Time Difference (min)	+6.5	+6.5	-10	-10
Speed (km/h)	85.0	85.0	120.0	120.0
Speed Difference (km/h)	-7.04	-7.04	+27.96	+27.96
Density (veh/km)	15.0	15.0	9.0	9.0
80% with 2 AVs lanes	1	2	3	4
Travel Time (min)	44.4	44.4	40.0	40.0
Time Difference (min)	-5.6	-5.6	-10	-10
Speed (km/h)	108.0	108.0	120.0	120.0
Speed Difference (km/h)	+12.9	+12.9	+24.9	+24.9
Density (veh/km)	7.1	7.1	16.9	16.9

Table 4.5: Travel Time, Speed and Density of Different Lanes in 4 Scenarios

The travel time for both CVs and AVs in scenario 2 and scenario 4 decreased. However, in the rest scenarios, the travel time for CVs increase and that for AVs decreases. The reason for speed change for CVs is mainly because of the change of density in CVs lanes. Both AVs and CVs' travel time would change, which means there is the cost or benefit for AVs and CVs. If travel time decreases, there would be a benefit for drivers, and vice versa, the increase means more travel time cost. The value of travel time saving could be monetized according to the travel type and the average wages (U.S. Department of Transportation, 2015). This document recommends time-saving at 70% of the salary for intercity personal travel and 100% of the salary for intercity business travel. In addition, this document also shows that the proportion of personal intercity travel is 78.6% and 21.4% for business travel (U.S. Department of Transportation, 2015). Thus, the value of time (VoT) could be counted based on the following equation:

$$\text{VoT}= 70\% * w * 78.6\% + w * 21.4\%$$

In which

w: average wage

According to the Statista, an employee's average annual salary working for non-private organizations in urban China is 82413 yuan (Statista, 2019), which is 11773.3 dollars. And the weekly working hours is 46 hours (Statista, 2018). Thus, the minutely wage in China can be calculated, which is about 0.082 dollars. Therefore, the calculated VoT is 0.0627 dollars per minute. In addition, according to Zhong et al.'s study, autonomous vehicles could reduce commuters' value of travel time by 18–32% compared to driving (Zhong et al., 2020). Therefore, this analysis estimated that the VoT for AVs is reduced by 25%. Thus, the VoT for AVs is 0.047 dollars per minute. To make the data more accurate, the number of passengers was also under consideration. This number is collected by observation due to a few approaches to this number from official reports and scientific thesis. This observation counted 200 cars to calculate the average number of passengers in a single-car (the observation results are shown in Appendix-B). The average number of passengers calculated by the collected data is 2.6 per car. Therefore, the travel time value of the selected section can be calculated by the data mentioned above. Table 4.6 shows the value of time for one AV or CV in different scenarios and the difference between baseline and project cases. Comparing with the result of Table 4.5, higher speed means less time spent on the travel and thereby leads to the change of VoT.

	Baseline (dollars per car)	***Alternative (dollars per car)***	***Difference (dollars per car)***
20% with 1 AVs lane			
AVs	2.417	1.874	-0.543
CVs	3.223	3.332	+0.109
50% with 1 AVs lane			
AVs	2.444	1.874	-0.569
CVs	3.258	2.777	-0.481
50% with 2 AVs lanes			
AVs	2.444	1.874	-0.569
CVs	3.258	3.528	+0.27
80% with 2 AVs lanes			
AVs	2.366	1.874	-0.491
CVs	3.154	2.777	-0.377

Table 4.6: VoT and Its Difference for a Single Car in Different Scenarios and Base Case

4.6.2 Fuel consumption

Ahn et al.'s model shows some relationship among speed, Instantaneous speed and acceleration levels (Ahn et al., 2002). Also, Davis and Boundy's study shows the simple relationship between speed and fuel consumption for midsize conventional gasoline cars (Davis & Boundy, 2020).

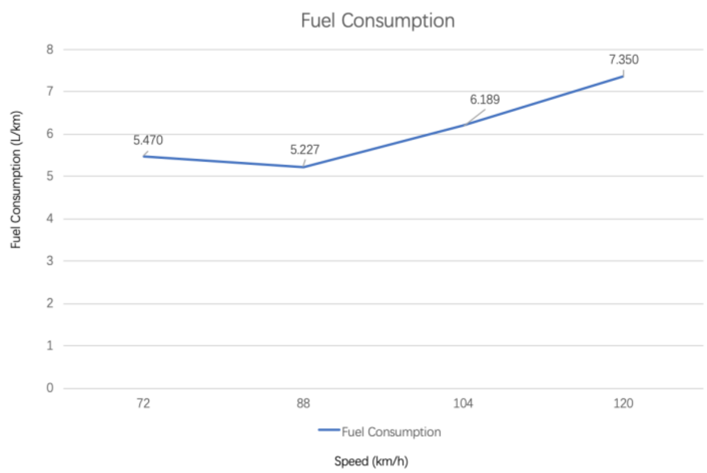


Figure 4.7: Relationship Between Fuel Consumption and Speed

Figure 4.7 demonstrates the relationship between speed and fuel consumption based on the data from Davis and Boundy's study. The fuel consumption could be calculated by the following formulas:

$$f = \begin{cases} -0.0152v + 6.5635\ (72 < v \leq 88) \\ 0.0664v - 0.61125\ (88 < v \leq 120) \end{cases}$$

in which

f: fuel consumption

v: speed

Therefore, the fuel consumption for different scenarios could be counted in Table 4.7:

	Baseline (l/100km)	***Alternative (l/100km)***	***Difference (l/100km)***
20% with 1 AVs lane			
AVs	5.53	7.35	+1.82
CVs	5.53	5.33	-0.2
50% with 1 AVs lane			
AVs	5.48	7.35	+1.87
CVs	5.48	6.44	+0.96
50% with 2 AVs lanes			
AVs	5.48	7.35	+1.87
CVs	5.48	5.27	-0.21
80% with 2 AVs lanes			
AVs	5.7	7.35	+1.65
CVs	5.7	6.44	+0.74

Table 4.7: Fuel consumption and Its Difference for Different Scenarios and Base Case

The price of gasoline is 0.83 dollars per litre in China. And according to the *notice on continuing to increase the consumption tax on refined oil*, the fuel tax for gasoline is 0.232 dollars per litre (State Taxation Administration, 2015). Thereby, the value of fuel consumption and fuel tax revenue could be computed with the fuel price and the tax rate. Table 4.8 shows the cost of fuel for both case and project case. Also, the difference between the base case and the project case is also illustrated in

Table 4.8.

	Baseline (dollar per car)	***Alternative (dollar per car)***	***Difference (dollar per car)***
20% with 1 AVs lane			
AVs	3.672	4.880	+1.208
CVs	3.672	3.539	-0.133
50% with 1 AVs lane			
AVs	3.639	4.880	+1.241
CVs	3.639	4.276	+0.637
50% with 2 AVs lanes			
AVs	3.639	4.880	+1.241
CVs	3.639	3.499	-0.14
80% with 2 AVs lanes			
AVs	3.785	4.880	+1.095
CVs	3.785	4.276	+0.491

Table 4.8: Cost of Fuel for Baseline case and 4 Alternative Case

	Baseline (dollar per car)	***Alternative (dollar per car)***	***Difference (dollar per car)***
20% with 1 AVs lane			
AVs	1.026	1.364	+0.338
CVs	1.026	0.989	-0.037
50% with 1 AVs lane			
AVs	1.017	1.364	+0.347
CVs	1.017	1.195	+0.178
50% with 2 AVs lanes			
AVs	1.017	1.364	+0.347
CVs	1.017	0.978	-0.039
80% with 2 AVs lanes			
AVs	1.058	1.364	+0.306
CVs	1.058	1.195	+0.137

Table 4.9: Tax Revenue of Fuel for Baseline case and 4 Alternative Case

If the fuel consumption increases, the drivers cost more for fuel while the government could have more fuel tax revenue. Vice versa, if the fuel consumption decreases, the drivers are beneficial while the government will have less income. Table 4.9 shows the fuel tax revenue for both base case and alternative case and the difference between these two kinds of cases. The calculation of fuel consumption does not consider the penetration of electric vehicles or other new energy vehicles such as hydrogen vehicles due to the future's complicated market. However, it is not complicated to calculated the energy cost in a mixed situation. The following formula could calculate the average cost of energy:

$$AC = \sum_{1}^{n} a_n * p_n$$

in which

AC: average cost of energy (dollars per 100km)

a_n: price of energy n (dollars per 100km)

p_n: penetration of energy n (%)

AC could replace the fuel price to calculated the spend of energy in mixed vehicle market in the future.

4.6.3 Safety

According to Shefer and Rietveld's study, the accident fatalities is related to density (Shefer & Rietveld, 1997).

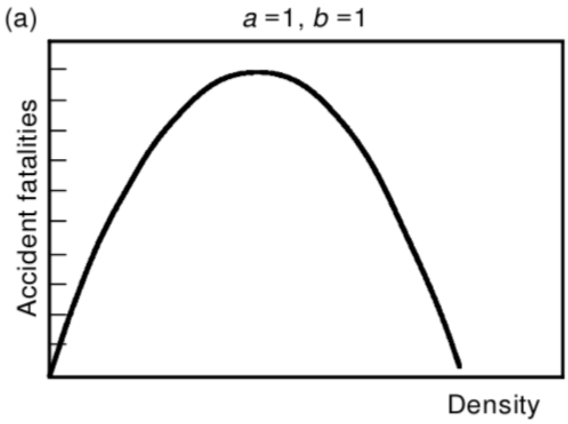


Figure 4.8: relationship between fatalities and Density (Shefer & Rietveld, 1997)

Figure 4.8 shows the relationship between safety and density. Considering the low density on the motorways, this analysis roughly regards the relationship as a linear relationship. Moreover, the fatality rate is closely relative to AVs penetration. Their results indicated the reduction of conflicts was 12–47%, 50–80%, 82–92% and 90–94% for the 25%, 50%, 75% and 100% penetration rates respectively (Papadoulis et al., 2019). In the calculation, the reduction of conflicts for 20%, 50% and 80% was estimated at 12%, 65% and 87% respectively. Therefore, the accident rate could be roughly calculated by the following formula:

$$R = R_a * (1 + D) * (1 - k)$$

in which

R: Accident rate

R_a: Average accident rate

D: Change of density

k: reduction of conflicts because of AVs (12%, 65% and 87%)

The change in the accident rate represents the accident cost change. According to the Handbook on the external costs of transport, the external cost for the accident in Europe is 4.5 cent euro per pkm (passenger- kilometre). In Essen et al.'s study, the cost of fatalities, serious injuries and slight injuries are 3,273,909 euros, 498,591 euros and 38,514 euros (Essen et al., 2019). However, based on Tan et al.'s study, the cost of these three kinds of accidents in China is 413,168 euros, 112,408 euros and 2626 euros, respectively (Tan et al., 2020). The cost in Europe is roughly ten times that in China. Thus, this analysis assumed that the accident cost in China is 0.45 cent euro (0.54 cent dollar) per pkm. The following table shows the value of safety for a single vehicle in different situations. AVs had a good performance in safety when running in 100% AV penetration; therefore, the cost of safety for AVs decreased. And for CVs, they were in 0% AV penetration. Thus they were more likely to have an accident and have higher safety cost.

