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Assessing the Socioeconomic Impacts of Intelligent Connected Vehicles in China: A Cost–Benefit Analysis

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Abstract: The deployment of intelligent connected vehicles (ICVs) is regarded as a significant solution to improve road safety, transportation management, and energy efficiency. This study assessed the safety, traffic, environmental, and industrial economic benefits of ICV deployment in China under different scenarios. A bottom-up model was established to deal with these impacts within a unified framework, based on the existing theories and literature of ICVs' cost–benefit analysis, as well as China's most recent policies and statistics. The results indicate that the total benefits may reach 13.25 to 24.02 trillion renminbi (RMB) in 2050, while a cumulative benefit–cost ratio of 1.15 to 3.06 suggests high cost-effectiveness. However, if the government and industry only focus on their own interests, the break-even point may be delayed by several years. Hence, an effective business model is necessary to enhance public–private cooperation in ICV implementation. Meanwhile, the savings of travel time costs and fleet labor costs play an important part in all socioeconomic impacts. Therefore, the future design of ICVs should pay more attention to the utilization of in-vehicle time and the real substitution for human drivers.

Keywords: intelligent connected vehicle; socioeconomic impacts; cost–benefit analysis; scenario analysis; China

1. Introduction

The increasing number of vehicles is posing severe social problems worldwide, including accidental fatalities and injuries, traffic congestion, energy consumption, and air pollution. Intelligent and connected vehicles (ICVs) have been introduced to achieve effective and sustainable mobility, with capabilities of environment sensing, information exchange, intelligent planning, and automated control [1,2]. Furthermore, ICVs will also create considerable economic benefits for both the automotive industry and other related businesses by saving operating costs and integration into a digital economy [1,3]. Thus, ICVs are regarded as a vital component of intelligent transportation systems (ITS) and a sustainable automotive industry.

China has been the largest automotive market around the world with a vehicle population of 240 million at the end of 2018, leading to many challenges in transportation management, energy security, and environmental protection. Hence, China's government is formulating policies and expanding investment to promote the development and implementation of ICVs [4], and many enterprises are devoting themselves to relevant businesses [1]. China is regarded as one of the first regions to deploy ICVs on a large scale [5]. During this long-term evolution, a large number of resources will be needed to promote the wide deployment of ICVs and their corresponding infrastructures. Therefore, a comprehensive and in-depth study into the benefits and costs of ICVs is essential for policy

makers and business managers to formulate future strategies. Additionally, a cost–benefit analysis in China will also provide a useful reference for other countries.

ICVs can be defined as a new generation of vehicle equipped with advanced sensors, controllers, and actuators as well as communication technologies to accomplish driving tasks efficiently and safely instead of human drivers [4]. It consists of three core technologies, namely automated driving systems (ADS), internet of vehicles (IoV), and in-vehicle artificial intelligence [1]. Due to its technical complexity and significant influences, it should be developed and implemented step by step.

The advanced driving assistance system (ADAS) is the first stage of the ICV's deployment, therefore governments and enterprises in developed countries have investigated their social effects for decades. ADVISORS is one such research program supported by the European Commission to assess the impacts of several ICV technologies on road safety, driver comfort, and network efficiency. It conducted a multicriteria analysis from the perspectives of users, society, and manufacturers to rank the implementation priorities of different ADAS, and provided suggestions to overcome their deployment barriers [6]. Following this, more projects were completed including SEiSS and eIMPACT, which evaluated the socioeconomic impact of intelligent vehicle safety systems [7,8]. The assessment indicators included safety, mobility, efficiency, energy and environment, productivity, and customer satisfaction. Based on field tests, traffic simulations, and statistical methods, a cost–benefit analysis (CBA) found that all systems could improve road safety, while most of them could make both ends meet. These studies have mostly focused on economic feasibility and deployment roadmaps of separate ADAS.

Aside from the governmental concern, extensive researchers have also explored different impacts of ICV technologies. Several studies have considered ICVs as a part of ITS and conducted assessments of the whole system. Lu, Wevers, et al. [9] compared the effects of ADAS and inherently safe infrastructure based on a literature review and experts' knowledge, with the application of gray relational analysis. The results indicated that although ADAS would be more effective in improving traffic safety, a combination of ADAS and safety infrastructure should be the most feasible solution. Psaraki, Pagoni, et al. [10] considered the impacts on road capacity and greenhouse gas (GHG) emissions of ADAS, automated highway system (AHS), and commercial vehicle operations (CVO). They found that AHS had the most significant benefits with double capacity and 20% less fuel consumption and GHG emissions, while CVO could be the most cost-effective technology to reduce GHG emissions. The other studies concentrated on the impacts of some specific ADAS [8,11–18]. For instance, adaptive cruise control (ACC) could change the longitudinal behavior directly and has attracted most researchers. Benmimoun, Putz, et al. [11] investigated the effects of ACC and forward collision warning (FCW) based on the field operational test data of about 1000 vehicles. The ADAS application decreased the number of critical time-headways by 73%, while ACC reduced the fuel consumption by 2.77% on motorways, which means that the overall fuel-saving potential for passenger cars could reach 693.9 million liters and GHG emissions could decrease by 1.7 million tons in 27 European countries. Kuang, Zhao, et al. [12] employed traffic simulations to explore the traffic impacts of ACC in China, and the results showed that the average travel time could decrease by about 30% on urban roads, and about a 10% reduction on highways and rural roads. However, these results only paid attention to partial social issues of several ADAS applications, and the ADAS were only parts of ICVs and might be replaced by future ADS.

With the emergence of new technologies and products, there is increasing literature on the benefits and costs of autonomous and connected vehicles [2,19–29]. Fagnant and Kockelman [19] summarized the potential impacts of autonomous vehicles in the forms of traffic safety, congestion mitigation, fuel saving, and travel demand. It was estimated that a comprehensive annual saving per autonomous vehicle could be as high as \$3900 and the economic benefits would reach \$442 billion in the U.S. with a 90% market penetration. Another study by Stephens, Gonder, et al. [20] estimated the upper and lower bounds of autonomous and connected vehicles' effects on travel demand and fuel efficiency based on a literature review, and the result of potential changes in national light-duty vehicle fuel use in the U.S. varied from a drop by 60% to an increase by 200%. Wadud, MacKenzie et al. [21] also used a coherent energy decomposition framework to identify the influence mechanisms of autonomous vehicles. Four

scenarios composed of different assumptions about energy intensity and fleet mileage were considered, and the results indicated that total road transport energy could decline by 40% or grow by more than 100%. These studies provide a comprehensive insight into how ICVs affect different aspects of transportation, as well as quantitative analyses from a perspective of national implementation. Nonetheless, most results were limited to only a few aspects of the benefits of ICVs [20–24,26–29], and some considered only full autonomous vehicles [19,22,23]. They also ignored the ICVs' enormous industry economic value, which might be the most important impetus for automotive manufacturers and technology companies to develop ICV products. An innovation in business model will be essential to commercialize ICV technologies in view of their high costs and long payback period.

To sum up the literature review above, first, the social and economic impacts of ICVs are varied and complicated, and the literature has often only focused on a limited range of functions or benefits. Moreover, the results of different aspects could not be discussed together due to their different assumptions and dimensions. Therefore, a comprehensive and coherent assessment framework is necessary to consider all key functions and major benefits in different contexts. Furthermore, many studies only worked out the potential benefits of ICVs, but did not pay much attention to their costs. A detailed cost–benefit analysis could help policy makers to better understand the rationality and affordability of ICV deployment, and then formulate implementation plans as well as establish a new partnership among different stakeholders. Finally, most studies conducted scenario analyses by assuming a certain penetration rate of ICVs, but did not indicate when that would happen. A time series forecast may offer clearer references for the automotive industry to take next steps.

This paper aims to propose a detailed and unified assessment framework to estimate the potential socioeconomic effects and costs of ICV deployment in China. The research tries to answer three questions:

1. How can the socioeconomic impacts of ICVs be measured at the country level?
2. Can the benefits of ICVs cover their deployment costs and how long will it take?
3. What are the key factors that will influence the ICVs' benefits and deployment?

The following study is structured in four parts. Section 2 introduces the framework and methods, as well as the literature and data sources. The quantitative results are presented and analyzed in Section 3. Some further discussions about sensitivity analysis are provided in Section 4. Section 5 concludes the whole study and makes several suggestions.

2. Materials and Methods

There are a variety of potential social and economic benefits from ICV deployment. Based on the literature review [2,7,8,19] and authors' summary, four major aspects of benefits were studied in this paper, i.e., safety, traffic, environmental and industrial economic benefits. They reflect the major impacts of ICVs, and represent the primary concern of government, industry, and customers. Though many other impacts may also emerge, like changes in land use and parking locations [2,19], they are affected by many other factors rather than the technology itself. Therefore, we concentrated on the most important targets of sustainable mobility and industry to develop ICVs. Figure 1 explains the assessment framework, and the detailed methods and data resources are elaborated in the following part. Particularly, this paper mainly focused on the impacts of ICVs on the current transportation structure in China, and did not consider the effects of large-scale new mobility. Though ICVs enable new moving paradigms like car sharing and ride hailing [2,5], there exist great uncertainties about their regulatory policies, user acceptance, security issues, and business models. Thus, their wide implementation and influences remain to be explored in detail. However, we also tried to make a simple analysis on the impacts of car sharing, and proved that the bottom-up model proposed in this paper would allow to add in these factors in the future research.

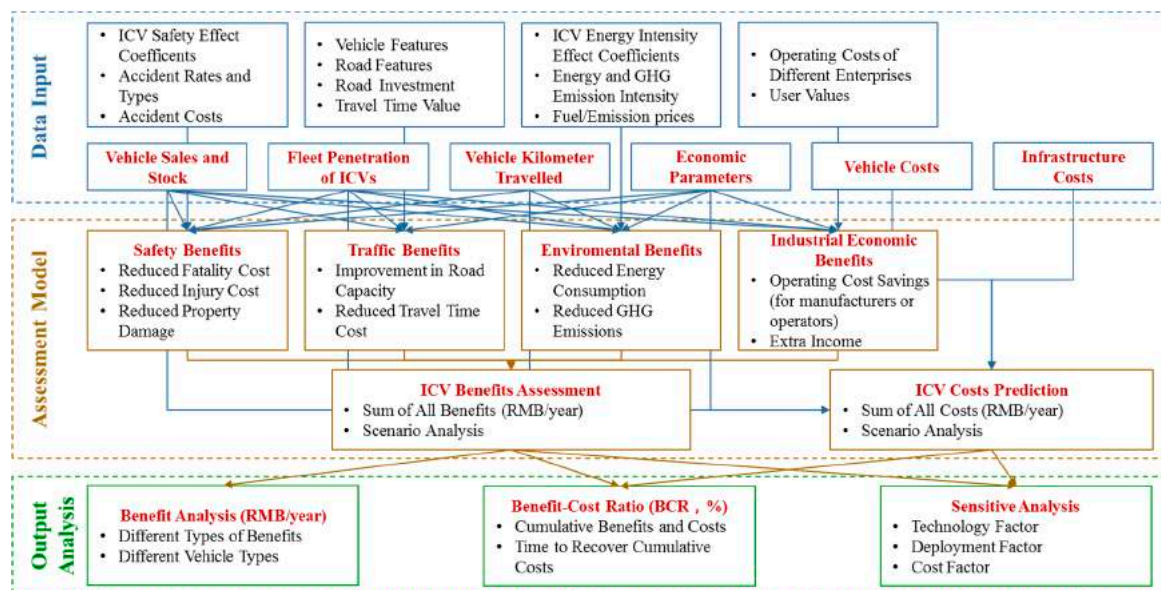


Figure 1. The research framework. GHG: Greenhouse gas; ICV: Intelligent connected vehicles.

