C-V2X direct communications-based tolling: China Case Study

5GAA Automotive Association
Technical Report

Conducted by Tongji University Cooperative Automated Transportation (CAT) Lab for 5GAA

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Abbreviation

MTP	Motorway Tolling plaza
AET	All Electronic Tolling
FF ETC	Free-Flow Electronic Toll Collection (with Dedicated Communication)
ORT	Open Road Tolling (GNSS + 4G/5G)
MOT	Ministry of Transportation
NDRC	National Development and Reform Commission
MIIT	Ministry of Industry and Information Technology
MOJ	Ministry of Justice
MOF	Ministry of Finance
MPS	Ministry of Public Security
CBRIC	China Banking and Insurance Regulatory Commission
RIOH	Research Institute of Highway
LKYW	Liang Ke Yi Wei refers to tour coach, intercity coach and the truck carrying dangerous goods

1. Introduction

1.1. Introduction of 5GAA

The 5G Automotive Association (5GAA) is a global, cross-industry organisation of companies from the automotive, technology, and telecommunications industries (ICT), working together to develop end-to-end solutions for future mobility and transportation services.

Since its inception, 5GAA has rapidly expanded to include key players with a global footprint in the automotive, technology and telecommunications industries. This includes automotive manufacturers, tier-1 suppliers, chipset/communication system providers, mobile operators, and infrastructure vendors. 5GAA membership comprises more than 130 companies.

Diverse both in terms of geography and expertise, 5GAA members are committed to helping develop C-V2X-based intelligent transport solutions, which will help our societies attain safer roads and cleaner cities.

1.2. Background and Motivation

Driven by traffic congestion and infrastructure financing needs, electronic toll collection (ETC) is taking off.

Today widely used barrier-based tolling is moving towards free-flowing/non-stop tolling with connected and electronic toll technologies; 63% of today's toll sites are expected to become gate-free by 2025.

Worldwide, the market will double from 200 million ETC subscriptions in 2016 to over 400 million in 2025, largely due to the growth in the Chinese market.

In China, already the country with the largest tolling infrastructure (more than 171,100km of tolled roads by the end of 2019), active DSRC-based ETC began to be deployed in 2019 and generated over RMB486.82 billion by 2020 – highway: RMB456.62 billion; first-class country road: RMB8.5 billion; second-class country road RMB2.2 billion RMB, bridge and tunnel: RMB19.48 billion (reference: 2020 年全国收费公路统计公报). This establishes that expressways are the main tolling scenario in China.

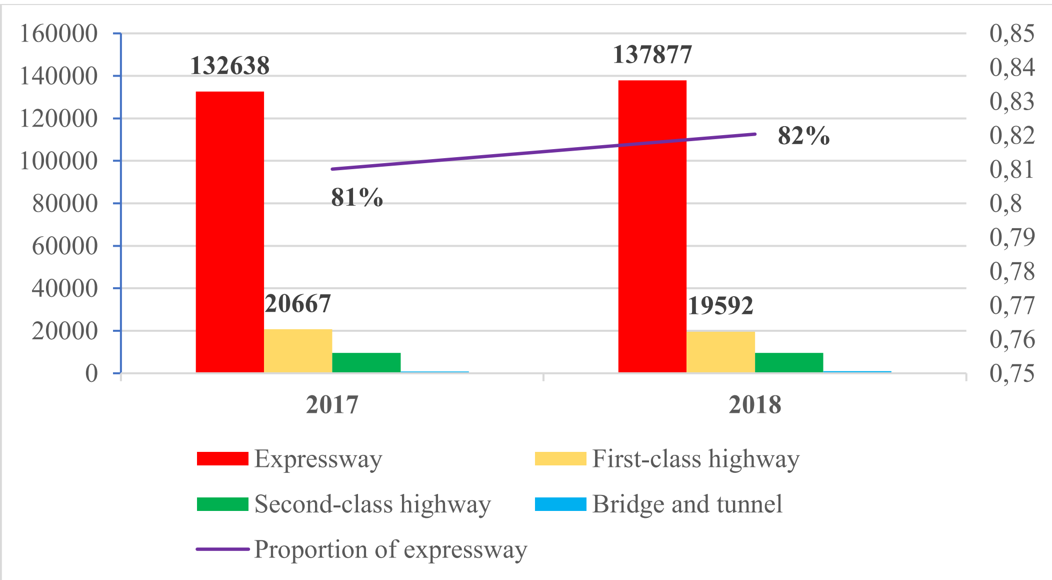


Figure 1 Toll road network length

Intelligent and cooperative intelligent transport systems (ITS/C-ITS), as key components of digital infrastructure, will promote not only new intelligent traffic business opportunities and autonomous driving, but also more traditional road industry businesses, such as tolling.