	Baseline (dollar per car)	***Alternative (dollar per car)***	***Difference (dollar per car)***
20% with 1 AVs lane			
AVs	1.071	0.029	-1.041
CVs	1.071	1.303	+0.232
50% with 1 AVs lane			
AVs	0.426	0.084	-0.342
CVs	0.426	0.936	+0.510
50% with 2 AVs lanes			
AVs	0.426	0.042	-0.384
CVs	0.426	1.404	+0.978
80% with 2 AVs lanes			
AVs	0.146	0.079	-0.067
CVs	0.146	0.660	+0.514

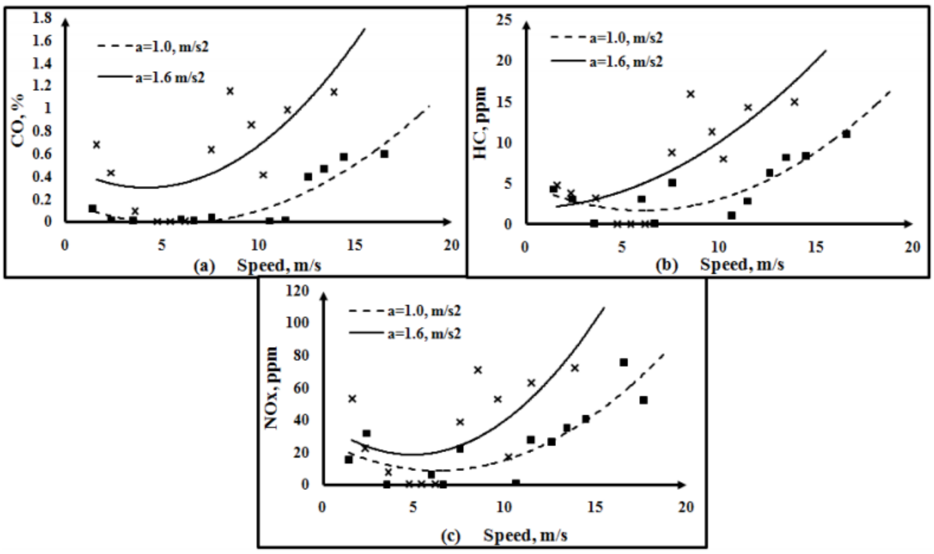
Table 4.10: The Cost and Benefit of Safety for Baseline case and 4 Alternative Cases

4.6.4 Noise

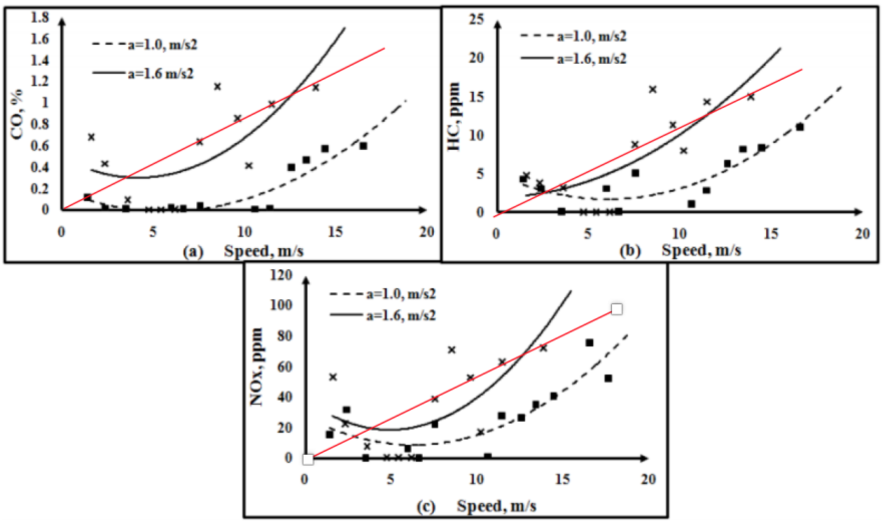
Traffic noise is often considered useless and comes with a high cost. With the increase of urbanization and traffic volume, the emission of traffic noise has brought more and more serious environmental problems (Essen et al., 2019). This analysis ignores the noise spend because the selected highway is far away from the city. Therefore, the impact of noise is small which can be ignored.

4.6.5 Emission

Previous study illustrated that the emission is related to the speed (Oneyama et al.,2001; Shridhar Bokare& Kumar Maurya, 2013). Figure 4.8 (a) demonstrated the relationship between speed and emission.



(a)



(b)

Figure 4.9: (a) Relationship between Speed and Emission; (b) Simplified fitting curve (Shridhar Bokare& Kumar Maurya, 2013)

This analysis assumed that the correlation is a linear correlation to simplify the relation between speed and emission (see Figure 4.9 b). Due to the assumption of linear correlation for different emission gas, the analysis considered all emission gas as a whole to simplify the analysis and calculation. According to the study made by Istamto, the weighted willingness to pay for air pollution is about 40 euros per month in five countries (Istamto et al., 2014). And in China, the willingness to pay for emission is about 26 euro per year (Duan et al., 2014). Thus, the WTP in Europe is roughly 18 times that in China. According to the Handbook on the external costs of transport, the external cost for air pollution and climate change in Europe is 1.89 cent euro per pkm (Essen et al., 2019). Therefore, the external cost for emission in China is estimated at 0.1 cent euro (0.0012 dollars) per pkm. And thereby, the cost of emission, in this case, could be calculated in the following formula:

$$C_e = AC_e * n_c * n_p * L$$

In which

AC_e: Average cost of emission (0.0012 dollar per pkm)

C_e: Cost of emission

n_c: Car quantity

n_p: Passenger quantity

L: distance

Therefore, the cost of emission on the selected highway could be calculated. However, due to the small value of ACe the value of Ce is also small comparing with another spending. Table 4.11 shows the cost and benefit of emission for AVs and CVs in 4 scenarios. As similar with fuel consumption, the emission also did not consider the new energy vehicles such as electric cars and hydrogen cars. In the future, the cost of emission was changed because of the introduction of new energy vehicles. Comparing with Table 4.5, the higher speed leads to higher emission and thus, the cost of emission increases with the improvement of speed.

	Baseline (dollar per car)	***Alternative (dollar per car)***	***Difference (dollar per car)***
20% with 1 AVs lane			
AVs	0.09304	0.12	+0.02696
CVs	0.09304	0.09	-0.00304
50% with 1 AVs lane			
AVs	0.09304	0.12	+0.02696
CVs	0.09304	0.108	+0.01496
50% with 2 AVs lanes			
AVs	0.09304	0.12	+0.02696
CVs	0.09304	0.085	-0.00804
80% with 2 AVs lanes			
AVs	0.09510	0.12	+0.0249
CVs	0.09510	0.108	+0.0129

Table 4.11: The Cost and Benefit of Emission for Baseline case and 4 Alternative Case

4.6.6 Equipment

To manage the exclusive AV lanes and ensure that CVs and AVs could run on the corresponding lanes, some enforcement was designed to preserve order. As the method used now, the most common traffic law enforcement in China is the traffic rules. Thus, this case study assumes that the traffic administration will add some new rules for exclusive AV lanes and if CVs or AVs break the rules, the drivers will be fined. To comply with traffic regulations and punish the drivers who violate the rules, some new traffic camera will be applied for management. Therefore, the cost of camera instalment was defined as one of the costs for the application of exclusive AV lanes.

It is different compared with other costs when considering the equipment cost because traffic cameras have service life which means this kind of cost is long-term cost. Therefore, this cost-benefit analysis analysed the cost and benefit for several years, and thereby the discounted rate was also under consideration.

However, the price of traffic cameras exclusively provided by the traffic department is not transparent. Hence, this study interviewed several engineers who work for the camera companies to obtain some relative information including price of camera and control system, service life, cost of maintenance and instalment density. According to the data collected from the 8 engineers working for Hikvision and Dahua, the two largest surveillance and security manufacturers in China, every single camera with the control system is around 6,350 dollars (40,000 yuan). Besides, the service life is about 5 years, and there is no follow-up maintenance cost for cameras based on the information provided by the engineers (see Appendix-C). Thus, this study's period of calculation is equal to the service life of cameras, which is 5 years. In addition, the recommended instalment density is about one camera per kilometres. Thus, in this case study, the selected road needs 80 cameras to regulate the exclusive AV lanes. Consequently, the cost of equipment is 508,000 dollars and the service life is 5 years. Therefore, there existed long-term cost in analysis, and the values of different costs and benefits were discounted to see if the policy is beneficial in a period. As mentioned above, the period is 5 years which is one service life of cameras. And according to the World Factbook, the discounted rate in China is 2.25% (Central Intelligence Agency, 2017). The following formula is aimed to calculate the discount factor:

$$\frac{1}{(1+i)^n}$$

in which,

i= discount rate

n= year in which costs and benefits are discounted

4.7 Overview of costs and benefits & Presentation of Results

This case study analyses the benefit and the cost of a new policy for autonomous vehicles and conventional vehicles on the motorway in a selected stretch of road in Eastern China to figure out the net value of this new policy. In this analysis, three different stakeholders (autonomous vehicles, conventional vehicles and government respectively) are involved and 5 aspects, including travel time, fuel consumption, emission & noise, equipment and safety, are considered. In these 5 aspects, travel time, fuel consumption, equipment and safety play significant roles in this CBA; however, the impact of emission and noise is tiny. Table 4.12 illustrated the overview result for 4 different scenarios in 5 years.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cost	-103.2	-205.5	-262.9	-187.0
Benefit	72.0	288.4	144.1	256.2
NPV	**-31.2**	**82.8**	**-118.1**	**69.2**
B/C Ratio	0.698	1.403	0.548	1.370

Table 4.12: Overview Result for 4 Different Scenarios in A 5-Year Period (in million dollars)

According to Table 4.12, the NPV in scenario 1 and scenario 3 is negative, meaning the exclusive AV lanes would cost more. On the contrary, the NPV in scenario 2 and 4 are active, representing that the exclusive AV lanes are beneficial to society. For different aspects shown in the conceptual model, Table 4.13 demonstrate the change in various aspects. In Table 4.12, negative values mean cost and positive values represent benefits. It is clear that the cost of fuel consumption, emission and safety increased in all four scenarios.