2.1. Definition and Basic Assumptions

2.1.1. Basic Definitions and Scenarios

In order to evaluate the effects of ICVs, a specific description of technology is necessary to confirm assessment boundary. In this paper, ICV is classified as three levels according to different autonomous and connected levels, which refer to current standards and policies [4,30], as shown in Table 1. Level I ICV is a combination of L1 to L2 autonomous driving and primary connected functions, which can assist human drivers in simple driving tasks and exchange basic information. Level II ICV has a L3 ADS which can accomplish all operations in a particular situation with backup from human drivers, as well as stronger communication capabilities with surroundings and mobile internet. Level III ICV can both drive itself with a L4 to L5 ADS, and integrate into the internet of things to realize a life-cycle connection. Furthermore, the impacts of ICVs also depend on their operation environment. Thus, six vehicle types and eight road types are considered to describe different ICV usage scenarios according to existing literature [31,32], as well as Chinese vehicle and road engineering standards including CJJ 37-2016 and JTG B01-2014, as shown in Tables 2 and 3. Moreover, A and B in Table 3 are the model parameters of the Bureau of Public Roads (BPR) function for different types of roads, which are introduced in Subsection 2.3.2.

Table 1. Different levels and functions of ICV in this paper. ADS: Automated driving systems.

Function Types	ICV Levels		
	I	II	III
Autonomous Functions [30]	Level 1 to 2 ADS	Level 3 ADS	Level 4 to 5 ADS
Connected Functions	- Basic information exchange, like navigation information and vehicle status - Integrated with automotive services	- Surrounding information fusion, like data from other vehicles or infrastructure - Integrated with other digital services	- Work as a part of the cooperative transportation system and smart city - Integrated with the internet of things

Table 2. Vehicle types and features.

Vehicle Type	Usage	Stock Assumption	Average Length (m)
Passenger Vehicle (PV)	Noncommercial Passenger Vehicle (NPV), e.g., Private, Business Commercial Passenger Vehicle (CPV), e.g., Taxi, Fleet of Transportation Network Company	Calculated on sales prediction 2 per 1000 urban residents by 2050	4.5 [12]
Bus	Urban Bus (UB) Highway Bus (HB)	1 per 1000 urban residents by 2050 Calculated on sales prediction	7 [23]
Truck	Urban Truck (UT) Highway Truck (HT)	Calculated on sales prediction Proportion in truck fleet may drop to 50% by 2050	10 [23]

Table 3. Road types and features.

	Road Levels	Design Speed (km/h)	A	B
Urban Roads [32]	Express Way	80	1.448	1.435
	Arterial Road	60	0.905	3.497
	Secondary Trunk Road	40	0.726	5.897
	Bypass	30	0.596	1.457
Highways [33]	Super Highway	100		
	National and Provincial Highway	80	0.15	4
	Rural Highway	30		
	Rural Roads	20		

Since the effects of ICV show great uncertainty and complexity as found in the literature review, scenario analysis approach will be employed to describe their potential ranges. This paper defines three basic scenarios. Business as usual (BAU) scenario is set as a baseline, where the transportation and automotive industry in China continue current development trend, without any impacts of ICV. Optimistic (OPT) scenario means that ICV can maximize their socioeconomic benefits in all aspects. And under the conservative (CON) scenario, ICV's deployment may only bring small benefits or even increase the social burden. Furthermore, car sharing optimistic (CS OPT) and conservative (CS CON) scenario are set to estimate the impacts of car sharing, based on OPT and CON scenarios, respectively. It is assumed that half of the annual sales of Level III NPVs (noncommercial passenger vehicle) will be replaced by Level III CPVs (commercial passenger vehicle) from 2025, with a five-to-one replacement rate according to their use intensity [31].

2.1.2. Vehicle Stock and Fleet Penetration

A bottom-up method is used to establish the whole vehicle fleet in China. Vehicle stock and fleet penetration of ICVs are calculated by the following equations [31,34]:

$$Stock_{y,i} = \sum_{t \in T} \sum_{age=0}^{life_t} Sale_{y-age,t} \times Share_{y-age,i} \times r_t(age) \quad (1)$$

$$\beta_{y,i} = \frac{\sum_{t \in T} Stock_{y,i}}{\sum_{t \in T} \sum_{i=0}^3 Stock_{y,i}} \quad (2)$$

where, $Stock_{y,i}$ is the stock of level i ICV in year y (unit); $Sale_{y-age,t}$ is the sales of vehicle type t in year $(y-age)$ (unit); $Share_{y-age,i}$ is the market share of level i ICV in the total sales in year $(y-age)$ (%); $r_t(age)$ is the survival rate of vehicle type t in the (age) th year (%); $life_t$ is the service life of vehicle type t (year); and $\beta_{y,i}$ is the fleet penetration of level i ICV in year y (%). When $i = 0$, it means conventional vehicles.

The automotive market in China has experienced a rapid development for more than 10 years, and will have a lower growth rate in the next decades. The past sales data until 2018 come from the

statistics of China Association of Automobile Manufactures, and the future prediction refers to the research of Liu, Zhao, et al. [34]. Furthermore, the market share of ICV is calculated with a logistic function which is often used in innovation diffusion modelling. It is assumed that ICV started to enter the market in 2015, with a low market share at only 3% [35], and according to *Technology Roadmap for Energy Saving and New Energy Vehicles* in China [4], the market share of Level I and II ICVs will reach 50%, 80%, and 100% by 2020, 2025, and 2030, respectively. Besides, Level III ICV will start its commercialization in 2025 and its penetration in new vehicles will reach 10% by 2030. Based on these historical data and targets, the logistic function is calibrated and annual market share of ICVs can be then determined. Since the roadmap does not set respective targets for different vehicle types, we assume the same market share of ICVs for all vehicle types. Then the survival rate and service life of different vehicle types are extracted from existing literature [31].

The results are presented in Figure 2. The fleet penetration of Level I to III ICVs will respectively reach 57.01%, 11.05%, and 2.70% by 2030, while 8.35%, 7.80%, and 83.84% by 2050. Level II ICV may be regarded as a transitional product, thus it only occupies a relatively small part in the fleet. The whole fleet will keep growing and end up with 522.89 million by 2050. However, under the CS scenarios, the vehicle stock in China will peak at 450.81 million units in 2036 and then drop to 369.41 million units in 2050, with a significant reduction in level III ICVs. Since fewer Level III ICVs will enter the market, the fleet penetration of Level III ICVs will decrease to 1.81% by 2030, and 77.13% by 2050.

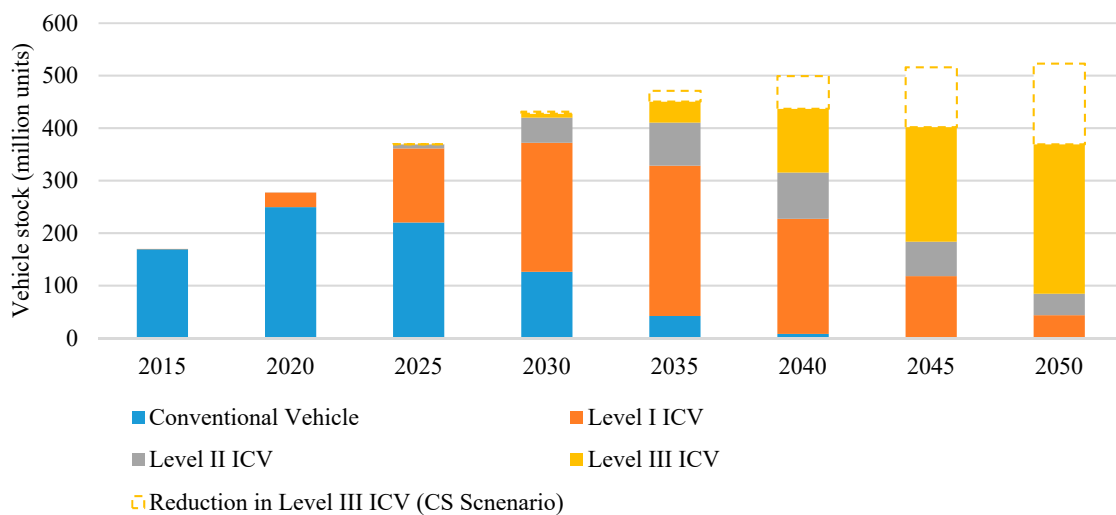


Figure 2. Prediction of vehicle stock of different ICVs in China. CS: Car sharing.

2.1.3. Vehicle Kilometers Travelled

Vehicle kilometers travelled (VKT) are the total kilometers traveled by all vehicles annually, which affects the number of accidents, fuel consumption, and emissions of the whole fleet. Different vehicle types have distinct travel distances which are subject to various factors, such as fuel costs, traffic conditions, and passenger or logistics demand. Therefore, a statistical average is usually used to describe vehicle usage intensity. Furthermore, a vehicle's travel distance may decline as it gets older [36]. Hence, the VKT variation ratios over vehicle lifespan are taken into account. Fleet VKT of vehicle type t in year y under BAU scenario can be calculated as following [31]:

$$VKT_{y0,t} = \sum_{age=0}^{life_t} [Sale_{y-age,t} \times r_t(age) \times AVKT_{y,t} \times rvkt_t(age)] \quad (3)$$

where, $AVKT_{y,t}$ is the average VKT of vehicle type t in year y (km/year); and $rvkt_t(age)$ is the VKT ratio of vehicle type t in the (age) th year (%). All parameters come from relevant studies in China [31,36].

However, VKT will be significantly influenced by ICV's deployment. On one hand, ICV may reduce VKT due to less hunting for parking places and more ridesharing. However, on the other hand, more underserved population and unmanned driving tasks are able to make use of ICVs with high-level ADS, while decreased travel costs will also lead to more travel demand and transportation modes shift. For different types and levels of ICVs, these effects will be quite different. Hence, fleet VKT with ICVs may vary from the baseline under different scenarios. The modified fleet VKT are shown in Equation (4).

$$VKT_{y,t} = VKT_{y0,t} \times \left\{ \prod_{m \in M} [1 + \sum_{i \in L} (\beta_{y,t,i} \times EC_{VKT,m,i})] \right\} \quad (4)$$

where, $EC_{VKT,m,i}$ is the effect coefficient of mechanism m on level i ICV's VKT (%). The coefficients used in this paper are illustrated in Table 4.

Table 4. Vehicle kilometers travelled (VKT) effect coefficients of different ICVs (under 100% penetration rate scenario). CON: Conservative scenario; OPT: Optimistic scenario.

Mechanisms	Applied Vehicle Types	Level I and II ICV		Level III ICV		Sources
		OPT	CON	OPT	CON	
Less Hunting for Parking	NPV	−5%	−2%	−11%	−5%	[22,37]
More Travel due to Higher Efficiency	All	4%	13%	14.5%	60%	[21,27,28]
More Travel of Underserved Population	PV	0	0	2%	14%	[27,38]
Ridesharing	PV	0	0	−12%	0	[22]
Empty Mileage	PV	0	0	0	8.68%	[39]
Transit Modes Shift	NPV	0	0	0	10%	Estimated based on [40]

Figure 3a–c show the predictions of fleet VKT. Passenger vehicles contribute the major portion to fleet VKT, followed by highway trucks. Under the BAU scenario, fleet VKT will reach 3.80 trillion kilometers in 2030 and 4.89 trillion kilometers in 2050. And there will be only little change under the OPT scenario, with an increase by 0.02% in 2030 and a decrease by 2.02% in 2050. Meanwhile, a significant growth can be observed under the CON scenario by 9.96% and 79.74%, respectively. Figure 3d indicates that if we consider the additional effects of car sharing, there will be an extra reduction in fleet VKT because of the higher mobility efficiency of CPV than NPV. Furthermore, the share in transport of CPVs increase to almost 20%, comparing to only around 1% in BAU scenario.