In this context, 5GAA's Working Group 5 'Business Models and Go-To-Market Strategies' has carried out a study on C-V2X direct communications-based tolling, focusing on China, to investigate the potential benefits this technology could bring to the ecosystem.

1.3. Technical Report Introduction

This Technical Report provides a business study on C-V2X-based tolling in China based on the concept of free-flow ETC. The study focuses on C-V2X direct PC5 communication-based tolling applications on highways or in highway scenarios.

The study was conducted by Tongji University Cooperative Automated Transportation (CAT) Lab for 5GAA.

Note*: The backend system and detailed technical solution for the tolling application is not in the scope of this study. It focuses more on business analysis, including a rough proposal for a roadmap and for PC5 communication-based tolling scenarios, investment analyses of the infrastructure side, and PC5 industrial chain development on the vehicle side, in order to verify the migration possibility and its path between C-V2X ITS and the traditional tolling business model. The purpose is to provide C-V2X industrial stakeholders and related policy-makers a valuable reference for C-V2X business development.*

2. Study of Chinese ETC Market

2.1 Overview of Tolling in China

2.1.1. Introduction of Chinese ETC system

In 1988, the first tolling plaza was deployed on the Shanghai expressway. From 1999 to 2001, several emerging technologies were tested in ETC, including 900MHz, 2.4GHz, RFID etc. but the results were mixed. In 2002, the Chinese government proposed a 5.8GHz dedicated DSRC-based tolling solution. From 2002 until now, 5.8GHz DSRC-based ETC has continued to evolve.

Currently, 5.8GHz DSRC is still used as the mature ETC technology in China. This is because it is widely used in the world. In 2007, China released its national standard GB/T20851 for 'ETC-dedicated short-range communication' [2]. This was the first such technology standard in ETC (further revised in 2019) and it is still used today.

While electronic toll collection now dates back two decades in China, the government is still exploring new solutions to improve the quality of tolling services.

I. National Coordinated Tolling

From 2002 to 2014, the tolling standard differed in various provinces or regions. The same on-board unit (OBU) could not always be applied in different provinces or regions. This shortcoming held back the increase of ETC users and limited the development of ETC in China. To address this problem, the Chinese government proposed a coordinated national approach towards tolling in 2014, which was executed by the end of 2015. ETC users could then use a common OBU to travel through different provinces and regions in China. The success of the coordinated national approach means that a unified tolling system was achieved in China and that there would be more room for China's ETC market.

The coordinated national strategy on tolling also improved the administration of ETC transactions. When an ETC user passed through a toll point, the information would be uploaded to the provincial toll center which is responsible for reporting cross-provincial toll information to the national toll centre. The national or provincial centre sends the toll information to the relevant ETC card issuer, which then informs their bank to make a payment from the account linked to the ETC card, with the payment being collected at the national toll centre. The national centre is thus responsible for ETC revenue allocation. If the payment fails, the bank informs the ETC card issuer to add the user to a blacklist and for the national centre to limit or block the user's passage. The toll business flow can be found in Appendix 13.1.

II. Free-flow Tolling

After the coordinated national tolling strategy was adopted, with the development of the Chinese economy and increased traffic load, the existing ETC system adversely affected traffic flow. Congestion resulted when DSRC was introduced at toll plazas with dedicated entry/exit barriers: entry was granted only when a valid tolling transaction was recorded.

The Chinese government decided to upgrade the existing ETC system in order to achieve more free-flowing traffic, with a series of policies being proposed to remove expressway tolling plazas at provincial boundaries. With this, there are tolling plazas only at the entrance/exit point of the toll expressway and ETC gantries are deployed to improve free-flow tolling between provinces.