Moreover, the change in fuel consumption and safety is more significant than the change in emission. For travel time, in scenario 1 and 3, the travel time cost increased, and on the contrary, it decreased in scenario 2 and 4. For more detail, see Appendix-D.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Change in fuel consumption	-3.4	-104.5	-42.3	-114.0
Change in Time cost	-13.6	227.4	-20.1	203.7
Change in Safety cost	-13.5	-36.1	-55.0	-16.4
Change in Emission Cost	-0.09	-3.44	-0.89	-3.68
Equipment Cost	-0.51	-0.51	-0.51	-0.51
NPV	**-31.2**	**82.8**	**-118.1**	**69.2**

Table 4.13: Result of Different Aspects in 4 Scenarios (in million dollars)

As mentioned above, there are three different stakeholders in the analysis, including autonomous vehicles, conventional vehicles and governments. For different stakeholders, the impact of exclusive AV lanes is different. Table 4.14 shows the net value of AVs, CVs and government in 4 different situations for one day regardless of the long-term cost of traffic cameras.

	20% with 1 AVs lane	50% with 1 AVs lane	50% with 2 AVs lanes	80% with 2 AVs lanes
AVs	14619	19329	20803	15998
CVs	-33384	5741	-99682	-1102
Government	786	23737	9614	25894

Table 4.14: Net Value of different stakeholders in different scenarios in one day (in dollars).

According to Table 4.14, it can be concluded that:

- In all four situations, the government is beneficial because of the increase in fuel consumption to have higher revenue from fuel tax.
- For autonomous vehicles, they get to benefit from the new policy in all four scenarios. And it reaches a peak in situation 3 at 20,803 dollars. The benefit shows an increasing trend with the improvement of penetrations.
- While for conventional vehicles, the increase in cost exceeds the growth of benefit in scenario 1, 3 and 4. CVs will significantly cost more after the introduction of exclusive lanes in the first and third scenario. However, the extra cost in the last scenarios increases slightly.

For CVs in scenario 1and 3, the travel time and cost of accident increase while the fuel spending declines. It can be found that the average quantity of passenger in a single-car is relatively high (2.6). This will lead to higher travel time value and higher external cost of accidents which means the impact of safety and travel time will be enlarged. Even the average wages in China are low, and the fuel price is relative high, the fuel cost decrease cannot compensate for the value of time growth and the accident cost. Therefore, the passengers will spend more even they pay less on fuel. And in the last scenario, CVs will get benefit from saving travel time, but the increasing cost of fuel and accident exceeded the benefit; therefore, CVs will slightly cost more in this scenario. Additionally, for AVs in all situations, the value of time-saving and accident cost reduction exceeded the cost of fuel increase. This is also because the number of passengers is relatively high, magnifying the impact of travel time and safety.

It can be found that in the second scenario, all three stakeholders are beneficial. In this scenario, AVs' density in exclusive lanes increases, and the density of CVs declines. Due to AVs' better capacity in 100% penetration, AVs can still run at high speed. Meanwhile, the lower density in CVs lanes means that CVs can also drive faster to save the travel time. The situation in scenario 4 is similar, but the penetration change in scenario 4 is more significant than scenario 2. This leads to a more noticeable change in safety cost. This is why CVs in scenario 2 can be beneficial, but the CVs in scenario 4 is slightly cost more. Therefore, there is a preliminary conclusion that the policy will be beneficial for all three stakeholders when the penetration of AVs is higher than the proportion of exclusive lanes and the penetration should not be too high (for example, 80%).

The above conclusion and results are based on the undiscounted data, regardless of the cost of the equipment. Table 4.15 shows the results of CBA for different stakeholders in 4 scenarios in a 5-year period.

		20% with 1 AVs lane	**50% with 1 AVs lane**	**50% with 2 AVs lanes**	**80% with 2 AVs lanes**
Costs	AVs	-25.32	-75.89	-75.89	-137.78
	CVs	-77.43	-129.14	-186.50	-48.71
	Gov.	-0.51	-0.51	-0.51	-0.51
	Total Cost	**-90.87**	**-205.54**	**-262.90**	**-187.00**
Benefits	AVs	50.28	108.90	111.42	165.10
	CVs	20.41	138.94	16.26	46.83
	Gov.	1.34	40.52	16.42	44.22
	Total Benefit	**69.91**	**288.37**	**144.10**	**256.16**
NPV		**-31.2**	**82.8**	**-118.1**	**69.2**
B/C Ratio		**0.698**	**1.403**	**0.548**	**1.370**

Table 4.15: Overview of CBA for 4 Different Scenarios (in million dollar)

According to Table 4.15, the NPV in scenario 1 and scenario 3 is negative, meaning the exclusive AV lanes would cost more. On the contrary, the NPV in scenario 2 and 4 are active, representing that the exclusive AV lanes are beneficial to society. Compared to the base case, the result is that AVs have better traffic capacity in 100% penetration. When the real AVs penetration is higher than the proportion of exclusive lanes (number of AV lanes/ number of all lanes), AVs could drive in a relatively high speed and in a high-level safety, even the density of AVs is higher in AV lanes. In the meanwhile, the car density in CV lanes declines, which make CVs drive faster. Thus, both AVs and CVs could get benefit from saving travel time. In addition, the cost of CVs in scenario 4 slightly exceeds the benefit. This is due to the significant change of penetration (decline form nominal 80% to nominal 20%), which plays an essential role in accident decrease. It leads to a higher external cost of accidents. But in scenario 4, this new policy is societally beneficial as a whole.

Overall, according to the results of CBA, there is a rough predict indication that when the real AVs penetration exceeds the proportion of exclusive AV lanes (quantity of AV lanes/ quantity of all lanes), the exclusive AV lanes is societally beneficial.

To better answer the research question, this research calculated the penetration when NPV is around 0. As shown in Table 4.16, for one exclusive AV lane, the real penetration is 15.5% when the NPV is about 0. The real penetration is 46.1% for two exclusive AV lanes when the NPV is around 0. According to the results shown in the Table 4.16, the research question could be answered: for one exclusive AV lane, when the real penetration exceeds 15.5%, the exclusive AV lanes are beneficial; for two exclusive AV lanes, the exclusive AV lanes are beneficial when the real penetration is more than 46.1%.

Quantity of AV lanes	1	2
Real Penetration	15.5%	46.1%
Change in fuel consumption	-9.2	-71.3
Change in Time cost	10.3	44.3
Change in Safety cost	-0.7	29.1
Change in Emission Cost	-0.4	-2.2
Equipment Cost	-0.5	-0.5
NPV	**-0.6**	**-0.6**
B/C Ratio	**0.983**	**0.996**

Table 4.16 Penetrations around 0 NPV (in million dollars)

5 Sensitivity Analysis

Sensitivity analysis is one of the commonly used methods to analyze uncertainty in investment projects' economic evaluation. This chapter introduce the variants and risks in CBA and the results of the sensitivity analysis. Section 5.1 describes the variants and risks in cost-benefit analysis. Section 5.2 describes the result of sensitivity analysis.

5.1 Analyse variants and risks

CBA is an ex-ante of policy measures which means that before the measure is taken, the costs, effects and related benefits of the measure will be evaluated in the CBA. However, this kind of cost and benefit forecast is uncertain, which makes the results of CBA uncertain. Due to some simplification and some assumption in this case study, some variants and risks should be under consideration in the future study or optimization. According to the general guidance for Cost-Benefit Analysis, there are three kinds of uncertainty: uncertainty about knowledge, uncertainty about policy and uncertainty about future developments (Romijn & Renes, 2013).

For uncertainty about knowledge, it is caused by the limitations of our knowledge about the influence of a new policy and how to value them. Following is the uncertainty about knowledge in this case:

- There is some simplification of the relation between speed and certain impacts, such as emission and accident rate. But these relations cannot reflect the correlation in real life, which will affect the results of this case study.
- As mentioned above, one of the most critical parameters is speed. The speed in the alternative policy is estimated by density. This approach could roughly predict the speed, but it may not be accurate enough. Thus, the change in velocity is uncertain.
- According to the CBA, it is found that the main change is travel time saving and fuel consumption. If the wage and fuel price changes, the result will be significantly affected. This means the specific impact of wages and fuel price is uncertain. Therefore, a sensitivity analysis is essential to show the effect of fuel price and wages.

For policy uncertainty, the policy environment may be changed in the future, which leads to the uncertainty about policy. In this case, this kind of uncertainty shows in the following aspects:

- This case study only considers in one situation that AVs can only use self-driving technology on exclusive lanes. They are not allowed to drive away from exclusive lanes. If taking the lane change into account, the situation will become more complex. And there is no extra fee for AVs and CVs for using the exclusive lanes.

- This case study assumed that the administration would use a monitoring system to regulate the exclusive AV lanes. However, some other way to manage this new policy is installing the fence between AV lanes and CV lanes.

The uncertainty about future development stems from the fact that the future may differ from expectations. Thus, the following aspects show the uncertainty about future development in this case study.

- The willingness of using self-driving cars on highways is uncertain in the future. The assumption was not very accurate.
- This case study does not take new energy cars, such as electric vehicles, into account. The application of new energy vehicles will affect energy spending, thereby significantly impact the results.

There are also some other variants and risk in the calculation process:

- Some data are collected by observation on the spot. And also, some calculation used the average data. These two kinds of data may not be convincing due to the inadequate sample.

5.2 Sensitivity Analysis

Sensitivity analysis is one of the commonly used methods to analyze uncertainty in the economic evaluation of investment projects. Identify the sensitive factors that have an important impact on the investment project's economic performance indicators from multiple uncertain factors, analyze and calculate the degree of influence and sensitivity on the economic performance indicators of the project, and then judge the project's ability to withstand risks. In addition, consistency between the results of primary analysis and the results of sensitivity analysis may strengthen the conclusions or credibility of the findings. Thus, it is essential to have a sensitivity analysis to assess the robustness of the results (Saltelli, 2002).

As mention in the variant and risk part, there exists uncertainty about knowledge and future development. These uncertainties will impact the development of costs and benefits. In this case study, for example, with economic development, the average wage will increase in the future, which means the VoT will also grow up. Hence, the impact of exclusive AV lanes in travel time saving will change correspondingly. According to the case mentioned in Saltelli's study, this sensitivity analysis used +/- 10% alteration to measure the alteration of NPV.

NPV	Scenario1		Scenario2		Scenario3		Scenario4	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
Fuel Price	-28.35	-27.33	74.90	96.17	-112.72	-103.41	56.83	79.42
Wage	-28.91	-28.91	108.37	62.69	-109.03	-107.11	88.43	47.83
Safety	-28.98	-27.84	82.28	88.79	-107.11	-103.03	69.91	66.35
Emission	-27.86	-26.77	85.18	85.88	-108.17	-107.96	67.76	68.49
Equipment	-27.89	-28.98	85.48	85.58	-108.12	-108.02	68.08	68.18

Table 5.1: NPV of Sensitivity Analysis for +/-10% alteration (in million dollar)

Change in NPV	Scenario1		Scenario2		Scenario3		Scenario4	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
Fuel Price	1.837%	-1.837%	-12.430%	12.430%	4.309%	-4.309%	-16.579%	16.579%
Wage (VoT)	3.846%	-3.846%	26.704%	-26.704%	0.889%	-0.889%	29.800%	-29.800%
Accident Cost	4.082%	-4.082%	-3.806%	3.806%	4.659%	-4.659%	2.611%	-2.611%
Emission Cost	0.053%	-0.053%	-0.408%	0.408%	0.096%	-0.096%	-0.536%	0.536%
Equipment Cost	0.182%	-0.182%	-0.059%	0.059%	0.047%	-0.047%	-0.075%	0.075%

Table 5.2: Change in NPV of Sensitivity Analysis for +/-10% alteration

Table 5.1 and Table 5.2 show that the change in fuel price means the change of fuel consumption. In addition, the change in wage represents the change of VoT, which impact the value of travel time-saving. Table 5.2 shows that an alteration of 10% in emission and equipment results in a slight change (<1%). The change in fuel price, wages and accident cost plays a more significant role in this sensitivity analysis.