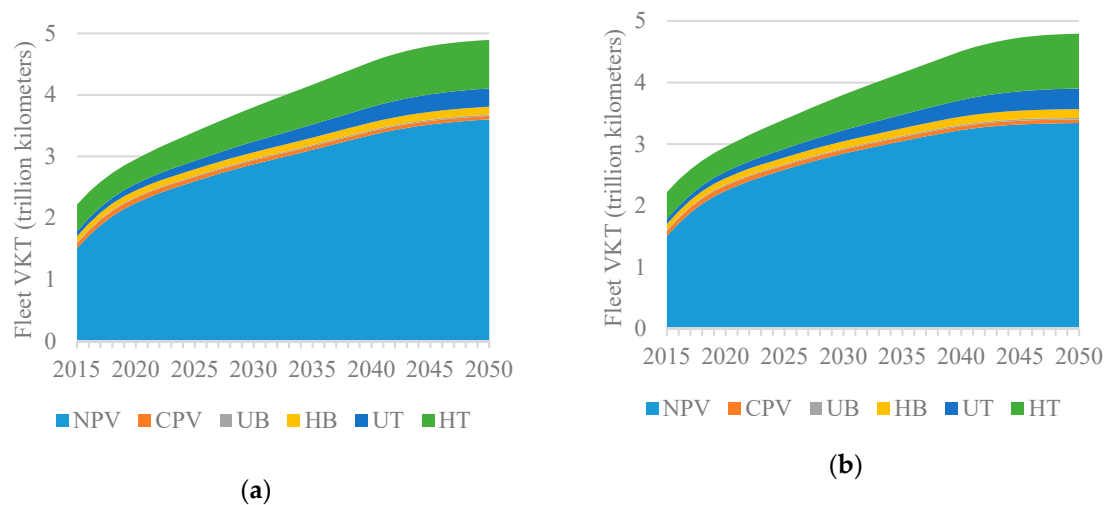


Figure 3. Cont.

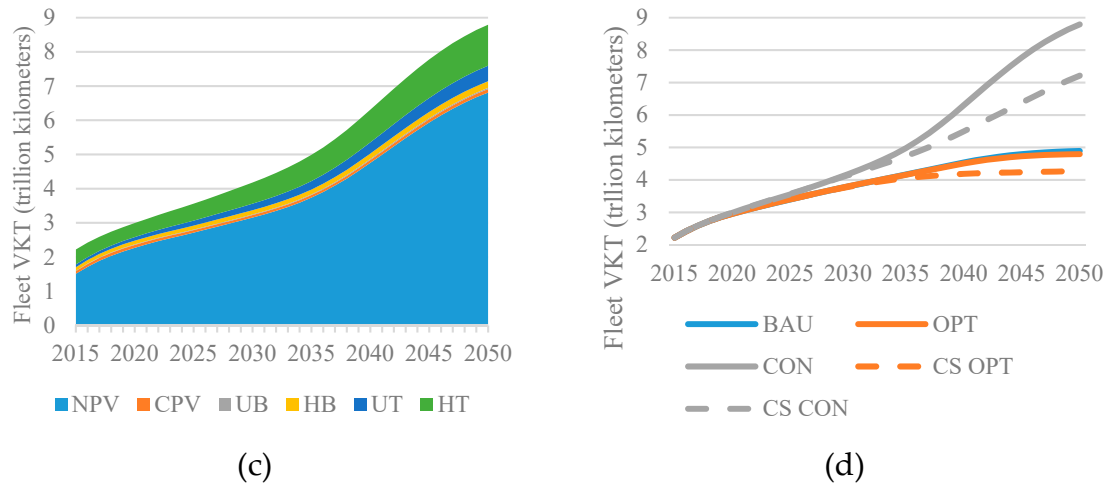


Figure 3. Fleet VKT predictions under different scenarios: (a) Business as usual (BAU) scenario; (b) OPT scenario; (c) CON scenario; (d) all scenarios.

2.1.4. Economic Assumptions

In order to conduct CBA of ICV, monetization of all kinds of benefits is necessary. To exclude the influence of inflation, we assume that all the prices and costs in this paper, like accident costs and fuel prices, will remain the same from 2015, which means 2015 constant values are used for benefit and cost estimation. Only emission prices and vehicle costs will change significantly, due to the policy regulations and technology advancement, which will be discussed in Sections 2.4.3 and 2.6.1, respectively. Thus, all the benefits and costs are measured in constant 2015 renminbi (RMB), and the exchange rate of U.S. dollar to RMB adopts the average value in 2015 according to National Bureau of Statistics. Other economic parameters, including total population, urban population, and per-capita gross domestic product (GDP) in China, refer to the research of Lu, Zhou et al. [31]. Moreover, this paper uses the method of present value to calculate the cumulative benefits, costs and benefit–cost ratios, with a social discount rate at 8%.

2.2. Safety Benefits

2.2.1. Impacts on Number of Accidents

Traffic safety can be defined as the expected number of fatalities and injuries in a specific area during a certain period. Hence, it consists of three primary dimensions, namely exposure, risk, and consequence [41]. Exposure describes the duration when vehicles are in danger of accidents, which can be measured in VKT. Risk represents the probability of being involved in accidents per unit of exposure, and consequence shows the expected fatalities or injuries in each accident. ICV will change fleet VKT as previously mentioned, and also reduce accident possibility by correcting driving behaviors and improving driving abilities. Therefore, the effects of ICV on traffic safety mainly apply to road exposure and risk. The impacts on the number of fatalities can be calculated as following:

$$\Delta Fatal_y = \sum_{i \in L} \sum_{f \in F_i} \sum_{a \in A} Fatal_y \times PA(a) \times EC_{fatal}(f, a) \times CF(f, \beta_{y,i}, IP_y) \times \frac{VKT_{y,t}}{VKT_{y0,t}} \times (1 - \frac{VKT_{y,t}}{VKT_{y0,t}}) \quad (5)$$

where, $\Delta Fatal_y$ is the decrease of fatalities in year y (person); $Fatal_y$ is the number of fatalities under BAU scenario in year y (person); $PA(a)$ is the proportion of accident type a in all accidents (%); $EC_{fatal}(f, a)$ is the safety effect coefficient of function f on the fatalities of accident type a (%); and $CF(f, \beta_{y,i}, IP_y)$ is the correcting factor of function f considering fleet penetration $\beta_{y,i}$ and road infrastructure penetration IP_y (%). The impacts on injuries can also be derived from this equation by replacing fatality-related parameters with injury-related ones.

The BAU number of fatalities can be derived from vehicle stock and fatality rate per 10,000 vehicles (FR). FR in China declined from 4.33 in 2008 to 2.06 in 2017 [42], which approaches the road safety level of U.S. in 1997 [43]. And FR in U.S. has been stable at about 1.20 since 2014 [43]. Therefore, we assume that FR in China will reach the same level in 2034 and stabilize from then on. Moreover, injury rate shows a linear correlation with FR, and it is assumed as 3.4 times greater than FR, based on historical data from 2008 to 2017 [42]. The proportions of different accident types is assumed as constant values since 2016 [42].

The safety effect coefficient measures how many accidents can be avoided with ICV functions. Based on a literature survey, all coefficients used in this paper are shown in Table 5. For Level I and II ICVs, their safety improvements are expressed as the sums of potential accident decreases caused by corresponding functions. Some types of accidents can be reduced by various functions, which results in double counting. Thus, this paper decouples these interrelationships by assuming equal weights for each function which can work in the same specific accident type, due to lack of detailed data on accident causes. For instance, Full-speed range adaptive cruise control (FSR ACC), electronic stability control (ESC), and traffic sign recognition (TSR) can all reduce the accidents caused by overspeed. So it is assumed that one third of overspeed accidents can be avoided by each function. Particularly, for Level III ICV, due to its high-level autonomous driving ability, it can cut down all kinds of accidents by 90% [3].

Table 5. Safety effect coefficients of different ICV functions (under 100% penetration rate scenario).

Functions ¹	ICV Levels		Accident Types [42]	Injury Reduction %		Fatality Reduction %		Sources
	I	II		CON	OPT	CON	OPT	
FSR ACC	✓	✓	Overspeed, improper acceleration	16	30	16	45	[44,45]
PCS	✓	✓	Improper braking, accident with pedestrians	20.9	30.6	9.9	19.9	[15]
LCA	✓	✓	Illegal lane change, illegal overtaking, improper steering	27	90	27	90	[13,44]
LKA	✓	✓	Driving against traffic, improper steering	29	32	25	27	[46]
ESC	✓	✓	Overspeed, improper steering	7	35	21.6	32	[14,16]
AP	✓	✓	Illegal reverse, illegal parking	75	100	75	100	[47]
NV	✓	✓	Night accidents	0	20	0	20	[44]
DM	✓	✓	Drunk driving, driver fatigue	75	99.3	75	99.3	[48,49]
AFS	✓	✓	Illegal lighting usage	0	91	0	88	[18]
TSR		✓	Overspeed, driving against traffic, illegal turning back, illegal road occupation	95	99	95	99	[50]
eCall	✓	✓	All fatalities	0	0	2.4	4.6	[17]
IMA		✓	Illegal meeting, illegal overtaking, violation of traffic signals, do not give way	22.7	62	22.7	62	[25,44]
WILLWARN		✓	Do not give way, road related accidents	1.4	2	2	2.5	[44,51]
		✓	Adverse weather	4.7	6.8	6.2	13	

¹ Abbreviations: Full-speed range adaptive cruise control (FSR ACC); Precollision system (PCS); lane change assist (LCA); lane keep assist (LKA); electronic stability control (ESC); automated parking (AP); night vision (NV); driver monitoring (DM); adaptive front-lighting system (AFS); traffic sign recognition (TSR); emergency call (eCall); intersection movement assist (IMA); wireless local danger warning (WILLWARN).

The fleet penetration and road infrastructure penetration of ICV functions also determine their practical effects. ICV functions can be divided into four categories according to operating mechanisms: Single-vehicle and multiple-vehicle functions either based on on-board sensors, or based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. These categories have different correcting factors, as shown in Table 6 based on [24]. Infrastructure penetration represents the proportion of road infrastructure equipped with V2I ability. The recent Chinese official plans require a 90% coverage of V2I network in cities and highways by 2020, and a full coverage by 2025. Therefore, it is assumed that the network construction can satisfy the demand of high-level ICV's development, and infrastructure penetration is regarded as 100%.

Table 6. Correcting factors of different ICV functions.