Based on the following relevant policies[3], the Chinese government started to implement large-scale free-flow ETC in 2019, and completed the deployment at the end of that year. The steps leading up to that accomplishment were as follows:

- In May 2018, at the executive meeting of the State Council, the Chinese government identified the need to remove expressway tolling plazas at the provincial boundary.
- In December 2018, Li Xiaopeng, the minister for transportation, proposed that nationwide free installation of ETC on-board equipment and on-line payment for tolls should be achieved in 2019.
- In March 2019, at the government work report meeting, President Li Keqiang proposed that the tolling plazas at the provincial boundary should be removed within two years.
- In May 2019, the Chinese government proposed tolling plazas at the provincial boundary should be completely removed by the end of the year.

These policies and regulations indicate that Chinese ETC had entered the first stages of a new era dedicated to free-flow tolling. Plans were also tabled for further developments in technologies and regulations associated with ETC.

2.2 Introduction of 5.8GHz DSRC-based Free-flow Tolling

In this section, 5.8GHz DSRC-based free-flow tolling is explained, focusing on the following points:

- Description of the current tolling scenario
- Deployment of the tolling infrastructure
- Technical specifications for roadside units and on-board units
- Business models of current ETC ecosystem
- Challenges of current free-flow tolling

2.2.1 Introduction of Tolling Scenario

Before 2019, tolling plazas with physical barriers were the only infrastructures in place for tolling. They were not only deployed along the mainline (central) plaza and entrance/exit ramps, but also at provincial boundaries. The tolling scenario and plazas are described in the following figures.