In scenario 2 and 4, the change in wage leads to a significant change in NPV (26.704% and 29.800% respectively). This is because both CVs and AVs benefit from travel time saving due to the introduction of the exclusive AV lanes. Thus, when the wage changes, the benefit of time-saving also significantly change. Also, fuel price plays an important role in this sensitivity analysis. Both CVs and AVs increase their speed which makes higher fuel consumption so that the cost of fuel consumption obviously grows up. This is also why the relation between wage change and NPV change is active, and the relation between fuel price changes and NPV changes is negative.

However, in scenario 1 and 3, the change of accident cost plays the most significant role in the sensitivity analysis. 10 % alteration in accident cost respectively leads to 4.082 % and 4.695% in NPV change in scenario 1 and 3. Besides, in scenario 3, a 10% change in fuel price leads to 4.309% change in NPV, which is obviously impacting the NPV.

In addition, the change of different components is usually not equal in the reality. Table 5.2 just dedicates the impact of single component's change to find out which component has the most significantly determine the outcomes. If these components change, the new NPV will also change in proportion.

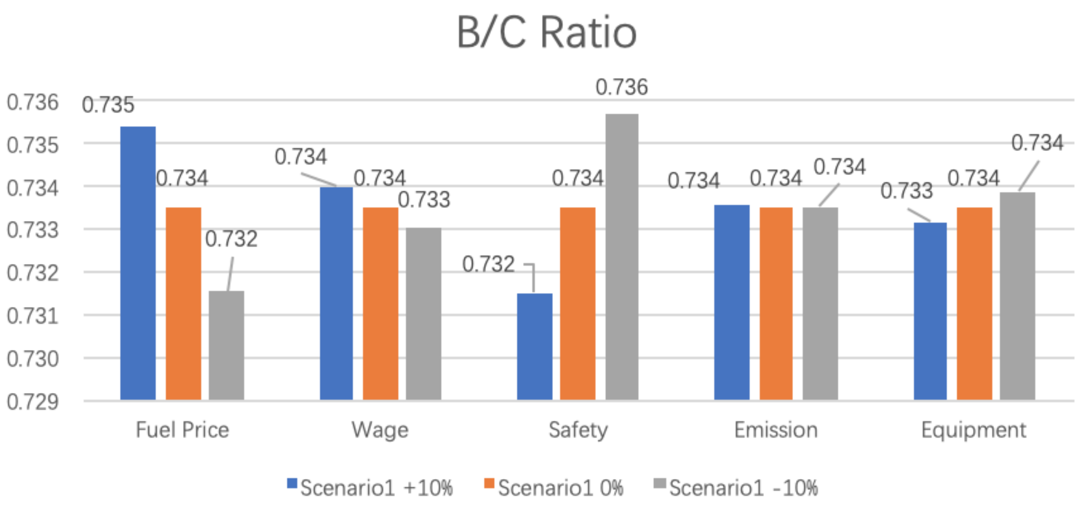


Figure 5.1: B/C Ratio of Sensitivity Analysis in Scenario 1

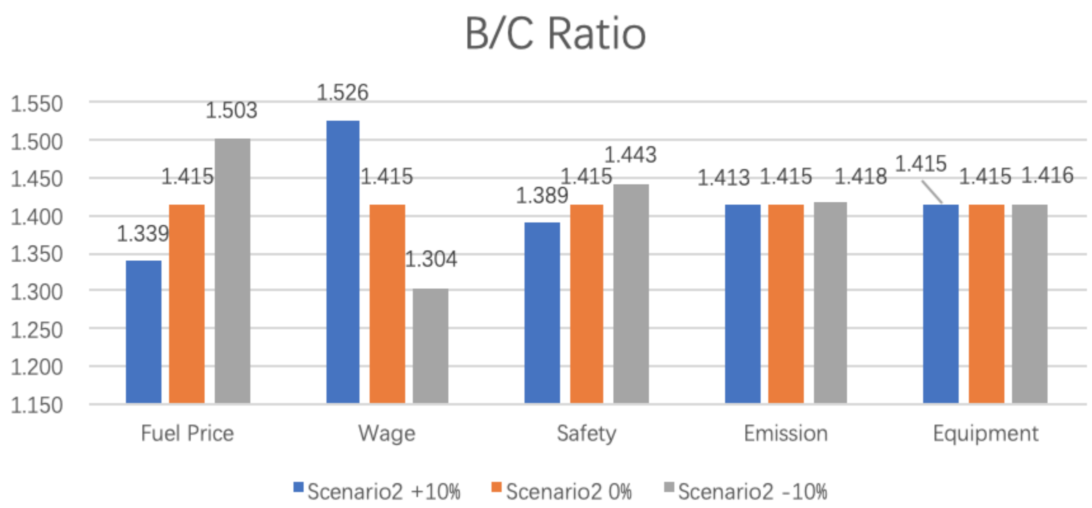


Figure 5.2: B/C Ratio of Sensitivity Analysis in Scenario 2

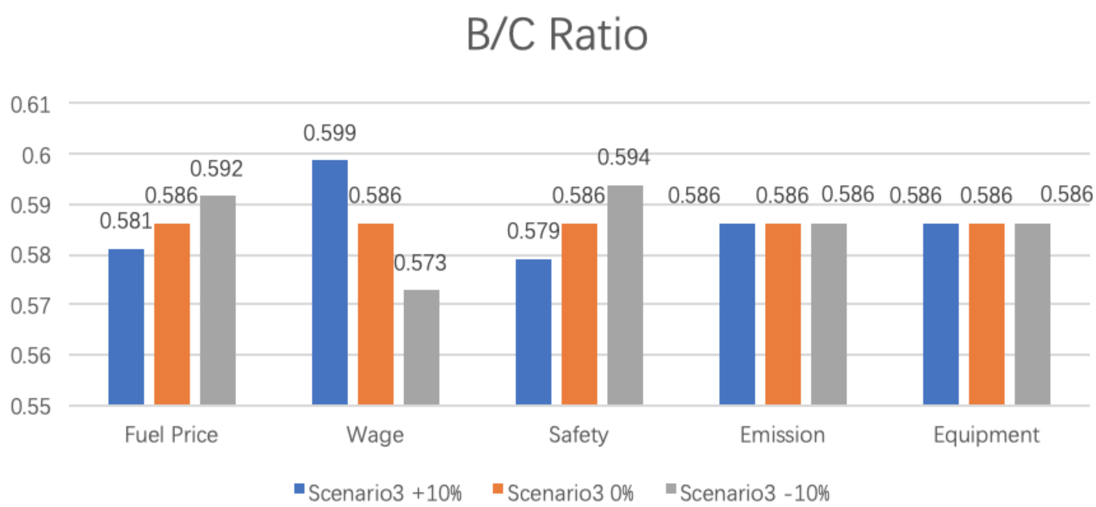


Figure 5.3: B/C Ratio of Sensitivity Analysis in Scenario 3

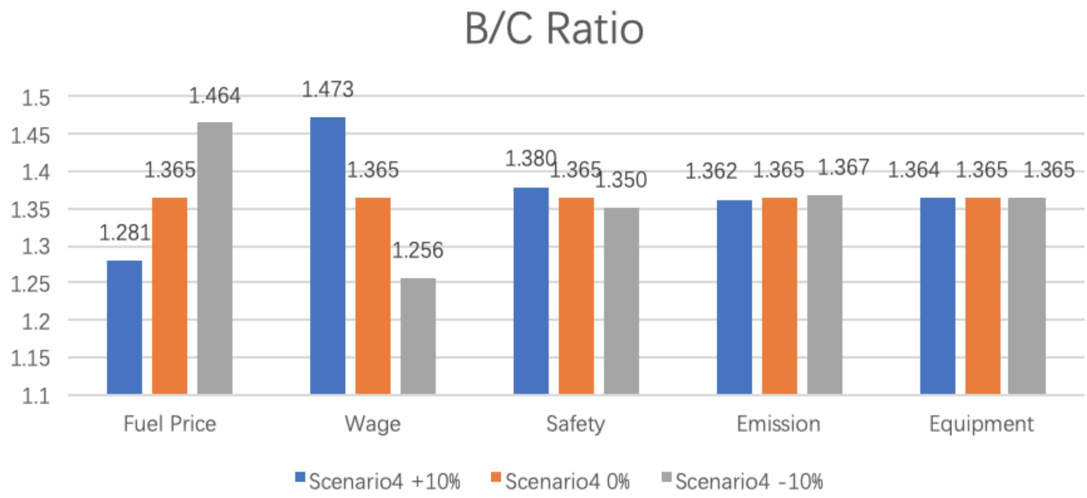


Figure 5.4: B/C Ratio of Sensitivity Analysis in Scenario 4

Figure 5.1-5.4 show the results of B/C ratio in the sensitivity analysis for four different scenarios. It is found that the change in fuel price, wage and safety leads to the obvious change in B/C ratio for all the four scenarios. In addition, the change in emission and equipment makes unconsidered changes in B/C ratio in all four scenarios.

6 Discussion

In the early process of this research, two significant scientific gaps were found. First, little research studied the exclusive AV lanes and clearly understood the impact of this new road management. Secondly, no research used CBA to analyse the societal impact of exclusive AV lanes. Therefore, this study focused on these two gaps and used a case study to understand the effects of exclusive AV lanes and used quantitative analysis to see if this policy is societal beneficial in different scenarios. In this chapter, the weak points and the strong points are discussed.

6.1 Strong Points

For strong point, this study considered a proper design and used proper enforcement to manage the order of exclusive AV lanes. And in this research, several scenarios and policies were under consideration. This is the basic to do the case study and the cost-benefit analysis. In this research, the exclusive AV lanes is not newly-built lanes but reallocated lanes based on the normal lanes. The cost of newly-built lanes is high and the construction period is long, which means newly-built exclusive AV lanes is difficult to be realized. In addition, the newly-built lanes may conflict with the original road plan. For example, a newly-built lane leads to higher traffic flow, but this area may have such a higher traffic flow. This will lead to a waste of resources. Therefore, in this research, lanes reallocation is applied to realize the exclusive AV lanes. To be more specific, the traffic department will reallocate the lanes and divide them into AVs lanes and CVs lanes. Besides, traffic administration will also introduce new traffic rules to manage the order in exclusive AV lanes; for example, drivers cannot change their lanes during the travel. Moreover, some equipment such as traffic camera will be installed to monitor cars' behavior to ensure the good order in exclusive AV lanes. In this research, four scenarios/ design are studied:

- 20% AVs with one exclusive lane
- 50% AVs with one exclusive lane
- 50% AVs with 2 exclusive lanes
- 80% AVs with 2 exclusive lanes

Additionally, considering different design could help policymakers flexibly adjust their decision to meet different stages of AV’s development.