Function Types	Functions	Scenario	CF(β , IP)
Single Vehicle	FSR ACC, PCS, LDW, LKA, ESC, AP, DM, TSR, eCall	Vehicle equipped	$\beta \times 1$
Multiple Vehicle	AFS, NV	None vehicle equipped	$(1 - \beta)^2 \times 0$
		Single vehicle equipped	$2(1 - \beta)\beta \times 0.5$
		Both vehicles equipped	$\beta^2 \times 1$
Vehicle to Vehicle	-	None vehicle equipped	$(1 - \beta)^2 \times 0$
		Single vehicle equipped	$2(1 - \beta)\beta \times 0$
		Both vehicles equipped	$\beta^2 \times 1$
Vehicle to Infrastructure	IMA, WILLWARN	Neither equipped	$(1 - \beta)(1 - IP) \times 0$
		Only vehicle equipped	$\beta(1 - IP) \times 0$
		Only infrastructure equipped	$(1 - \beta)IP \times 0$
		Both equipped	$\beta \times IP \times 1$

2.2.2. Accident Costs

To monetize safety benefits, average accident costs of fatality and injury in China are estimated. Accident cost includes victim related cost, property damage, and administration cost [52,53]. The value of statistical life or injury (VSL or VSI) quantifies the potential benefits of avoiding these accidents, and it is usually expressed as a form of per-capita GDP. A wide range of ratios are recommended in different studies [52–55], and we adopt the suggestion of iRAP project that VSL is 70 times of GDP per capita [52]. VSI is also expressed as a fraction of VSL. An average ratio of different injury severity levels is calculated, according to the official guidance of U.S. Department of Transportation [55]. Furthermore, direct property damage is considered separately and historical data from 2008 to 2017 shows that it costs around 20,000 RMB per death on average [42].

2.3. Traffic Benefits

2.3.1. Impacts on Road Capacity

Under the OPT scenario, ICV can improve average travel speed with smoother driving strategy, and increase traffic density by shortening headways between vehicles. Several previous studies believe that widespread ICVs may even double current road capacity [23,29]. However, these impacts will be distinct for different vehicle and road types, because drivers of buses and trucks will remain longer headways in case of emergency brakes, and vehicles on highways will also stay farther away from others due to higher speeds. Thus, the impacts on basic capacity under ideal traffic conditions are evaluated. The road capacity can be determined as Equation (6) based on the traffic flow theory, with a modified speed–flow–density relationship [23]. Since Level I ICV only has L1 or L2 ADS without cooperation functions and is operated by human drivers most of the time, it is treated as the same type with the conventional vehicle in this equation.

$$Cap_{y,r} = \frac{v_r \times 3600}{\sum_{t \in T} \omega_{y,t} (\beta_y^2 v_r T_{aa,r} + \beta_y (1 - \beta_y) v_r T_{ah,r} + (1 - \beta_y) v_r T_{hx,r,t} + L_t)} \quad (6)$$

where, $Cap_{y,r}$ is the capacity of road type r in year y (vehicles per hour per lane); v_r is the design speed for road type r (m/s), as listed in Table 3; $\omega_{y,t}$ is the stock proportion of vehicle type t in year y (%); β_y is the fleet penetration of Level II and III ICVs, which can be expressed as $\beta_{y,2} + \beta_{y,3}$ (%); $T_{aa,r}$ is the time gap between two ICVs on road type r (s); $T_{ah,r}$ is the time gap that a Level II or III ICV will keep when following a human-driven vehicle on road type r (s); $T_{hx,r,t}$ is the time gap that a human-driven vehicle of type t will keep from others on road type r (s); and L_t is the sum of length of vehicle type t and a minimum safety distance (m).

For passenger vehicles, $T_{aa,r}$, $T_{ah,r}$, and $T_{hx,r,PV}$ are set as 0.3 s, 0.6 s, and 0.6 s, respectively on urban roads, while 0.5 s, 0.9 s, and 1.15 s, respectively on highways and rural roads [23]. As for buses and trucks, the time gap parameters of Level II and III ICVs are the same, and the ones of human drivers can be adjusted by Huber's equation [56].

$$PCE_{r,t} = \frac{v_r \times T_{hx,r,t} + L_t}{v_r \times T_{hx,r,PV} + L_{PV}} \quad (7)$$

where, $PCE_{r,t}$ is the passenger car equivalent factor of vehicle type t on road type r . According to Chinese road engineering standards, the factors for buses and trucks are 2.0 and 2.5 on urban road, and change to 1.5 and 2.5 on highways and rural roads.

Under the CON scenario, ICV may not bring such ideal improvements to road capacity. Some studies indicated that mixed traffic of ICVs and conventional vehicles might result in interference, and ICVs could not cut down headways as low as possible in consideration of passengers' comfort and feelings [57,58]. Hence, it is supposed that there will be no increase in road capacity.

2.3.2. Impacts on Travel Time

ICV can travel at more stable speeds, change lanes and pass intersections quickly, and avoid congestion with dynamic navigation systems. To estimate the reduction in travel time, the Bureau of Public Roads (BPR) function [33] is modified as following.

$$\Delta Time_{y,r} = \left(\frac{1 + A_r \times IC_{y,r,ICV}^{B_r}}{1 + A_r \times IC_{y,r,non-ICV}^{B_r}} - 1 \right) \times 100\% \quad (8)$$

$$IC_{y,r,ICV} = \frac{Flow_r}{Cap_r} \times \sum_{i \in L} [\beta_{y,i} \times PCEA_{i,r} \times \sum_{t \in T} (\omega_{y,t} \times PCE_{r,t})] \quad (9)$$

where $\Delta Time_{y,r}$ is the reduction rate of travel time on road type r in year y (%); A_r and B_r are the model parameters of road type r , which are shown in Table 3; $IC_{y,r,ICV}$ is the ratio between actual traffic flow and road capacity on road type r in year y , in consideration of ICVs' effects; and $PCEA_{i,r}$ is the passenger car equivalent factor of level i ICV on road type r . $PCEA_{1,r}$ equals 1.0 because Level I ICV behaves almost the same with human drivers, while $PCEA_{2,r}$ and $PCEA_{3,r}$ are derived from Huber's equation with their time gap parameters [56].

Value of $Flow_r / Cap_r$ represents the level of service on road type r . To estimate the bounds of ICVs' effects, it is assumed to be 0.35 under the CON scenario based on standard JTG B01-2014, which describes a free flow and ICVs' improvements in travel time are tiny. Under the OPT scenario, traffic flow surpasses road capacity and this value equals 1.0, when ICVs will maximize their benefits in mitigating congestion.

2.3.3. Road Capacity Cost and Travel Time Value

Increasing road capacity may allow governments to reduce investment in road construction and maintenance. Therefore, the fixed investments in different roads in China are used to monetize the improvements in road capacity, according to yearbook data from Ministry of Housing and Urban-Rural Development and Ministry of Transport. An annual growth rate of 2% is assumed since 2015.

Travel time value is the cost per unit time spent on travel, and varies for drivers and passengers of different vehicle types. It is usually compared with prevailing wages, with the premise that all the time savings will be devoted to working. We employ Litman's recommended adjustment factors to reflect specific conditions and preferences of vehicle occupants [59]. However, this paper focuses on the socioeconomic impacts, thus per-capita GDP per time unit is used to evaluate travel time value instead of personal income or wages. The average number of passengers per trip is estimated based on transportation statistics, as 2 persons for CPVs, 0.5 for NPVs, 45 for buses, and 1 for trucks.

Furthermore, travel time value will decrease due to the more efficient utilization of time, when human drivers are able to pay less or no attention to traffic conditions and spend hours working or relaxing in autonomous vehicles. Several studies indicated that for Level I ICV, travel time value would decrease by 0 to 5%, and 50% to 80% for Level III ICV [26,27]. Since Level II ICV is driven by human drivers and ADS together, an average reduction rate is applied, which means 25% to 42.5%.

2.4. Environmental Benefits

2.4.1. Impacts on Energy Consumption

ICV will affect the use intensity and energy intensity of fleet energy consumption, based on a modified Kaya Identity method [22]. On one hand, ICV can influence use intensity by changing fleet VKT, as discussed before. On the other hand, ICV will change energy intensity in three ways. First, ICV may change current vehicle configurations and designs. Extra components such as cameras, radars, LiDARs, and communication modems will consume more energy and add curb weights. And vehicles may also increase their air drag because of external installation of ICV hardware, while reduce their weights by cancelling passive safety devices and downsizing for higher occupancy. Second, ICV can improve fuel efficiency through eco-driving strategies and vehicle platooning, and platooning is more energy efficient on highways. Third, ICV can contribute to a better traffic environment. There will be less congestion in urban areas, and fewer “stop and go” activities will help reduce energy waste. However, the average speed on highways will rise, which causes larger air resistance. Besides, fewer accidents may also reduce related traffic jams and then unnecessary braking and bypassing behaviors, which have currently increased fuel consumption to some extent. All these mechanisms and their effects are listed in Table 7.

Table 7. Energy intensity effect coefficients of different mechanisms (under 100% penetration rate scenario).

Mechanisms	Applied Vehicle Types	Effect Coefficient		ICV Levels			Sources
		CON	OPT	I	II	III	
Vehicle Design	Direct Energy Consumption	All	1.2%	0.9%	✓	✓	Estimated based on [60] [60] [21,60]
	Changes in Weight	All	1%	0.3%	✓	✓	
	Changes in Shape	All	−8.7%	−45%		✓	
Vehicle Usage	Eco-driving	All	0	−20%	✓	✓	[21] [21]
	Platooning	HB, HT	−3%	−25%		✓	
Traffic Environment	Less Congestion	PV, UB, UT	−2%	−4%	✓	✓	[21] [21] [20]
	Higher Speed	HB, HT	22%	7%		✓	
	Fewer Accidents	All	0	−1.9%		✓	

The fleet energy consumption under the BAU scenario and the OPT or CON scenarios can be calculated with Equations (10) and (11) [34].

$$EC_{y0,t} = \sum_{age=0}^{life} [Sale_{y-age,t} \times r_t(age) \times AVKT_{age,t} \times rvkt_t(age) \times AECR_{y,t}] \quad (10)$$

$$EC_{y,t} = EC_{y0,t} \times \frac{VKT_{y,t}}{VKT_{y0,t}} \times \left\{ 1 + \sum_{i \in L} \{\beta_{y,i} \times \left[\prod_{m \in M_{i,t}} (1 + \Delta EI_m) - 1 \right] \} \right\} \quad (11)$$

$$AECR_{y,t} = \frac{\sum_{ft \in FT} (Sale_{y,t,ft} \times ECR_{y,t,ft} \times LH_{ft} \times \rho_{ft})}{\sum_{ft \in FT} Sale_{y,t,ft}} \quad (12)$$

where, $EC_{y0,t}$ is the total energy consumption of vehicle type t in year y under the BAU scenario (MJ); $AECR_{y,t}$ is the average energy consumption rate of vehicle type t in year y (MJ/km); $Sale_{y,t,ft}$ and $ECR_{y,t,ft}$ are the sales and average energy consumption rate of vehicle type t of fuel type ft in year y

(kg/km or L/km), which are extracted from the study of Liu et al. [34]; LH_{ft} and ρ_{ft} are the low heat value and density of fuel type ft , as shown in Table 8; and ΔEI_m is the energy intensity effect coefficient of mechanism m (%), as illustrated in Table 7. The results of AECR are shown in Figure 4.

Table 8. Physical and economic properties of vehicle fuels.

Fuel Types	Low Heat Value (MJ/kg or MJ/m ³)	Density (kg/L)	Life Cycle GHG Emissions Factor (g CO ₂ eq./MJ)	Fuel Price ¹	Sources
Gasoline	43.1	0.73	100.8	6115.2 RMB/tonne	[34,61,62]
Diesel	42.6	0.84	102.5	5104.7 RMB/tonne	
CNG	38.9	-	69.4	5.12 RMB/liter	
LNG	38.9	0.45	75.4	3298.4 RMB/tonne	
Hydrogen	120	-	48.4	93.6 RMB/kg	Calculated based on [63,64]
Electricity	-	-	198.6 (in 2015) to 111.2 (in 2050)	388.25 RMB/kkWh	
PHEV ²	38% × Value of Fuel + 62% × Value of Electricity				[65]

¹ All fuel prices are the market prices on 31 December 2015 according to National Bureau of Statistics, except that hydrogen price is an estimation of experts. ² CNG: Compressed Natural Gas; LNG: Liquefied Natural Gas; PHEV: Plug-in Hybrid Electric Vehicle.