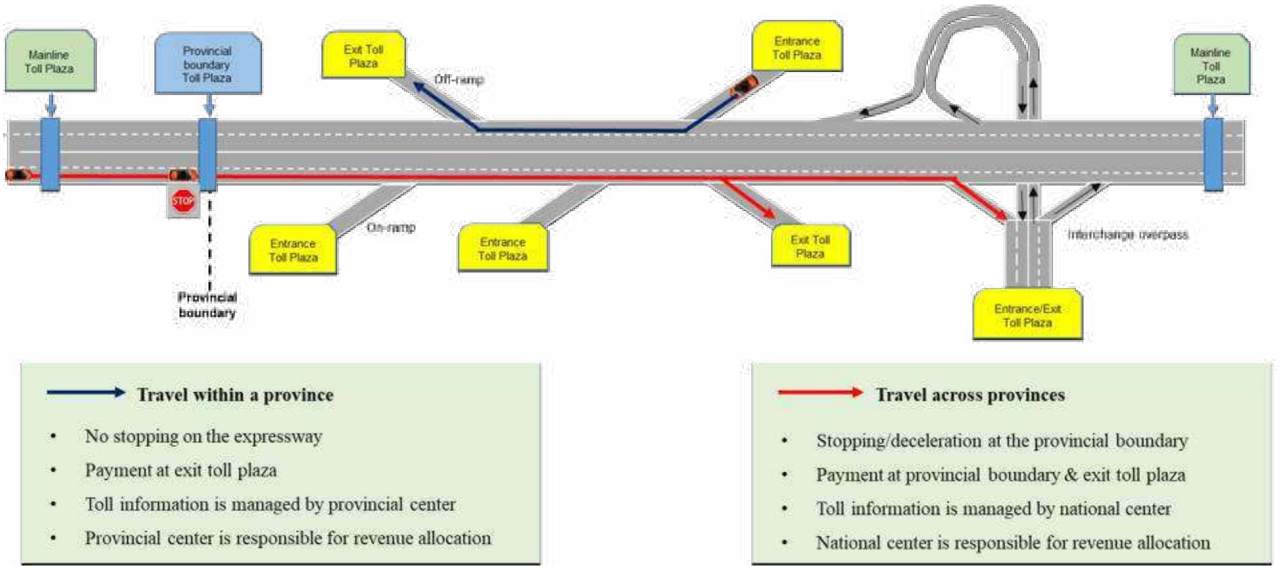


Figure 2 5.8GHz DSRC-based tolling scenario before 2019

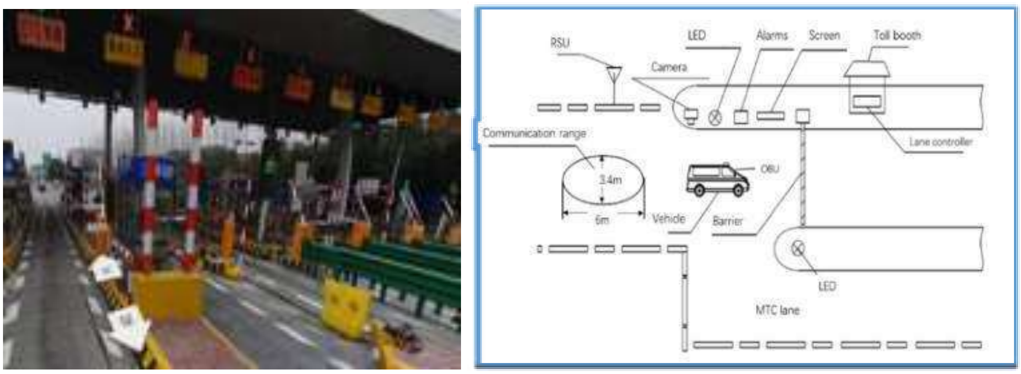


Figure 3 5.8GHz DSRC-based tolling plaza

This tolling was mainly based on manual toll collection (MTC), and ETC was not widespread in this phase yet. Two types of OBUs are used for tolling: i) a two-piece type, and ii) a single-piece type. Two-piece OBU-types could be used for tolling in both MTC and ETC, but a single-piece type could only be used in ETC.

(a) Two-piece type OBU (b) Singe-piece type OBU

Figure 4 5.8GHz DSRC ETC OBU

If the vehicle travels within a province, there is no need for it to stop or slow down on the expressway for tolling. The total toll would be charged at the exit tolling plaza. The toll information is managed by the provincial centre, which is also mainly responsible for revenue allocation. The revenue would be allocated to relevant road operators (local highway group or government) within the provinces.

If the vehicle travels across provinces, it would not only be required to pay the toll at the exit tolling plaza, but also to pay the toll at the provincial boundary. At each provincial boundary, the toll would have been charged according to the shortest driving path within the province. The toll information is managed by the national centre which is then responsible for allocating the revenue to relevant provinces. However, tolling at provincial boundaries would sometimes cause severe congestion on expressways.

In order to give a more intuitive explanation of the tolling scenario, an example is introduced below.

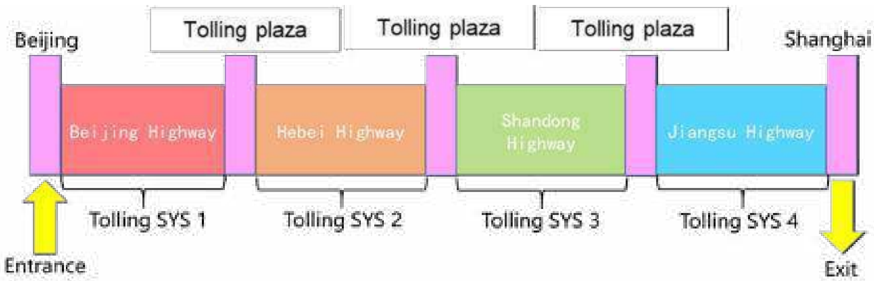


Figure 5 Example of 5.8GHz DSRC-based tolling before 2019

As shown in Figure 5, there is a trip example from Beijing to Shanghai. The vehicle needs to pass through four provinces. Between two adjacent provinces, there is a tolling plaza deployed at the provincial boundary. For example, if the vehicle arrives at the tolling plaza between Hebei highway and Shandong highway, the toll on Hebei highway would be calculated according to the shortest driving path principle, and the driver pays this toll at the tolling booth. This toll would be collected by the national toll centre responsible for revenue allocation.

After 2019, with the roll-out of free-flow tolling in China, the tolling plazas at the provincial boundaries were removed, and ETC gantries were deployed on the expressway. The 5.8GHz DSRC-based free-flow tolling scenario is shown in the following figure.