Secondly, this research considered the impacts in several aspects, including traffic flow, emission, safety, noise and fuel consumption. According to the previous research made by other scholars, the higher AVs penetration makes drive safer. In AVs lanes, the penetration is 100% so that the safety of AVs increased. However, the penetration in CVs lanes is 0% which means the safety of CVs declined. Additionally, the change in car density in CV lanes and AV lanes will also impact safety. Higher density means higher accident rate in a relatively low density in motorways. Considering AVs and CVs as a whole, the exclusive AV lanes had a negative impact on safety in all four scenarios. For fuel consumption, it consists of two parts. For drivers, the change in speed will change the fuel consumption, and therefore, the fuel cost will also be changed. For the government, the change in fuel consumption means the change in fuel tax revenue. Higher fuel consumption leads to higher fuel tax revenue. According to the results, there was more fuel consumption in all four scenarios. Thus, the cost of fuel increased and the fuel revenue also increased. Referring to the noise and emission, the exclusive AV lanes change the speed of AVs and CVs so that the emission and noise will correspondingly change. In this research, the motorway is far away from the urban area so that the impact of noise was not under consideration. For emission, in all four scenarios, the cost of emission increased. Besides, the impact to fuel consumption, emission and noise did not consider the application of new energy vehicles because this research only studies the impact of exclusive AV lanes.

Besides, in this study, the impacts were monetized by using the date in China to calculate the net present value in CBA. The value of time is closely related to the average wage, and the value for different trip purpose is also different. Combining with different trip purposes, including business trip and personal trip, CVs' VoT is 0.0627 dollars. In addition, according to previous studies, autonomous vehicles could reduce commuters' value of travel time compared to driving because passengers in AVs could do what they want during the trip. Thus, the VoT of AVs is about 0.047 dollars. The cost of fuel consumption is related to the price of fuel. In this research, the fuel price in China is 0.83 dollars per litre, and the fuel tax is 0.232 dollars per litre. Thus, the change in fuel consumption could be calculated using fuel quantity, fuel price and fuel tax. For emission and safety, this CBA uses estimation to obtain the monetized value. According to the Handbook on the external costs of transport, the data on safety and emission costs in Europe could be given. Comparing with the willingness to pay for emission in China and that in Europe, the external cost of emission, including air pollution and climate change, was estimated at 0.0012 dollars per pkm. Similarly, by comparing with accident cost in China and Europe, the safety cost was estimated at 0.54 cent dollars per pkm.

Lastly, for the strong points, this study did a sensitivity analysis to show the results' robustness. According to the result of sensitivity, the change in fuel price, wage and accident cost will have an obvious influence on the results. This is closely related to the economy and social situation in a certain area. The sensitivity analysis could provide some guidance for future study.

6.2 Weak Points

There also exists some weak points in this research. First, this research is based on a case study. Thus, the results are only suitable for a particular area (Eastern China). In China, the income level is lower than that in Europe, and the fuel price is higher than that in Europe. This will lead to the change in VoT and fuel consumption which will impact the CBA result. And in China, the external cost of safety and emission is relatively lower because of the lower willingness to pay for emission improvement and relatively poor economy and medical security system. For example, in some developed European country with a higher wage, lower gasoline price, and higher emission and safety cost, the result of exclusive AV lanes may be changed.

Secondly, China's policies and enforcement may not be suitable for all countries. There are a great number of traffic cameras to regulate the behaviour of drivers in China. However, in some western countries where privacy is essential, this kind of enforcement is not suitable. For example, government or administrations will higher cost to protect drivers' privacy in European countries due to the General Data Protection Regulation. Hence, some other measures, such as fences, should be done to ensure the order in exclusive AV lanes. Thus, the cost of equipment and maintenance will be changed and thereby affect CBA results.

Moreover, this case study only considers in one situation that AVs can only use self-driving technology on exclusive lanes. They are not allowed to drive away from exclusive lanes. If taking the lane change into account, the situation will become more complex. And there is no extra fee for AVs and CVs for using the exclusive lanes which are also uncertain in the future. And this case study did not consider the junction on motorways. When considering the junction on the highway, the situation of exclusive AV lanes will become more complex. This new road policy should think of the lane change rules, and the exclusive lanes will consequently be impacted. Therefore, this case study is only limited in simple road networks, and when networks become complicated, a more comprehensive CBA will be needed.

Another weak point is that the societal effect was not comprehensive. Due to the limitation of CBA, the moral effects of exclusive AV lanes were not taken into account. To be more specific, this case study did not consider the impact on public perceived safety, risk distribution, privacy and fairness. These aspects will also be influenced after the application of exclusive AV lanes. However, this case study did not calculate the cost and benefit of these effects.

Furthermore, some other costs were not included in the CBA. For instance, the social and legal costs of rethinking responsibility regimes. The public need to accept the accidents on exclusive AV lanes, and the administrations also need to introduce new laws to distribute the responsibility of accident on exclusive AV lanes. Besides, the new algorithm might be needed to teach AVs how to drive on exclusive AV lanes. And the environmental cost of fuel consumption was overlooked. These kinds of cost were not considered in this case study.

This analysis is also regardless of the impact of other technology, such as electric cars. It will impact fuel consumption, emission and noise. For further study, the involvement of new energy cars could make the analysis more accurate. For data collection, some data were collected by observation which is not very precise for the calculation. And some assumption was used during the calculation process. For example, the willingness to use AVs on the motorway was assumed in the calculation which is actually uncertain in the future. This will also influence the accuracy of the results. And even this study has considered several impacts in different aspects, and they're still some other aspects that could also be involved, such as the impact to AV market and so on.

7 Conclusion and Recommendations

7.1 Conclusion

With autonomous vehicles' development, the mixed traffic situation becomes a hot topic. By 2020, autonomous driving has not mass-produced L3 or L4 high-level autonomous driving as expected a few years ago. On the other hand, although the concept of exclusive AV lanes has been proposed, it is still challenging due to technical and market reasons. Besides, the impact of these kinds of new road policy is uncertain, and there is little research study the effect of exclusive AV lanes quantitatively. Therefore, the purpose of this research is to use cost-benefit analysis to analyze the impact of exclusive AV lanes and find if this new policy is societally beneficial. In this research, impacts were monetized. The net present value was calculated for four different scenarios (20% AVs with one exclusive lane, 50% AVs with one exclusive lane, 50% AVs with two exclusive lanes and 80% AVs with two exclusive lanes respectively). This CBA is an ex-ante CBA that was done before the launch of the project. This analysis could help the policymakers clearly understand the impact of exclusive AV lanes and help them decide based on the real situation. In this research, a case in eastern China was selected to provide the data for CBA, and the results were given based on the situation in this Chinese case.

The research question of this thesis is: Under which conditions are exclusive autonomous vehicle lanes societally beneficial? This question was answered in chapter 4. Using the data in China, four scenarios were studied, and the NPVs of these four scenarios were calculated. It is clear that the NPV of scenario 1 and 3 is negative, and that of scenario 2 and 4 is positive. This represents that the exclusive AV lanes are beneficial in scenario 2 and 4 and unbeneficial in scenario 1 and 3. After comparing these four situations, it could be roughly concluded that the exclusive AV lanes are societal beneficial when the (real) penetration exceeds the proportion of AV lanes (quantity of AV lanes/quantity of all lanes). To be more specific, in this situation, the AV lanes will become more crowded, and CV lanes will become more spacious. Then, AVs could still drive in a high speed in 100% AV penetration even it is crowded in AV lanes due to its autonomous drive capacity and CVs could also run faster due to the lower car density. Therefore, both CVs and AVs could save travel time. Although there was an increase in other costs such as safety, fuel and emission, the benefit of travel time could make up this change. In a whole, the exclusive AV lanes could be beneficial in the situation mentioned above. To be more accurate, the penetration at 0 NPV was calculated to answer the research question: for one exclusive AV lane, when the real penetration exceeds 15.5%, the exclusive AV lanes are beneficial; for two exclusive AV lanes, the exclusive AV lanes are beneficial when the real penetration is more than 46.1%. Therefore, the government (policymakers) could regard CBA as a reference to make decisions and flexibly adjust their policies in different stages or other penetrations to benefit the whole society.

However, the result is not suitable for all areas and countries because this study is a kind of case study and used data from China. The used data might be different from other countries and regions; therefore, the results might be different. Thus, this CBA provides a model to analyze the impact of exclusive AV lanes in a quantitative way. For further study, data in certain areas could be used to see if this policy is beneficial to these areas. Also, more societal and moral effects, including environmental cost, fairness, privacy and etc., and the impact of other technology such as electric cars could be under consideration to increase the accuracy of the analysis.

In conclusion, this research use cost-benefit analysis to find conditions which exclusive AV lanes are societally beneficial. Additionally, this research could help policymakers have a clear understanding of exclusive AV lanes and play roles in decision-making and adjustment process of this new road policy.

7.2 Recommendations

This section focusses on the recommendations for stakeholders who are involved in exclusive AV lanes.

7.2.1 Recommendations for Government

Government is the decision maker of implement of exclusive AV lanes and also group who most in need of analysis. In addition, Government have the power to adjust and control the market so that they could affect the cost and benefit. Therefore, they need to clearly understand the impact of exclusive AV lanes and comparing the local situation to make proper decision in different penetrations. Following is the recommendations for governments before and after application.

As mentioned above, CBA is a limited analysis which overlooks some ethical impacts. Therefore, governments should combine CBA with other analysis to comprehensively analyze the impact of exclusive AV lanes before the implementation. They should also consider the fairness, privacy, risk distribution and etc. during the decision-making process. Moreover, governments should use local data to make the analysis more accurate. The local data can reelect the real situation in a certain area and give the closest analysis result to help the decision-making process.

After the decision-making process, the government should find a proper situation (penetration, technology level, local situation and et al.) to implement exclusive AV lanes to make benefit for the society. During the application process, governments should choose proper enforcement to regulate the exclusive AV lanes, for example, using traffic camera. In addition, proper regulation of enforcement is needed, such as privacy protection system to solve the privacy issues brought by traffic cameras. The strictly manage traffic order in exclusive AV lanes could ensure the effectiveness of this new policy.

Lastly, governments should flexibly change the exclusive policy because the market share in different stage is dynamic. Therefore, the government should flexibly adjust the exclusive AV lanes policy to meet the changing penetration.