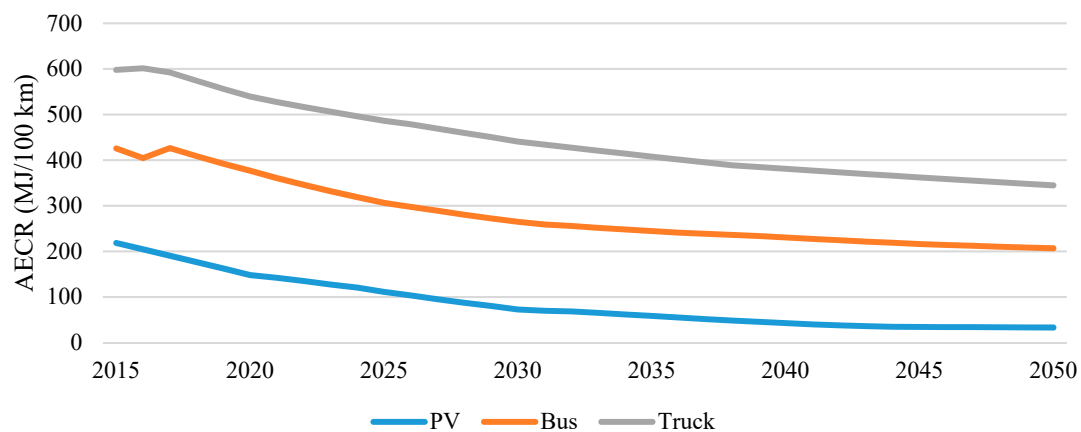


Figure 4. The average energy consumption rate of new vehicle sales in China. AECR: Average energy consumption rate of vehicle.

2.4.2. Impacts on GHG emissions

This paper considers the fleet GHG emissions in well to wheel stage. GHG emissions are proportional to energy consumption, and can be expressed as following [34]:

$$GHG_{y0,t} = \sum_{age=0}^{life} [Sale_{y-age,t} \times r_t(age) \times AVKT_{age,t} \times rvkt_t(age) \times GHGR_{y,t}] \quad (13)$$

$$GHG_{y,t} = GHG_{y0,t} \times \frac{VKT_{y,t}}{VKT_{y0,t}} \times \left\{ 1 + \sum_{i \in L} \{\beta_{y,i} \times \left[\prod_{m \in M_{i,t}} (1 + \Delta EI_m) - 1 \right] \} \right\} \quad (14)$$

$$GHGR_{y,t} = \frac{\sum_{ft \in FT} (Sale_{y,t,ft} \times ECR_{y,t,ft} \times LH_{ft} \times \rho_{ft} \times GI_{ft})}{\sum_{ft \in FT} Sale_{y,t,ft}} \quad (15)$$

where, $GHGR_{y,t}$ is the average GHG emission rate of vehicle type t in year y (g CO₂ eq./km); and GI_{ft} is the life cycle GHG emissions factor of fuel type ft as shown in Table 8.

2.4.3. Energy and GHG Emissions Costs

The energy savings of ICV are measured with fuel costs. The 2015 constant prices of different fuel types are presented in Table 8, and the benefit of reduction in GHG emissions is quantified with the

carbon market price. Since there is no unified carbon market in China currently, we regard Beijing as a representative market and its 2015 average price of carbon credits was 41.48 RMB/tonne. It is estimated that the reasonable price will increase to about 300 RMB/tonne in China by 2030 [66], and we assume that it will not change after that.

2.5. Industrial Economic Benefits

2.5.1. Impacts on Operating Costs

The commercialization of ICV will have influences on operating costs for both automotive manufacturers and commercial fleet operators, as shown in Table 9. For automotive manufacturers, ICV may either require higher investment in new technology research and development (R&D), or reduce R&D costs by providing real-time data for optimal design. ICV can also decrease production costs since it enables software-defined vehicles to promote modularization and intelligent manufacturing. Moreover, ICV can decrease marketing costs because it makes precision marketing and remote services possible [1].

Table 9. Impacts on operating costs of different enterprises.

	Cost Types	Initial Cost Per Vehicle (RMB Per Vehicle Per Year)	Mechanisms	Effect Coefficient	Sources
Automotive Manufacturers	R&D Cost	PV: 1259 Bus: 13,366 Truck: 2516	- New technology development requires higher costs - Optimize designs with ICV real-time data to reduce costs	OPT: −4% CON: +15.4%	[68]
	Production Cost	PV: 67,779 Bus: 292,733 Truck: 95,401	- Modularization and platformization of ICV reduces initial costs - Intelligent manufacturing with ICV data improves efficiency	OPT: −0.2% CON: 0	[69]
	Marketing Cost	PV: 6148 Bus: 24,430 Truck: 3478	- Precision marketing to reduce costs - Decrease in-site service and recall costs with remote services	OPT: −10% CON: 0	[70]
Commercial Fleet Operators	Financial Cost	NPV: 3700 CPV: 8000 Bus: 5400 UT: 3000 HT: 4500	ICV can avoid accidents, thus reducing insurance fee	Level I ICV: 0 Level II ICV: −25% Level III ICV: −50%	[67,71]
	Cleaning Cost	0	Driverless CPVs and buses will need extra cleaning	Level III ICV: Extra 50 RMB per 40 operations	[67]
	Labor cost	CPV: 67,200 Bus: 54,000 Truck: 107,000	CPVs, buses and trucks can save salaries of a driver per vehicle	Level III ICV: −100%	Based on market survey ¹

¹ The CPV and bus driver salaries data is from a Chinese recruitment website 58.com. The truck driver salary data is from [72].

Considering the operational cost structure of commercial fleet operators, main savings of ICV fleet compared with conventional vehicle fleet lie in insurance fee, cleaning cost, and driver salary [67]. First, ICVs have lower probability to be involved in accidents, thus they can obtain a lower insurance rate. Second, Level III ICVs without drivers will need cleaning more frequently, since passengers may

pollute their cockpits during nondriving activities. Third, Level III ICVs need no drivers and save labor costs. For different types of vehicles, these costs are estimated separately. Particularly, these cost savings are supposed to be the main target for automotive industry to develop ICVs, hence we presume that they will be the same for both OPT and CON scenarios.

2.5.2. Impacts on Income

ICV can not only cut down diverse costs, but also generate income for automotive manufacturers. Under the OPT scenario, an increasing user value will be realized because ICVs can strengthen the bond between users and product providers. First of all, customers are willing to pay incremental prices for ICV functions and devices. Then, users are able to enjoy digital automotive services such as on-site maintenance, intelligent charging, and online financial services, via ICVs' communication abilities. Finally, the big data generated by ICVs may allow the automotive industry to cooperate with other industries like tourism, e-commerce, and smart home. Table 10 shows ICVs' impacts on user values, and the same values are assumed for all vehicle types. However, users may also regard all these products and services as regular updates and will pay nothing more under the CON scenario.

Table 10. Impacts on user values of automotive manufacturers under the OPT scenario.

Value Types	Mechanisms	Additional Values of ICVs			Sources
		Level I	Level II	Level III	
Product Value (RMB per vehicle)	Extra value that consumers are willing to pay for ICV functions	23,504	33,580	38,866	[35,73]
Service Value (RMB per vehicle per year)	- More digital services related to vehicle usage, such as insurance and maintenance - Higher user loyalty and longer service cycle	187	280.5	374	[68]
Data Value (RMB per vehicle per year)	Integrated into the products and services of other industries such as tourism, e-commerce, and smart home	187	374	561	[68]

2.6. Implementation Costs

2.6.1. Vehicle Costs

Though implementation of ICVs will generate a variety of benefits, extra fixed cost and variable cost are required for the fleet to achieve these goals. The extra fixed cost is the purchase cost of ICV hardware and software. In the absence of statistics for ICV prices, this paper employed a learning curve model to predict the extra fixed cost, as shown in Equation (16). Thus, the initial prices are needed to estimate the future ones. For Level I ICV, Archambault, Delaney, et al. [74] surveyed its content increases per vehicle, and the prices of Tesla Autopilot and Google autonomous vehicles are assumed as the initial values for Level II and III ICVs. Therefore, the extra fixed costs for the different ICVs are \$765 (4765 RMB), \$5000 (33,142 RMB), and \$150,000 (934,260 RMB) in 2015, respectively.

$$FixedCost_{y,i} = FixedCost_{0,i} \times \left[\sum_{2015}^y (Sale_y \times \beta_{y,i}) \right]^{-r} \quad (16)$$

where, $FixedCost_{y,i}$ is the extra fixed cost for level i ICV in year y (RMB per vehicle); $FixedCost_{0,i}$ is the extra fixed cost of the first production for level i ICV (RMB per vehicle), which is calibrated with aforementioned values; 2^{-r} is the progress ratio, which implies how the cost could be decreased when cumulative production is doubled. Since there is no experience data for ICV production, the progress ratio of Ford Model T is considered as a reference: 85% [75]. According to this model, the extra prices for each level ICV will drop down to 1398, 9559, and 124,665 RMB at the beginning of commercialization in 2025, and even only about 1079, 4829, and 22,503 RMB in 2050.

Extra variable cost includes the maintenance cost and communication cost when passengers use ICV functions. The annual maintenance cost of ICV hardware and software is about 10% of the extra fixed cost. According to statistical bulletins of Chinese communications industry in 2017 to 2018, a mobile network user spends around 536 RMB on mobile data yearly on the average. We assume that Level III ICVs will double this cost because both passengers and vehicles will need such communication services. Hence, the communication costs for the different ICVs are 536, 804, and 1072 RMB per vehicle per year, respectively.

2.6.2. Infrastructure Costs

Level II and III ICVs require not only upgrading of vehicles, but also construction and operation of new infrastructure [2]. Two kinds of key infrastructure are studied, i.e., V2I road infrastructure and high-definition (HD) maps. All these constructions may be completed by 2025, according to the plans and roadmaps of Chinese government. V2I road infrastructure is composed of roadside units, traffic signal controllers, security management systems, and other elements. Thus, its deployment triggers more designing and planning, hardware purchasing, and installation and inspection costs. There are hardly any detailed cost analyses about V2I infrastructure in China, hence these costs are evaluated based on the report of U.S. Department of Transportation [76]. Furthermore, there are two types of V2I technologies: Dedicated short range communication (DSRC) and cellular V2I (C-V2I) communication. DSRC offers a safe, robust, and well-developed solution, which has been deployed in many countries such as U.S. and Japan. C-V2I is featured with higher throughput and mobility at lower costs, but its deployment still demands progress in reliability and commercialization [77]. The recent ICV policies in China tend towards the C-V2I solution, so it is believed that C-V2I infrastructure will be implemented. Since there is no relative cost study in the C-V2I solution, the same unit values with DSRC are supposed, as shown in Table 11.

Table 11. Infrastructure costs for ICV deployment. DSRC: Dedicated short range communication. V2I: Vehicle-to-infrastructure.