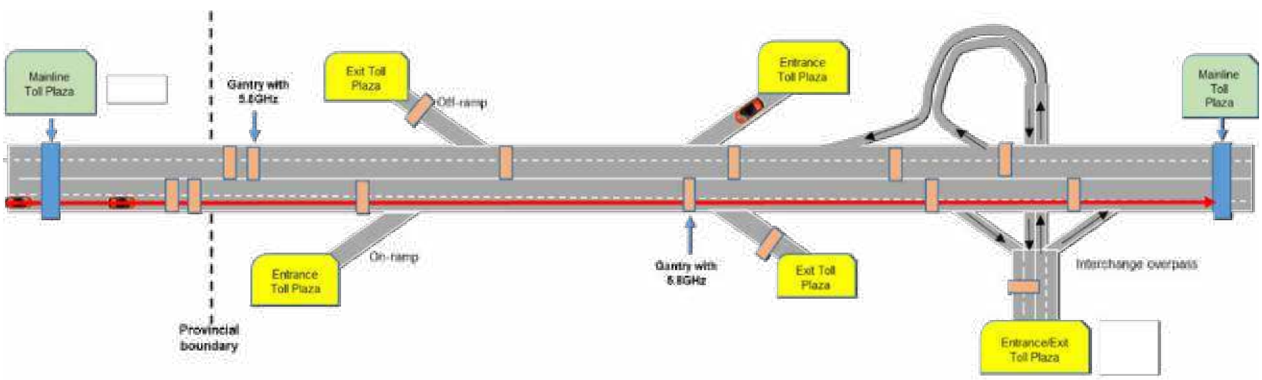


Figure 6 5.8GHz DSRC-based free-flow tolling (2019-present)

In the 5.8GHz DSRC-based free-flow tolling scenario, the toll is calculated according to the real driving path. Payment is settled once an ETC vehicle passes through a gantry. For non-ETC users, they can obtain a certified professional-driver card (CPC) at the entrance of the expressway. This card is also based on 5.8GHz DSRC, and can communicate with the roadside gantry units. CPC cards can record the toll, and the non-ETC users can pay the toll at the exit tolling plaza. Neither ETC users nor non-ETC users have to slow down or stop for tolling on the expressway.

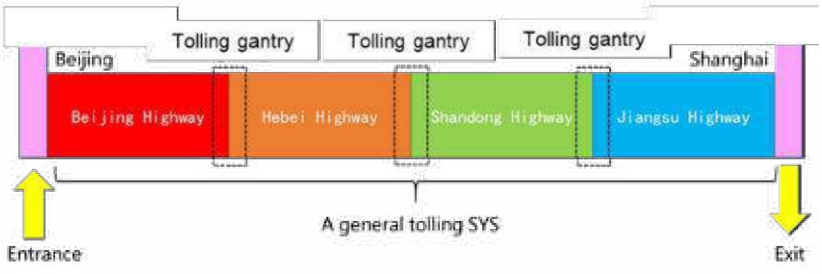


Figure 7 Example of 5.8GHz DSRC-based free-flow tolling (2019-present)

As shown in Figure 7, if a vehicle travels from Beijing to Shanghai, it does not need to stop or slow down on the expressway. At the entrance, the vehicle information can be checked (whether the vehicle is in the blacklist) and the entrance information (geolocation) then written into the OBU. At the provincial boundary, the vehicle could complete the transaction with the tolling gantry. Upon exiting, vehicle type, ID and charge information are all checked. Non-ETC users pay the toll at the exit according to the information recorded on the CPC card.

In pursuing free-flow tolling, the Chinese government invested heavily in infrastructure. There were 25,594 ETC gantries deployed and about 24.612 tolling plazas (ETC lanes, MTC lanes, and mixed lanes incl.) upgraded. This number is much larger than the number of ETC RSUs deployed between 2013-2018. The statistics of ETC RSUs are introduced in detail in the following table:

Table 1 Tolling infrastructure statistical data covering the past seven years

Tolling infrastructure statistical data from 2013-2019			
Infrastructure	Amount	Notes	Data source/calculation logic
Tolling plazas	24,612	Normal at entrance and exit of one operation area (not including plazas at provincial boundaries)	[49]
New ETC lanes	30,506	The lane at tolling plazas: ETC RSU per lane at tolling plazas	[52]
New MTC lanes	5,262	Lane at tolling plazas: ETC RSU per lane at tolling plazas	[52]
New Mixed lanes (ETC + MTC)	32,315	Lane at tolling plazas: ETC RSU per lane at tolling plazas	[52]
Old toll lanes (2013-2018)	29,749	Lane at tolling plazas: ETC RSU per lane at tolling plazas installed before 2018	It is the sum of the number of deployed 5.8GHz RSU from 2013-2018 [53][54] 2013: 2,300 2014: 2,783 2015: 6,444 2016: 4,505 2017: 7,484 2018: 6,234
Total ETC gantries in 2019	25,594	Transaction points along the highway	[50]
Calculated infrastructure data			
Infrastructure	Amount	Notes	Data source/calculation logic
Total ETC lane at Toll Plazas	97,831	= Total RSU at Toll plazas	[calculated value] = New ETC Lanes + New MTC Lanes + New Mixed Lanes + Old Toll lanes (2013-2018)
Average lanes number at tolling plazas	3.97≈4	=average Lane number at Toll plaza, **Assumption**: = average lanes number on highway	[calculated value] = Total number of toll lanes/number of tolling plazas
Newly deployed ETC RSUs on Gantries in 2019	170,459	Along the highway, most focus on Gantries environments	[calculated Value] = New ETC lanes, New MTC lanes and new mixed lanes) + 4* number of ETC gantries
Newly deployed ETC RSU in 2020	8,000	Assumption: In 2020, new ETC RSU only on Gantries, no RSU on Toll plaza, no new toll plaza.	[assumed value] During the research (no published information for 2020)
Total ETC RSUs in 2020	208,208	= Total RSU on Highway in 2020	Old toll lanes + ETC RSUs in 2019 + ETC RSUs in 2020 = 29,749 + 170,459 + 8,000

Table 2 The new deployed Gantry and Exit/Entrance Toll Plaza in 2019 in relevant Provinces

Province	Gantry	Tolling plaza (at entrance/exit of each operations section)
Jiangsu	926	1,515
Zhejiang	1,969	1,434
Guangdong	3,948	4,749
Hebei	670	1,228
Jiangxi	938	499

These statistics on infrastructure could be used for the investment evaluation of 5.8GHz ETC and proposed PC5-based tolling.

2.2.2 Free-flow Tolling Infrastructure

Under the government's promotion of free-flow tolling, there are currently 25,594 tolling gantries in China. These gantries are deployed at provincial boundaries, at off-ramps, and at points 1.5-3km upstream of the traffic junctions. There are mainly two deployment ways for tolling gantries [4]:

1. At the provincial boundary, two gantries are deployed in each direction. The distance between two gantries in the same direction must be greater than 500m. The distance between two adjacent gantries in different directions is greater than 30m.