7.2.2 Recommendations for Future Study

As shown in Chapter 6, this study has some weak points. Thus, further studies could focus on these weak points and improve the robustness of their research.

First of all, this research only did a CBA for a starch of motorway, and did not consider more complex road networks. Thus, for future studies, they could think of different networks such as motorway junction and urban road. These situations need more complex exclusive lanes design to ensure the effectiveness of this new road policy.

Secondly, due to the limitation of CBA mentioned above, further studies could consider more aspects including moral effects to increase the accuracy of outcomes. In addition, more societal effects should be taken account into the analysis. For instance, the environmental cost of fuel consumption, which is overlooked in this research. A more comprehensive analysis has higher reference value.

Thirdly, for future studies, they could improve the correction of calculations. In this CBA, there existed some assumptions. Therefore, further studies could make these assumptions more accurate to improve the accuracy veracity of outcomes. Also, they could use a more accurate relation to calculate the different parameters. This could also make the results more robust. Additionally, future research could add the development of other technology into consideration. For example, the development of electric vehicles could influence the cost of fuel, hence, impact the NPV.

Besides, the sensitivity analysis of this CBA is very simple, and only one value changes once. For future studies, they could focus on more complex sensitivity analysis and consider more changing situation to find out the degree of influence of different index changes on the results.

Lastly, this case study only used the data in China. Thus, future studies could use data from other areas to accurately calculate the NPV of these areas and compare the outcomes. According to the comparison, further studies could find out the difference of exclusive AV lanes between various areas. Also, they could design and test different enforcement in different areas to see if other enforcement could impact the outcomes.

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Appendix-A

Estimation of Travel Time in Different Time by Using Baidu Maps

Date	Time/Min	distance /KM	speed/ km/h
07/08/2020 0:00	112	196	105
07/08/2020 2:00	115	196	102.2608696
07/08/2020 4:00	113	196	104.0707965
07/08/2020 6:00	120	196	98
07/08/2020 8:00	130	196	90.46153846
07/08/2020 10:00	132	196	89.09090909
07/08/2020 12:00	121	196	97.19008264
07/08/2020 14:00	125	196	94.08
07/08/2020 16:00	135	196	87.11111111
07/08/2020 18:00	134	196	87.76119403
07/08/2020 20:00	120	196	98
07/08/2020 22:00	115	196	102.2608696
		Average	**96.27394758**

Appendix-B

Result of passenger observation

How many passengers in one car?

2	4	3	4	3	1	1	1
1	1	1	1	2	2	2	4
4	1	4	4	4	3	5	3
2	2	3	4	1	2	2	1
2	3	2	4	4	1	4	2
4	1	1	3	1	1	1	1
3	3	4	4	1	4	4	5
4	1	4	1	4	2	5	1
2	2	1	3	1	3	2	4
4	3	4	3	2	1	3	5
2	2	2	1	1	3	1	1
2	2	1	1	3	1	1	4
3	1	3	5	2	2	3	4
4	5	4	3	3	2	2	1
2	3	4	2	3	2	2	3
2	3	4	4	2	4	4	1
2	1	3	4	1	5	1	4
4	5	3	4	4	2	2	5
1	3	3	2	4	2	3	2
2	1	3	4	2	2	4	3
3	4	1	2	1	4	3	4
2	2	5	5	4	4	3	3
3	4	1	1	2	1	4	3
3	4	4	4	3	1	1	4
1	3	2	4	3	2	4	3

Average: **2.6** passengers per car

Appendix-C

Result of Interview about the Cost of Equipment

Company	Hikvision	Hikvision	Hikvision	Dahua
Name	Mr. Chen	Mr. Zheng	Mr. Hu	Mr. Ding
Position	Production Engineer	Production Engineer	Production Manager	Solution Engineer
Price of Camera & System (yuan)	40,000	30,000-50,000	50,000	20,000-60,000
Service Life (year)	5	3-5	5-10	5
Cost of Maintenance (yuan)	0	0	0	0
Instalment Density (km)	1	1~2	1	1~2

Company	Dahua	Hikvision	Hikvision	Dahua
Name	Anonymity	Mr. Zhong	Anonymity	Mr. Deng
Position	Solution Engineer	Solution Engineer	Production Manager	Production Engineer
Price of Camera & System (yuan)	30,000-40,000	50,000	Around 50,000	Around 40,000
Service Life (year)	3-8	3-5	5	5
Cost of Maintenance (yuan)	Depends on production	0	0	0
Instalment Density (km)	1	2	1	0.5-1

Interview Question:

1. What’s your name?

2. Which Company do you work for?

3. What is your job position in your company and what's your work content?

4. What is the price for a single camera and system?

5. How long could the cameras work?

6. In your experience, how far away do you need to install a traffic camera in China's road conditions?

7. What is the maintenance cost of traffic cameras?

8. Do you think if this enforcement is useful?

Note of Interview & Translation

Only 4 interviewees allowed me to record the interview, so there are only 4 notes showed in this appendix. This is because their works is related to the government and traffic department, thus they did not allow me to record the interview, and just give some brief answers.

Interviewee 1

1. What’s your name?

回答：您好，我姓陈

A: Hello, my last name is Chen

2. Which Company do you work for?

回答：我目前是在海康威视工作，在交通摄像头领域有五年的工作经验

A: I am currently working at Hikvision and have five years of work experience in the field of traffic cameras

3. What is your job position in your company and what's your work content?

回答：我在海康威视做的是产品经理的工作，工作内容一般是参与产品的设计，就是摄像头的设计。对市场进行一定的调查，针对用户的需求进行产品的设计。

A: What I do at Hikvision is the work of a product manager. The content of my work is generally involved in product design, that is, camera design. Conduct a certain survey of the market and design products according to the needs of users.

4. What is the price for a single camera and system?

回答：按照我的经验来讲，单个摄像头的价格大约是 4 万元人民币，其中包含了整套操控系统的价格。

A: According to my experience, the price of a single camera is about 40,000 yuan, which includes the price of the entire control system.

5. How long could the cameras work?

回答：一般摄像头的使用寿命大约是 5 年，但是不包括一些极端天气的使用情况导致的使用寿命缩短。

A: The service life of a general camera is about 5 years, but it does not include the shortened service life caused by some extreme weather conditions.

6. In your experience, how far away do you need to install a traffic camera in China's road conditions?

回答：按照我个人的经验，高速公路上摄像头的距离大概是 1 公里，在城市环境中会更加密集，每个路口都会有交通摄像头，具体的密度还是需要根据具体的路况来决定。

A: According to my personal experience, the distance of the cameras on the highway is about 1 km, which will be denser in an urban environment. There will be traffic cameras at each intersection. The specific density still needs to be determined according to the specific road conditions.

7. What is the maintenance cost of traffic cameras?

回答：摄像头安装之后一般不需要维护的成本，除非是因为一些特殊情况导致的摄像头损坏。

A: After the camera is installed, there is generally no maintenance cost, unless the camera is damaged due to some special circumstances.

8. Do you think if this enforcement is useful?

回答：交通摄像头是一种非常有效的方式来管理交通秩序，可以很有效的减少交通违章的发生。

A: Traffic cameras are a very effective way to manage traffic order, which can effectively reduce the occurrence of traffic violations.

Interviewee 2

1. What’s your name?

回答：你好，我叫郑天天

A: Hello, my name is Zheng Tiantian

2. Which Company do you work for?

回答：我目前是就职于海康威视，从事交通摄像头有关的工作

A: I am currently working for Hikvision and I am working on traffic cameras

3. What is your job position in your company and what's your work content?

回答：我在海康威视的职位是产品管理工程师，日常工作是负责与客户和开发人员沟通，将客户的需求整理，然后让研发人员按照客户的需求对产品进行研发和改进。此外，还需要对产品的生命周期进行管理，对相关的操作人员进行培训。

A: My position at Hikvision is a product management engineer. My daily job is to communicate with customers and developers, organize customer needs, and then let R&D personnel develop and improve products according to customer needs. In addition, it is necessary to manage the life cycle of the product and train the relevant operators.

4. What is the price for a single camera and system?

回答：我所涉及的相关产品的单价在三万人民币到 5 万人民币之间，这个价格包含了摄像头的硬件价格以及操作系统的软件价格。

A: The unit price of the related products I involved is between RMB 30,000 and RMB 50,000. This price includes the price of the hardware of the camera and the price of the software of the operating system.

5. How long could the cameras work?

回答：交通摄像头的使用周期大概是 3-5 年，超过这个时间之后红外探测仪会有可能出现一定的问题导致摄像头无法使用。

A: The life cycle of the traffic camera is about 3-5 years. After this time, the infrared detector may have certain problems and the camera cannot be used.

6. In your experience, how far away do you need to install a traffic camera in China's road conditions?

回答：我所负责的区域的高速公路摄像头密度大约是 1-2 公里一个。但是这只是一个平均数，

在不同的区域会有差别，比如在事故多发区域会设置更多的交通摄像头来警示司机谨慎驾驶。

A: The highway camera density in the area I am responsible for is about 1-2 kilometers. But this is only an average, and it will vary in different areas. For example, more traffic cameras will be set up in accident-prone areas to warn drivers to drive carefully.

7. What is the maintenance cost of traffic cameras?

回答：这一块我不是很熟悉，但是我认为摄像头在使用周期内出现损坏的概率很低，一般不需要额外的维护，仅仅是摄像头坏了之后需要更换、维修。

A: I'm not very familiar with this one, but I think the probability of camera damage during the life of the camera is very low. Generally, no additional maintenance is required. Only the camera needs to be replaced and repaired after it is broken.

8. Do you think if this enforcement is useful?

回答： 我认为交通摄像头是一个比较好的方式来管理司机，比如测速摄像头，可以很好地限制司机的超速行为。但是，我也有负责一定的海外业务，所以认为摄像头存在隐私方面的问题。如何保护司机的隐私是一项非常重要的关注点。

A: I think traffic cameras are a better way to manage drivers, such as speed cameras, which can well limit drivers' speeding behavior. However, I am also responsible for certain overseas business, so I think the camera has privacy issues. How to protect the privacy of drivers is a very important concern.

Interviewee 3

1. What’s your name?

回答： 早上好啊，我叫胡胜平。

A: Good morning, my name is Hu Shengping.

2. Which Company do you work for?

回答：我在海康威视的智能识别工作室工作

A: I work in Hikvision’s Smart Recognition Studio.

3. What is your job position in your company and what's your work content?

回答：我是负责智能识别系统的产品经理，主要是参与摄像头智能识别的设计开发，我们的产品主要是针对不同路况下的摄像头进行人工智能的开发，让摄像头能智能识别不同的目标，包括行人、自行车、小轿车、大货车等。

A:

I am the product manager in charge of the intelligent recognition system, mainly involved in the design and development of camera intelligent recognition. Our products are mainly aimed at the development of artificial intelligence for the camera under different road conditions, so that the camera can intelligently identify different targets, including pedestrians and bicycles. , Cars, trucks, etc.