	Cost Types	Assumptions	Cost Per Unit (RMB)	Total Cost (Billion RMB)
V2I Road Infrastructure [76]	DSRC	V2I Roadside Unit Construction	A roadside unit per 600 m	109,620
		V2I Backhaul Network Construction	There are respectively 1500, 1000, and 500 systems in tier 1, 2–3 and 4–5 cities in China	249,136
		Traffic Signal Control System Updating		19,931
		Annual Maintenance	Mainly for roadside units	18,997 per year
	C-V2X	V2I Roadside Unit Construction	Doubling communication range of DSRC, a road unit per 1200 m	109,620
		V2I Backhaul Network Construction	Based on existing 4G base stations	18,685
		Traffic Signal Control System Updating	The same with DSRC	19,931
		Annual Maintenance	Mainly for roadside units	18,997 per year
HD Maps	Professional mapping		\$5000 cost per kilometer [78]	31,142/km
	Crowdsourcing updating		Semidynamic information, upgrading per 30 seconds, cost rate at 2 cents per mile [79]	0.077/km

HD maps are essential to ICVs because they can provide dynamic surrounding information and a priori knowledge to assist in environment perception and route planning. However, they also require greater expenses due to higher precision and more frequent updates than normal navigation maps.

The data collection of HD maps can either be accomplished by specialized mapping vehicles with expensive devices like LiDARs and stereo cameras, or utilize crowdsourcing method by gathering data from running vehicles equipped with cheap sensors. The former has advantages of high precision and reliability, while the latter costs less and offers real-time updates. Therefore, a major solution to produce HD maps is to collect the initial data by professional mapping teams, and update them by numerous daily users. Their expenses are estimated based on a market survey, as indicated in Table 11.

3. Results

Based on the assessment methods and data, we conducted a comprehensive benefit and cost analysis of ICV deployment in China from 2015 to 2050. Figure 5 indicates the results under two scenarios. Under the OPT scenario, ICVs can generate 2.24, 10.46, and 24.02 trillion RMB of socioeconomic benefits in 2030, 2040, and 2050, respectively. Under the CON scenario, these values reduce to 0.28, 4.59, and 13.25 trillion RMB. The benefits will experience a rapid growth after 2030, when Level III ICVs start to enter the market on a large scale. Nonetheless, in the primary stage under the CON scenario, the increases in traffic accidents and energy consumption due to incremental fleet VKT may offset the positive effects of ICVs, which lead to a slightly negative result before 2025.

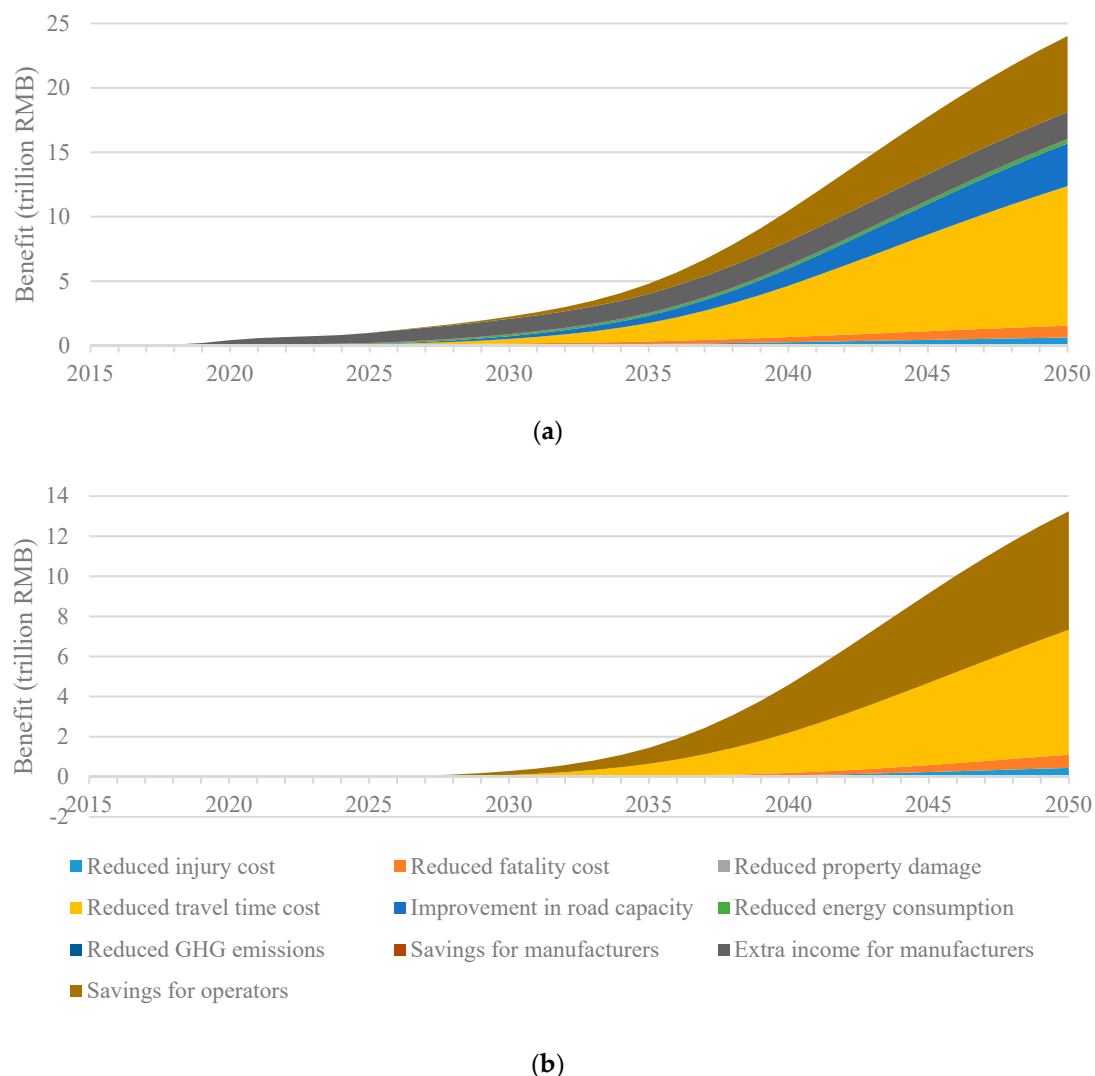


Figure 5. Comprehensive benefits of ICV deployment in China: (a) OPT scenario; (b) CON scenario.

3.1. Different Types of Benefits

As shown in Figure 5, different types of benefits can be compared. Though many people have put particular emphasis on the safety benefits of ICVs, the results state that travel time cost savings may be the most significant effect. For both the OPT and CON scenarios, the reduced time costs will account for nearly half of the whole benefits, reaching 6.37 to 10.82 trillion RMB in 2050. The decrease in operating costs of fleet operators also plays a large part, with 5.90 trillion RMB in 2050. Under the OPT scenario, the improvement in road capacity will save a large amount of investment, which can be up to 3.33 trillion RMB. However, if this effect is ignored conservatively, the avoidance of fatalities and injuries would become a major contributor, corresponding to 655.26 to 924.45 billion RMB and 441.73 to 617.97 billion RMB, respectively.

More specifically, from the aspect of road safety, ICVs will save 13,099 lives and reduce 34,848 injuries in 2030 under the OPT scenario, which are 21.85% and 17.10% fewer than the BAU scenario, respectively. These numbers may go up to 53,759 and 179,683 by 2050, meaning reduction rates of 85.68% and 84.22%, thanks to the widespread application of Level III ICVs. However, things are different when we consider the CON scenario. In 2030, there will be 4482 more injured people. This is because although accident risk drops, the fleet exposure increases by almost 10% and leads to more accidents on the road. Nonetheless, this negative impact will disappear by around 2033, and all accidents will decline by about 60% in 2050.

As for traffic benefits, Level II and III ICVs show high potential in enhancing road capacity under the OPT scenario. Among all the road types, national and provincial highways have the greatest increase by 6.6% in 2030 and 121.84% in 2050. The capacity of all kinds of highways can be improved by up to more than 70%, since they permit higher design speeds. Meanwhile, urban and rural roads only have the potential to raise their capacity by no more than 50% in 2050. ICVs will also reduce travel time on different roads. An optimistic estimation is that 46.40% of travel time can be saved on second trunk roads in 2050, while the reduction will be less than 20% on highways. Additionally, the conservative results indicate that express ways will have the most significant effect, with a decrease proportion of only 10.31%. There is almost no decline in travel time on highways. Therefore, we mainly considered the time-saving effects in urban areas, and an ICV can save 1.0 to 7.7 minutes per trip in 2050. Since CPVs and urban buses (UBs) run on roads for a long period per day and carry most passengers, they will have the highest time cost savings.

ICVs can also contribute to energy savings and emissions reduction. Since the Chinese government is sparing no effort in promoting new energy vehicles, the fleet energy will decline quickly in the next few decades under the BAU scenario, and ICVs may be conducive to this target. If we can take advantage of the positive impacts of ICVs on energy efficiency and avoid noticeable VKT growth, a total energy saving of 17.86 million tonnes of oil equivalent (Mtoe) can be anticipated in 2030, which accounts for 10.63% in the fleet energy consumption in the BAU scenario. Furthermore, in 2050, this proportion will increase to 27.22%, meaning a decline of 35.68 Mtoe. However, under the CON scenario, the fleet energy consumption will increase by 1.78% in 2030 and 10.54% in 2050, since ICVs induce more people to travel in automobiles, and highway vehicles can operate at higher speeds which cause greater air drag. Additionally, the fleet GHG emissions will present a similar trend due to its linear dependence on energy consumption. The total emissions may either decrease by 77.74 and 150.07 million tonnes of CO₂ equivalent (Mt CO₂ eq.) in 2030 and 2050, or increase by 12.91 and 54.06 Mt CO₂ eq., respectively.

3.2. Benefits for Different Types of Vehicles

All types of vehicles can benefit from ICV technologies. Owing to the large stock amount, NPVs will take up about 50% or more of the whole fleet benefits, as shown in Figure 6a,b. Therefore, NPVs are supposed to be the major market for large-scale applications of ICVs. Moreover, all vehicle types will face a temporary rise in social costs due to the negative effect of VKT growth under the CON scenario, especially for highway vehicles with higher energy consumption.