4. What is the price for a single camera and system?

回答： 我所负责领域的摄像头单价大约是 5 万人民币一个。

A: The unit price of the camera in my area is about RMB 50,000.

5. How long could the cameras work?

回答： 摄像头是仪表精密的设备，里面会有红外摄像机等高精设备，所以使用周期一般是 5-10 年。

A: The camera is a precision instrument with high precision equipment such as an infrared camera, so the service life is generally 5-10 years.

6. In your experience, how far away do you need to install a traffic camera in China's road conditions?

回答： 高速公路上大约是 1 公里左右会设置一个交通摄像头来管理车辆的驾驶行为，但是在城市路况中会更加密集。

A: A traffic camera will be set up on the highway for about 1 km to manage the driving behavior of vehicles, but it will be denser in urban road conditions.

7. What is the maintenance cost of traffic cameras?

回答： 摄像头的维护成本非常低，一般只会在损坏之后进行维修替换。

A: The maintenance cost of the camera is very low, generally only repair and replacement after damage.

8. Do you think if this enforcement is useful?

回答： 摄像头是一种非常有效的交通管理方式，通过限制驾驶人的行为，来维护交通秩序。

A: The camera is a very effective way of traffic management. It maintains traffic order by restricting the behavior of drivers.

Interviewee 4

1. What’s your name?

回答： 你好，我姓丁。

A: Hello, my last name is Ding.

2. Which Company do you work for?

回答：我目前是在浙江大华股份有限公司工作

A: I am currently working in Zhejiang Dahua Co., Ltd.

3. What is your job position in your company and what's your work content?

回答：我是解决方案工程师，主要是负责交通摄像头布置方案的设计。我日常的工作是针对不同的路况和道路设计不同的摄像头布置方案。我主要是负责城市道路的摄像头布置方案设计，会对不同的路口进行方案设计，用最少的摄像头完成设计目标，来管理路口的交通秩序。

A: I am a solution engineer, mainly responsible for the design of traffic camera layout. My daily work is to design different camera arrangements for different road conditions and roads. I am mainly responsible for the camera layout design of urban roads. I will design different intersections and use the fewest cameras to complete the design goals to manage the traffic order at the intersections.

4. What is the price for a single camera and system?

回答： 根据不同的种类，摄像头的价格是不一定的，但是一般都是在 2 万元至 6 万元的价格区间。这个价格取决于摄像头的清晰程度和功能。

A: According to different types, the price of the camera is not necessarily, but generally in the price range of 20,000 to 60,000 yuan. The price depends on the clarity and functionality of the camera.

5. How long could the cameras work?

回答： 摄像头一般可以工作 5 年左右，之后会因为部件的老化导致失效。

A: The camera generally can work for about 5 years, after which it will fail due to the aging of the components.

6. In your experience, how far away do you need to install a traffic camera in China's road conditions?

回答： 我主要还是负责城市的交通路况，城市中每个路口都会有交通摄像头。对于高速公路上的设计我不是特别熟悉，但是以我的经验来说应该是在 1-2 公里会设置一批摄像头。

A: I am mainly responsible for the traffic conditions in the city. There will be traffic cameras at every intersection in the city. I am not particularly familiar with the design of highways, but in my experience, a batch of cameras should be set up at 1-2 kilometers.

7. What is the maintenance cost of traffic cameras?

回答： 大概是 5 年左右

A: About 5 years

8. Do you think if this enforcement is useful?

回答： 交通摄像头可以很好的管理交通秩序，此外，对于警察的一些追捕任务也有很好的帮助。

A: The traffic camera can manage the traffic order very well. In addition, it is also very helpful for some police pursuit tasks.

Appendix D

Net Present Value of scenario 1

20% with 1 AVs Lane			Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Discount Factor			1	0.978	0.956	0.935	0.915	0.895	
Cost	AVs	Increase in Fuel		-5608084	-5481931	-5361512	-5246827	-5132143	-26830498
		Increase in Emission Cost		-125111	-122296	-119610	-117052	-114493	-598562
	CVs	Increase in Time Cost		-8791636	-8593869	-8405091	-8225303	-8045515	-42061414
		Increase in Safety Cost		-7209058	-7046891	-6892095	-6744671	-6597246	-34489960
	Gov.	Equipment Cost	-508000	0	0	0	0	0	-508000
							Cost	**-104488434**	
Benefit	AVs	Decrease in Time Cost		6553339	6405922	6265206	6131191	5997176	31352834
		Decrease in Safety Cost		4833570	4724840	4621051	4522205	4423359	23125026
	CVs	Decrease in Fuel		4124289	4031513	3942955	3858614	3774272	19731642
		Decrease in Emission		94411	92288	90260	88330	86399	451688
	Gov.	Increase in Tax Revenue		414748	405418	396512	388031	379549	1984258
							Benefit	**76645449**	
							NPV	**-27842985**	
							B/C Ratio	**0.733**	

Basic Infomation & Data	
Average daily traffic flow	100,000
Distance (KM)	80
Average Speed (km/h)	96
Cost of emision per year ($)	4,600,000
Daily Travel Distance per Car(KM)	45
Car Numbers in China	250 M
Cost of Emision per Car per KM ($)	0.0012
Accident Rate (total accident/total taffic)	0.03%
Average Cost of Traffic Crash ($)	1,016
Headway of AVs (s)	1.5
Headway of CVs (s)	3
Intercity Personal Travel (70%)	78.6%
Intercity Business Travel (100%)	21.4%
Average Wage per Year ($)	11773.3
Average Working Hours a Year(h)	2400
Average Wage per Min ($)	0.081759028
Average Passenger Number in a Car	2.6
Fuel Tax Rate	28%

Nomar Lanes

		0%	20%	Cost per Car	Cost
Traffic Flow	Time (Min)	50	51.591	3.223400638	838084.1658
	Speed (Km/h)	96	93.040		
	Density (Veh/Km)	12	13		
Fuel	Fuel Comsuption (L/100KM)	5.74	5.53	3.67192	367192
	Price ($/L)	0.83	0.83		
Emision				0.09304	9304
Safety		1.1232	1.070784	1.070784	107078.4
			Total	7.966104638	1312354.566
			AVs		157482.5479
			CVs		1154872.018

Result

AVs	Cost	Increse in Fuel Comsumption	14501.76
	Cost	Incresase in Emission	323.52
	Benefit	Decrease in Time Cost	16946.06183
	Benefit	Decrease in Safety Cost	12525.9264
	Benefit-Cost		14646.70823
CVs	Cost	Increase in Time Cost	24911.30314
	Cost	Increase in Safety Cost	20427.03187
	Benefit	Decrease in Emission	267.51696
	Benefit	Decrease in Fuel Comsuption	11686.2672
	Benefit-Cost		-33384.55085
Goverment	Benefit	Increase in Fuel Tax	785.954752
	Benefit-Cost		785.954752

Real Penetration		Distribution of Cars (Green for CVs, Red for AVs)			
Penetration	20%	1	2	3	4
Willingness to use AVs on Highway	60%	29%	29%	29%	12%
Real penetration	12%		Density Change		
		16%	16%	16%	-52%
			Car Count		
		29333	29333	29333	12000

Exclusive Lanes

		1	2	3	4
Traffic Flow	Time (Min)	53.333	53.333	53.333	40.000
	Speed (Km/h)	90	90	90	120
	Density (Veh/Km)	13.92	13.92	13.92	5.76
Fuel	Fuel Comsuption (L/100KM)	5.33	5.33	5.33	7.35
	Price ($/L)	0.83	0.83	0.83	0.83
Emision		0.09	0.09	0.09	0.12
Safety		1.302912	1.302912	1.302912	0.0269568

	1	2	3	4
		Cost per Car		
Time	3.332	3.332	3.332	2.499
Fuel	3.53912	3.53912	3.53912	4.8804
Emision	0.09	0.09	0.09	0.12
Safety	1.302912	1.302912	1.302912	0.0269568
Total Cost per Car	13.506	13.506	13.506	11.405
Total	396170.3207	396170.3207	396170.3207	136863.6324
			AVs	136863.6324
			CVs	1188510.962

Calculation Table in Excel for Scenario 1

Net Present Value of scenario 2

50% with 1 AVs Lane			Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Discount Factor			1	0.978	0.956	0.935	0.915	0.895	
Cost	AVs	Increase in Fuel		-16621594	-16247693	-15890788	-15550878	-15210968	-79521921
		Increase in Emission		-374245	-365826	-357790	-350137	-342484	-1790481
	CVs	Increase in Fuel		-14221457	-13901547	-13596178	-13305351	-13014524	-68039058
		Increase in Safety Cost		-11377573	-11121636	-10877332	-10644662	-10411991	-54433193
		Increase in Emission		-356008	-348000	-340355	-333075	-325795	-1703232
	Gov.	Equipment Cost	-508000	0	0	0	0	0	-508000
							Cost	**-205995885**	
Benefit	AVs	Decrease in Time Cost		19815398	19369653	18944169	18538946	18133723	94801888
		Decrease in Safety Cost		4573321	4470445	4372245	4278721	4185197	21879928
	CVs	Decrease in Time Cost		27925634	27297450	26697819	26126743	25555667	133603312
	Gov.	Increase in Tax Revenue		8620827	8426903	8241793	8065498	7889203	41244223
							Benefit	**291529352**	
							NPV	**85533467**	
							B/C Ratio	**1.415**	

Basic Infomation & Data	
Average daily traffic flow	100,000
Distance (KM)	80
Average Speed (km/h)	96
Cost of emision per year ($)	4,600,000
Daily Travel Distance per Car(KM)	45
Car Numbers in China	250 M
Cost of Emision per Car per KM ($)	0.0012
Accident Rate (total accident/total taffic)	0.03%
Average Cost of Traffic Crash ($)	1,016
Headway of AVs (s)	1.5
Headway of CVs (s)	3
Intercity Personal Travel (70%)	78.6%
Intercity Business Travel (100%)	21.4%
Average Wage per Year ($)	11773.3
Average Working Hours a Year(h)	2400
Average Wage per Min ($)	0.081759028
Average Passenger Number in a Car	1.5
Fuel Tax Rate	28%

Nomar Lanes

		0%	50%	Cost per Car	Cost
Traffic Flow	Time (Min)	50	52.150	3.258320811	847163.4109
	Speed (Km/h)	96	92.043		
	Density (Veh/Km)	12	13		
Fuel	Fuel Comsuption (L/100KM)	5.74	5.48	3.63872	363872
	Price ($/L)	0.83	0.83		
Emision				0.092042869	9204.286892
Safety		1.1232	0.42588	0.42588	42588
			Total	7.322920811	1253623.411
			AVs		438768.1938
			CVs		814855.2171