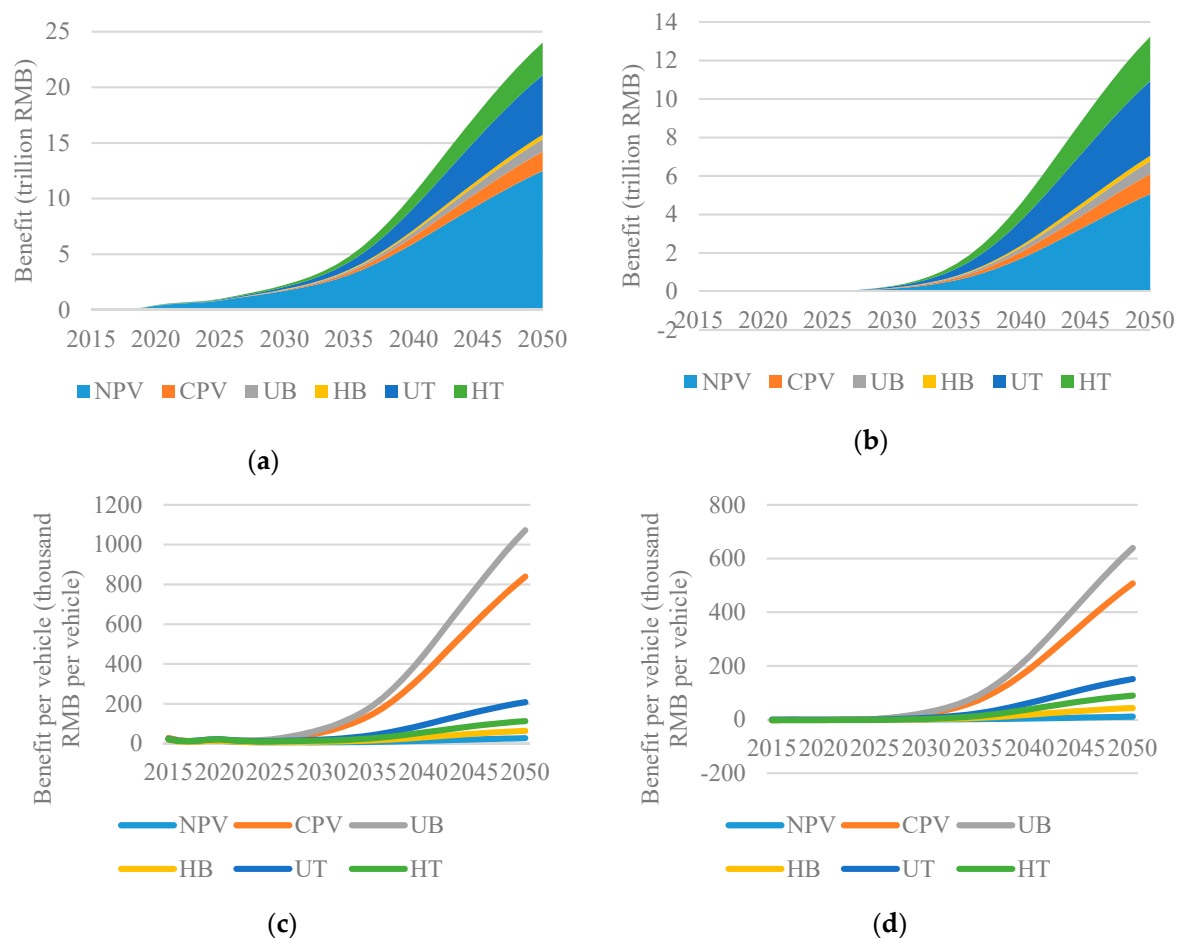


Figure 6. Comprehensive benefits of different vehicle types: (a) Total benefit under the OPT scenario; (b) total benefit under the CON scenario; (c) benefit per vehicle under the OPT scenario; (d) benefit per vehicle under the CON scenario.

Figure 6c,d indicate the distinction among the per-vehicle comprehensive benefits of different vehicle types. NPVs have a relatively low per-vehicle value, since other commercial vehicle types will obtain extra savings in labor costs after Level III ICVs enter the market on a large scale in 2030. Urban vehicles have higher benefits than highway vehicles as reduced time costs contribute to a major part of the total benefits. For the same reason, urban buses and CPVs with the most passenger person–time on roads will acquire the highest value per unit. Hence, the government and industry should give priority to early deployment in these fields. It is estimated that each urban bus can generate 26,405 to 71,013 RMB of total benefits by 2030, and 639,393 to 1,072,641 RMB annually by 2050.

3.3. Cumulative Cost–Benefit Analysis

The deployment of ICVs requires a long period and huge investments, thus the cumulative costs and benefits were analyzed with present values in 2015, as shown in Figure 7. The cumulative benefits will experience a rapid growth after 2030, thanks to the popularization of Level III ICVs. Meanwhile, the annual cost will gradually level off since the early infrastructure construction will be finished by 2025, and ICV prices will drop down to an affordable level. All inputs can be recovered by 2028 under the OPT scenario, but this will be delayed until 2048 if all conservative assumptions are made. However, the cumulative benefit–cost ratio (BCR) could reach 1.15 to 3.06 by 2050, indicating the economic rationality and feasibility of ICV deployment under all scenarios.

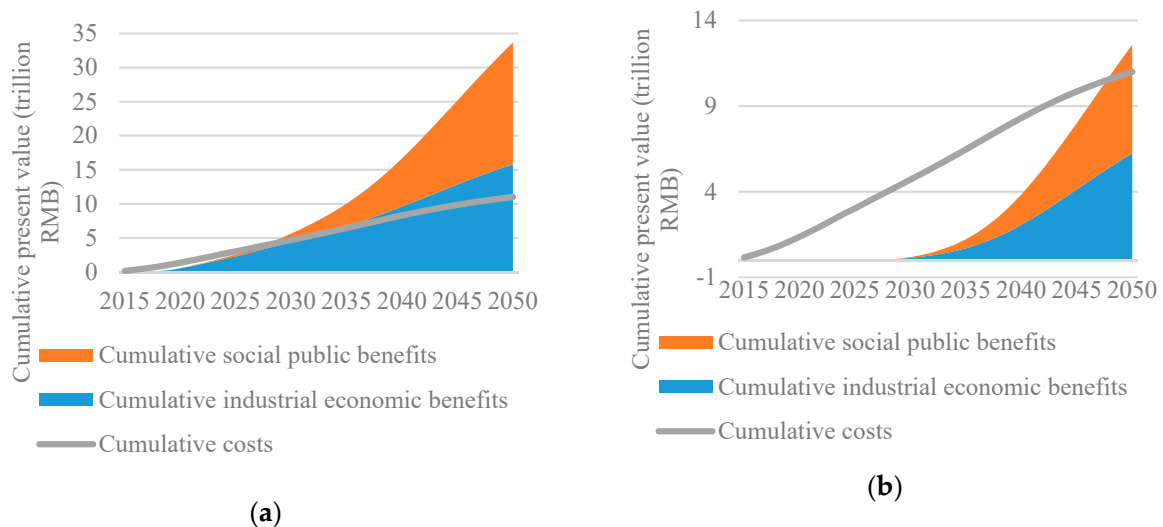


Figure 7. Cumulative benefits and costs of ICV deployment: (a) OPT scenario; (b) CON scenario.

Furthermore, in this paper, safety, traffic, and environmental benefits are defined as social public benefits, which are the main concern of government. Additionally, automotive and other industries pay more attention to industrial economic benefits. Under the OPT scenario, if industrial economic benefits or social public benefits are considered alone, the break-even point will be put off until 2033 or 2042. Under the CON scenario, the country cannot recover all costs with either type of benefits. Therefore, the general consensus and cooperation between government and industry are necessary to take full advantage of ICVs.

3.4. Impacts of Car Sharing

If household vehicles are partly replaced by sharing vehicles, the total benefits under CS scenarios will become a little higher at 14.93 to 24.95 trillion RMB in 2050, as shown in Figure 8. Fewer NPV sales will lead to a decrease in the manufacturers' revenue, and the lower fleet penetration rate will also impair the ICVs' potential to improve traffic efficiency and save travel time. However, car sharing will also greatly reduce operating costs since fewer human drivers are needed. Moreover, implementation costs of expensive Level III NPVs can be cut down by more than 20% in the end. Hence, a higher cumulative BCR at 1.53 to 3.53 is expected in 2050, and all the costs will be recouped between 2028 and 2045.

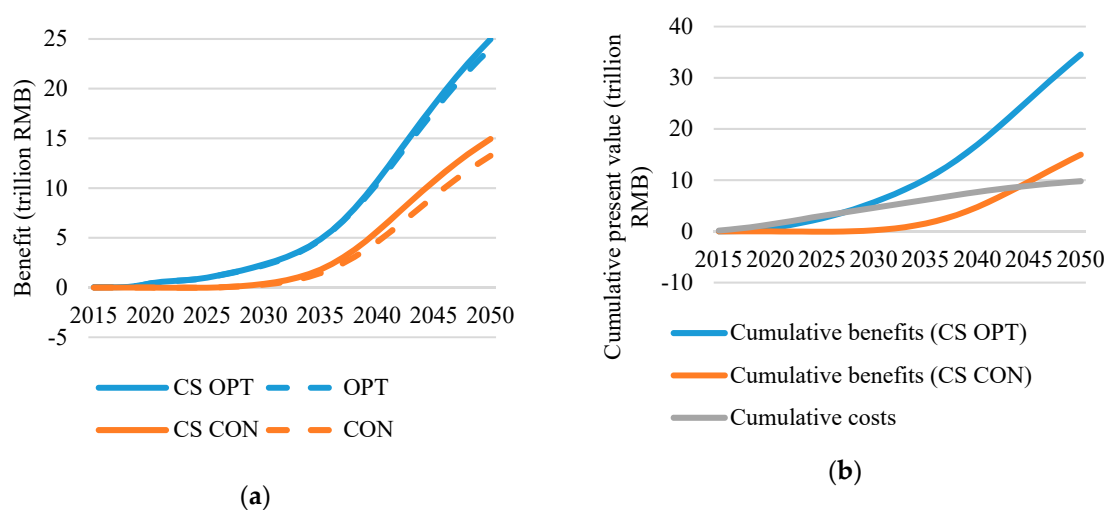


Figure 8. Impacts of car sharing: (a) Comprehensive benefits under different scenarios; (b) cumulative benefits and costs under CS scenarios.

4. Discussion: Sensitivity Analysis

As stated in the introduction, the effects of ICVs are complicated and may be influenced by many factors. To have a further discussion about uncertainties, several sensitive analyses were conducted.

4.1. Technology Factor

The socioeconomic impacts of ICV technologies vary from level to level. To distinguish their effects, their comprehensive benefits were compared under the same deployment conditions, with 100% fleet penetration and other technology and economic assumptions in 2050. Figure 9 shows the results under both scenarios. In consideration of the OPT scenario, the annual BCRs were 6.62, 11.56, and 8.61 for each level. Level II ICV had the highest cost-effectiveness, since it can provide a large amount of traffic and environmental benefits at a relatively low price. Both social public benefits and industrial economic benefits can cover all of the costs for the three levels. However, under the CON scenario, the ratios declined to −0.62, 3.22, and 4.22. Negative impacts appeared for Level I ICV as the increasing fleet VKT caused more accidents and energy consumption, while also enhancing the operating costs of the automotive industry. Furthermore, Level III ICV always generated the greatest industrial economic benefits, which is an important reason why many automotive and technology companies endeavor to directly develop high-level ADS.

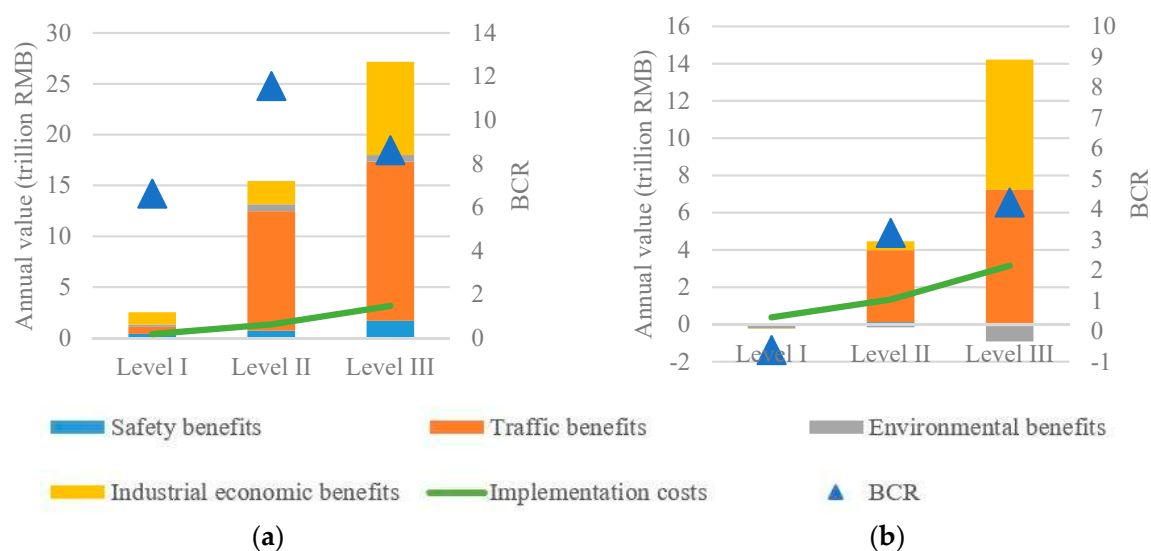


Figure 9. Comparative CBA of different levels of ICV, with a penetration rate at 100% in 2050: (a) OPT scenario; (b) CON scenario. BCR: Benefit–cost ratio.