Result

AVs	Cost	Increse in Fuel Comsumption	43458.8
	Cost	Incresase in Emission	978.4995878
	Benefit	Decrease in Time Cost	51809.31552
	Benefit	Decrease in Safety Cost	12153.96
	Benefit-Cost		19525.97594
CVs	Cost	Increase in Safety Cost	33147.04566
	cost	Incresase in Emission	1037.181606
	Benefit	Decrease in Time Cost	81357.62102
	Cost	Increase in Fuel Comsuption	41432.32512
	Benefit-Cost		5741.068637
Goverment	Benefit	Increase in Fuel Tax	23726.56947
	Benefit-Cost		23726.56947

Real Penetration		Distribution of Cars (Green for CVs, Red for AVs)			
Penetration	50%	1	2	3	4
Willingness to use AVs on Highway	70%	20.83%	20.83%	20.83%	35.00%
Real penetration	35.0%	Density Change			
		-17%	-17%	-17%	40%
		Car Count			
		21666	21666	21666	35000

Exclusive Lanes

		1	2	3	4
Traffic Flow	Time (Min)	44.444	44.444	44.444	40.000
	Speed (Km/h)	108	108	108	120
	Density (Veh/Km)	9.9984	9.9984	9.9984	16.8
Fuel	Fuel Comsuption (L/100KM)	6.44	6.44	6.44	7.35
	Price ($/L)	0.83	0.83	0.83	0.83
Emision		0.108	0.108	0.108	0.12
Safety		0.93585024	0.93585024	0.93585024	0.078624

	1	2	3	4
	Cost per Car			
Time	2.777	2.777	2.777	2.499
Fuel	4.27616	4.27616	4.27616	4.8804
Emision	0.108	0.108	0.108	0.12
Safety	0.93585024	0.93585024	0.93585024	0.078624
Total Cost per Car	12.432	12.432	12.432	11.457
Total	269350.6315	269350.6315	269350.6315	400993.9465
			AVs	400993.9465
			CVs	808051.8944

Calculation Table in Excel for Scenario 2

Net Present Value of scenario 3

50% with 2 AVs Lanes			Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Discount Factor			1	0.978	0.956	0.935	0.915	0.895	
Cost	AVs	Increase in Fuel		-16621594	-16247693	-15890788	-15550878	-15210968	-79521921
		Increase in Emission Cost		-374245	-365826	-357790	-350137	-342484	-1790481
	CVs	Increase in Time Cost		-21822469	-21331575	-20862994	-20416727	-19970459	-104404223
		Increase in Safety Cost		-15660644	-15308359	-14972088	-14651829	-14331571	-74924490
	Gov.	Equipment Cost	-508000	0	0	0	0	0	-508000
							Cost	**-261149116**	
Benefit	AVs	Decrease in Time Cost		19815398	19369653	18944169	18538946	18133723	94801888
		Decrease in Safety Cost		5137155	5021596	4911289	4806234	4701180	24577453
	CVs	Decrease in Fuel		3110994	3041012	2974212	2910592	2846973	14883782
		Decrease in Emission		157131	153596	150222	147009	143796	751754
	Gov.	Increase in Tax Revenue		3776457	3691506	3610416	3533188	3455960	18067528
							Benefit	**153082405**	
							NPV	**-108066710**	
							B/C Ratio	**0.586**	

Basic Infomation & Data

Average daily traffic flow	100,000
Distance (KM)	80
Average Speed (km/h)	96
Cost of emision per year ($)	4,600,000
Daily Travel Distance per Car(KM)	45
Car Numbers in China	250 M
Cost of Emision per Car per KM ($)	0.0012
Accident Rate (total accident/total taffic)	0.03%
Average Cost of Traffic Crash ($)	1,016
Headway of AVs (s)	1.5
Headway of CVs (s)	3
Intercity Personal Travel (70%)	78.6%
Intercity Business Travel (100%)	21.4%
Average Wage per Year ($)	11773.3
Average Working Hours a Year(h)	2400
Average Wage per Min ($)	0.081759028
Average Passenger Number in a Car	1.5
Fuel Tax Rate	28%

Nomar Lanes

		0%	50%	Cost per Car	Cost
Traffic Flow	Time (Min)	50	52.150	3.258320811	847163.4109
	Speed (Km/h)	96	92.043		
	Density (Veh/Km)	12	13		
Fuel	Fuel Comsuption (L/100KM)	5.74	5.48	3.63872	363872
	Price ($/L)	0.83	0.83		
Emision				0.092042869	9204.286892
Safety		1.1232	0.42588	0.42588	42588
			Total	7.322920811	1253623.411
			AVs		438768.1938
			CVs		814855.2171

Result

AVs	Cost	Increse in Fuel Comsumption	43458.8
	Cost	Incresase in Emission	978.4995878
	Benefit	Decrease in Time Cost	51809.31552
	Benefit	Decrease in Safety Cost	13529.88
	Benefit-Cost		20901.89594
CVs	Cost	Increase in Safety Cost	67228.2
	Cost	Increase in Time Cost	45625.87714
	Benefit	Decrease in Emission	457.7864798
	Benefit	Decrease in Fuel Comsuption	9063.6
	Benefit-Cost		-103332.691
Goverment	Benefit	Inearease in Fuel Tax	9614.08
	Benefit-Cost		9614.08

Real Penetration

		Distribution of Cars (Green for CVs, Red for AVs)			
Penetration	50%	1	2	3	4
Willingness to use AVs on Highway	70%	32.50%	32.50%	17.50%	17.50%
Real penetration	35.0%	Density Change			
		30%	30%	-30%	-30%
		Car Count			
		32500	32500	17500	17500

Exclusive Lanes

		1	2	3	4
Traffic Flow	Time (Min)	56.471	56.471	40.000	40.000
	Speed (Km/h)	85	85	120	120
	Density (Veh/Km)	15.6	15.6	8.4	8.4
Fuel	Fuel Comsuption (L/100KM	5.27	5.27	7.35	7.35
	Price ($/L)	0.83	0.83	0.83	0.83
Emision		0.085	0.085	0.12	0.12
Safety		1.46016	1.46016	0.039312	0.039312

	1	2	3	4
	Cost per Car			
Time	3.528	3.528	2.499	2.499
Fuel	3.49928	3.49928	4.8804	4.8804
Emision	0.085	0.085	0.12	0.12
Safety	1.46016	1.46016	0.039312	0.039312
Total Cost per Car	14.133	14.133	11.418	11.418
Total	459322.847	459322.847	199809.013	199809.013
			AVs	399618.026
			CVs	918645.694

0.000393836	-0.0916490
0.000278967	-0.0917639

Calculation Table in Excel for Scenario 3

Net Present Value of scenario 4

80% with 2 AVs Lanes			Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Discount Factor			1	0.978	0.956	0.935	0.915	0.895	
Cost	AVs	Increase in Fuel		-27611401	-26990286	-26397403	-25832753	-25268102	-132099944
		Increase in Emission		-627519	-613403	-599929	-587096	-574263	-3002210
	CVs	Increase in Fuel		-5156783	-5040782	-4930053	-4824598	-4719142	-24671357
		Increase in Safety Cost		-5398854	-5277408	-5161482	-5051076	-4940669	-25829489
		Increase in Emission		-135379	-132334	-129427	-126658	-123890	-647688
	Gov.	Equipment Cost	-508000	0	0	0	0	0	-508000
							Cost	**-186758688**	
Benefit	AVs	Decrease in Time Cost		32157432	31434054	30743557	30085941	29428325	153849308
		Decrease in Safety Cost		1681435	1643611	1607506	1573121	1538736	8044409
	CVs	Decrease in Time Cost		10277850	10046651	9825961	9615780	9405599	49171842
	Gov.	Increase in Tax Revenue		9159300	8953262	8756590	8569283	8381977	43820412
							Benefit	**254885971**	
							NPV	**68127283**	
							B/C Ratio	**1.364787758**	

Basic Infomation & Data	
Average daily traffic flow	100,000
Distance (KM)	80
Average Speed (km/h)	96
Cost of emision per year ($)	4,600,000
Annual average daily driving volume	3,200,000,000
Car Numbers in China	250 M
Cost of Emision per Car per KM ($)	0.0012
Accident Rate (total accident/total taffic)	0.03%
Average Cost of Traffic Crash ($)	1,016
Headway of AVs (s)	1.5
Headway of CVs (s)	3
Intercity Personal Travel (70%)	78.6%
Intercity Business Travel (100%)	21.4%
Average Wage per Year ($)	11773.3
Average Working Hours a Year(h)	2400
Average Wage per Min ($)	0.081759028
Average Passenger Number in a Car	1.5
Fuel Tax Rate	28%

Nomar Lanes

		0%	80%	Cost per Car	Cost
Traffic Flow	Time (Min)	50	50.473	3.153560291	819925.6755
	Speed (Km/h)	96	95.101		
	Density (Veh/Km)	12	12		
Fuel	Fuel Comsuption (L/100KM)	5.74	5.7	3.7848	378480
	Price ($/L)	0.83	0.83		
Emision				0.095100511	9510.051107
Safety		1.1232	0.146016	0.146016	14601.6
			Total	7.084376291	1213007.276
			AVs		873365.2384
			CVs		339642.0372

Result

AVs	Cost	Increse in Fuel Comsumption	78883.2
	Cost	Increasase in Emission	1792.763203
	Benefit	Decrease in Time Cost	91870.78626
	Benefit	Decrease in Safety Cost	4690.4832
	Benefit-Cost		15885.30625
CVs	Cost	Increase in Safety Cost	13523.328
	Cost	Increasase in Emission	361.1856899
	Benefit	Decrease in Time Cost	27420.8723
	Cost	Increase in Fuel Comsuption	13758.08
	Benefit-Cost		-221.7213909
Goverment	Benefit	Inearease in Fuel Tax	25894.912
	Benefit-Cost		25894.912

Real Penetration		Distribution of Cars (Green for CVs, Red for AVs)			
Penetration	80%	1	2	3	4
Willingness to use AVs on Highway	90%	14.00%	14.00%	36.00%	36.00%
Real penetration	72.0%	Density Change			
		-44%	-44%	44%	44%
		Car Count			
		14000	14000	36000	36000

Exclusive Lanes

		1	2	3	4
Traffic Flow	Time (Min)	44.444	44.444	40.000	40.000
	Speed (Km/h)	108	108	120	120
	Density (Veh/Km)	6.72	6.72	17.28	17.28
Fuel	Fuel Comsuption (L/100KM)	6.44	6.44	7.35	7.35
	Price ($/L)	0.83	0.83	0.83	0.83
Emision		0.108	0.108	0.12	0.12
Safety		0.628992	0.628992	0.0808704	0.0808704
		0.000312116	0.000394	0.0000819	
			0.000354452	0.0000423	

	1	2	3	4
	Cost per Car			
Time	2.777	2.777	2.499	2.499
Fuel	4.27616	4.27616	4.8804	4.8804
Emision	0.108	0.108	0.12	0.12
Safety	0.628992	0.628992	0.0808704	0.0808704
Total Cost per Car	12.125	12.125	11.459	11.459
Total	169751.2864	169751.2864	412531.7868	412531.7868
			AVs	825063.5735
			CVs	339502.5729

Calculation Table in Excel for Scenario 4