4.2. Deployment Factor

The aforementioned results show that reduced time costs in traffic benefits and reduced labor costs in industrial economic benefits are major contributors to the comprehensive benefits. Nonetheless, it may be hard to achieve these goals due to several realistic deployment constraints. The reduction in travel time values depends on the premise that ICVs can enable production and consumption activities in vehicles. However, some surveys have indicated that more users will tend to take a break or monitor the driving state, which will make hardly any improvements in travel time values. Figure 10a shows the result without regard to travel time value changes. In this case, the cost-effectiveness will drop down to 0.64 to 2.29 by 2050, which means it will be impossible to reach the break-even point before 2050 under the CON scenario. Furthermore, in this situation, the social public benefits alone cannot recover the cumulative costs under both scenarios, which entails the involvement of the automotive industry to exploit the economic benefits of ICVs.

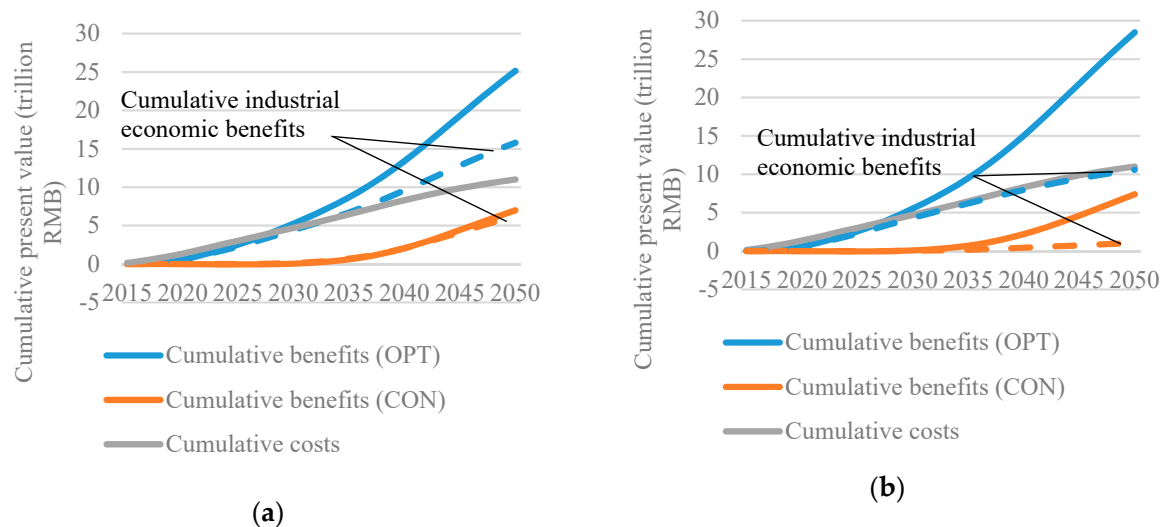


Figure 10. (a) Sensitivity analysis of travel time value: Without considering travel time value changes; (b) Sensitivity analysis of labor cost: Without considering replacement of human drivers.

Another deployment problem is whether human drivers can really be replaced by ADS. Despite targeting level III ICVs on cancelling human drivers, if they are not safe enough to substitute for human drivers, fleet operators will have to create new positions like safety drivers or fleet supervisors to ensure road safety. Thus, labor costs will be inevitable. Figure 10b indicates that in this circumstance, the investment can still be recouped at the same break-even point under the OPT scenario. However, under the CON scenario, the industrial economic benefits will face a sharp decline and the break-even point will be put off to later than 2050. Moreover, the automotive industry will not profit from deploying ICVs unless the government provides investment funds, subsidies, or other favorable policies.

4.3. Cost Factor

Two kinds of costs were studied in the CBA results, which are also highly uncertain due to various technology solutions and technical progress. Figure 11 discusses the impact of changes in vehicle fixed costs and V2I road infrastructure costs. Since historical data of ICV production are not available, the progress ratio cannot be determined and may vary in a reasonable range, usually from 70% to 95% [75]. If the production cost drops more quickly, there will be almost no other extra fixed costs for level III ICVs and the break-even point will be advanced by one to five years. Meanwhile, if the higher progress ratio is applied, level III ICVs will hold an extra cost as high as 288 thousand RMB by 2050. Additionally, the cumulative BCR is only 0.26 to 0.71, which means it will become impossible to recover all of the costs in many years.

V2I road infrastructure costs depend on its technology solution and maturity. If the DSRC solution is adopted, higher infrastructure costs are expected. However, since the infrastructure costs are relatively small when compared with vehicles costs, this variation will only put off the break-even point by three years. Additionally, there will be a tiny decrease in the cumulative BCR, which will be 0.99 to 2.66 by 2050. Therefore, even if C-V2I technology is unable to be implemented in the next few years, DSRC still offers an affordable way of building the essential network environment for ICVs.

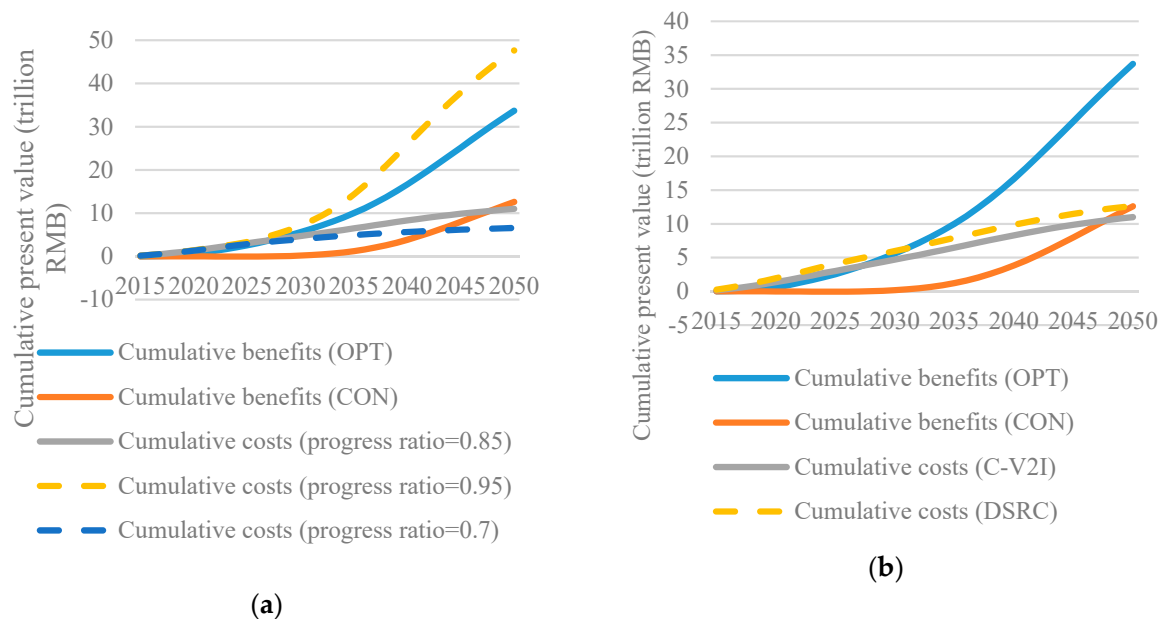


Figure 11. Sensitive analyses of: (a) vehicle fixed cost; (b) V2I road infrastructure cost.

5. Conclusions

This study established a comprehensive assessment framework to analyze the socioeconomic benefits of ICV deployment. Based on the latest policies, transportation, and market data, we provided an estimation of the future benefits and costs to deploy ICVs in China and investigated some of the key factors that will impact the cost-effectiveness of ICVs. This framework can also be employed for any other country or region to make assessments and suggestions for the government and industry.

The results indicate that according to the official roadmap, the total penetration of ICVs will attain 70.77% by 2030, and all vehicles will be equipped with different ICV technologies after 2047. However, fleet VKT may also increase by almost 80% in extreme situations, which will offset the benefits from ICV deployment. Therefore, green and sustainable transit modes, like ridesharing and carpooling, may be necessary in the ICV era. In fact, ICV is regarded as the most important solution to facilitate car sharing and travel on demand, which will be conducive to reductions in vehicle stock and VKT [2,5]. It is estimated that up to 10 household-owned vehicles could be replaced by a sharing vehicle [19]. Thus, higher benefits and lower costs can be expected to help ICVs achieve better cost-effectiveness, as the results suggest. However, the aim of this paper was to discuss the impacts of ICV technologies rather than business innovations, and only a simplified analysis on car sharing scenarios was conducted. More new travel modes should be considered in the upcoming research agenda, and further thoughtful discussions about the interaction between them and ICVs are necessary to improve this assessment framework, especially when Level III ICVs are accessible.

Different types of benefits were also discussed. First, the increase in fleet VKT under the CON scenario will cause more accidents during the early stage, but with the introduction of Level II and III ICVs, a positive road safety trend can be expected. Second, Level II and III ICVs can significantly improve road capacity by more than doubling as well as save a considerable amount of travel time on urban roads. Third, ICVs will influence the fleet energy consumption and GHG emissions by both increasing use intensity and reducing energy intensity, thus their environmental effects can be either negative or positive. Finally, ICVs are able to enhance industry income and reduce expenditure, and the savings in labor costs through the deployment of Level III ICVs will account for a large part.

By monetizing all the effects, it is estimated that the whole country will obtain 13.25 to 24.02 trillion RMB comprehensive benefits in 2050, among which the reduced time costs and labor costs are major contributors. Though increasing social costs may be possible in the early stage, the cumulative implementation costs can be recovered by 2028 to 2048. Nevertheless, if only the social public benefits

or industrial economic benefits are considered, the break-even point will be delayed. Therefore, it is essential for the government and industry to create a new industry organization or partnership, which can exploit all the benefits and split the costs reasonably. Furthermore, CPVs and UBs have the highest benefits per vehicle, which should be the first field of ICV pilot deployment. However, in order to achieve break even, NPV is the most important market for large-scale commercialization.

Some single-factor analyses were also conducted. First, all levels of ICVs could realize high BCRs under the OPT scenario, and Level III ICV had the greatest potential for industrial economic benefits. Then, future in-vehicle applications and functions should be designed to help passengers take advantage of spare travel time. Additionally, if human drivers cannot be totally replaced, the government has to subsidize or fund the industry to promote ICVs. Finally, a rapid decline in ICV price is necessary to guarantee the cost-effectiveness.

This study also has several limitations. First, due to a lack of reliable and systematic data on the effects of ICVs and Chinese contexts, some assumptions and estimations refer to other industries and countries, which may influence the accuracy of the results. Second, there are other factors that may affect the deployment and benefits of ICVs, such as the aforementioned new mobility as well as user acceptance and usage frequency. If vehicle occupants doubt the ICVs' reliability or find them uncomfortable, they may switch off the ICV functions, thus depressing their positive effects. Therefore, more deployment elements should be supplemented in the future. Third, this paper assessed the ICVs' benefits from the perspective of the whole society rather than the stakeholders. A further study is needed to explore the corresponding benefits and costs for different stakeholders as well as how to build a new business model or ecosystem to exploit ICV technologies in a sustainable way.

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