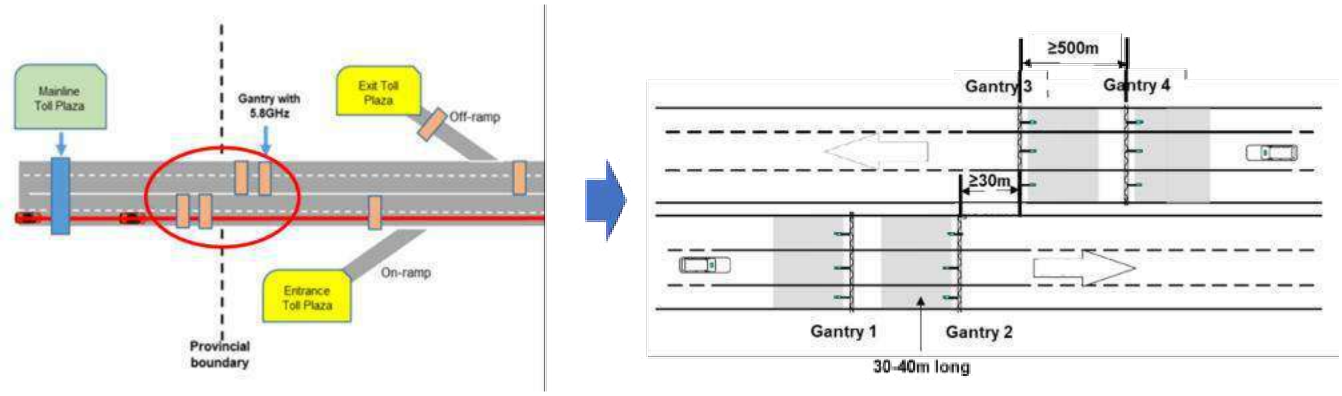


Figure 8 Deployment of 5.8GHz DSRC-based tolling gantry at provincial boundary

2. On other general road segments and expressways, only one gantry is deployed in each direction for tolling.

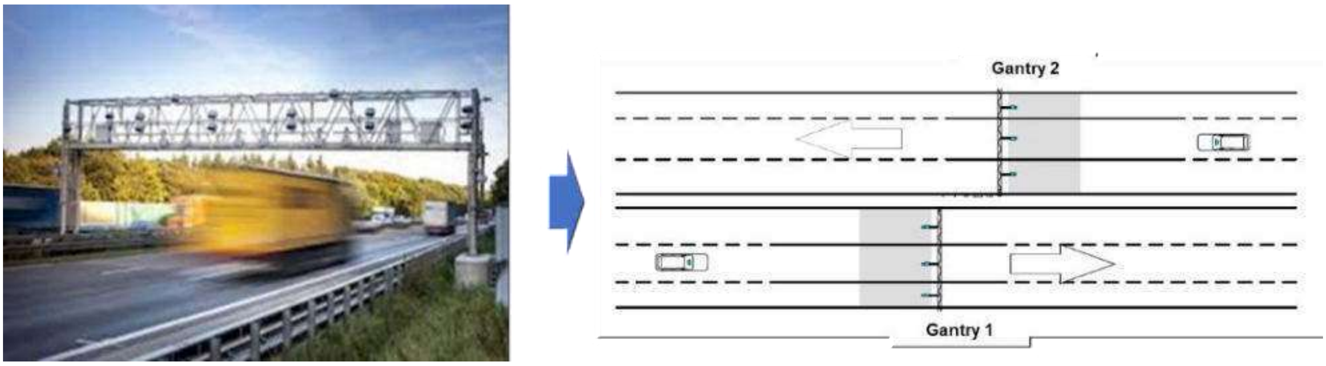


Figure 9 The deployment of 5.8GHz DSRC-based tolling gantry on general road segment

Equipment on tolling gantry:

The equipment on an ETC gantry includes a 5.8GHz RSU, an automatic number plate recognition (ANPR) system, a surveillance camera, LED, lane controller, and power supply.

On an expressway with N lanes, N+1 5.8GHz RSUs will be deployed on the ETC gantry. One RSU covers each lane and an extra RSU is deployed along the emergency lane. The communication range of one RSU is a lane-wide rectangle (30-40m in length). The tolled vehicle's feasible maximum speed is the equivalent speed limit of the expressway mainline. The relevant regulation [4] also requires that:

For single-piece type OBUs, if the speed is between 0-120km/h, the successful rate of transaction is greater than 99.9%, and a successful reading rate greater than 99.99%,

For two-piece type OBUs, if the speed is between 0-120km/h, the successful rate of transaction is greater than 98.0%, and a successful reading rate thus greater than 99.5%, and

If vehicle the speed is in 0-200km/h, the accuracy rate of licence-plate recognition is greater than 95%.

In current 5.8GHz DSRC-based free-flow tolling scenarios, the key factors of 5.8GHz RSU at gantry and entrance/exit are summarised in the following table.

Table 3 Key factors of 5.8GHz RSU at gantry and entrance/exit plaza

	At gantry	At entrance/exit
Communication range	3.75-4m wide 30-40m long	3.4m wide 6m long
RSU amount	N+1 RSUs deployed on a road segment with N lanes	One RSU for each lane
Data read from OBU	Driving path Vehicle ID Vehicle type Vehicle size	Driving path Vehicle ID Vehicle type Vehicle size
Data sent to OBU	Payment result Geolocation of transaction point (provincial boundary)	Payment result Geolocation of transaction point (entrance/exit)
Security module	PSAM card	PSAM card
Power request	60W/unit	60W/unit

However, current 5.8GHz RSUs in free-flow tolling scenario have some shortcomings:

i) Since the message type/data sent by 5.8GHz OBUs is limited (

Table **3**: Data read from OBU), the 5.8GHz ETC system (RSU) cannot identify the direction of the vehicles, which could result in charge loss or in a billing error.

ii) The 5.8GHz ETC system cannot support concurrent communication. This means that a single 5.8GHz RSU cannot cover vehicles on all lanes. Therefore, there is a need to deploy 5.8GHz RSUs on each lane, but this deployment model results in much higher capital expenditure (CAPEX) on new ETC systems.

2.2.3 Functional Specification for Free-flow Tolling

This section focuses on the functional specification for 5.8GHz DSRC-based free-flow tolling in order to make a logical estimation of investment requirements for a C-V2X/PC5-based tolling solution. The communication specification is not the key factor in this research, therefore it is not considered in this section (find the detailed information in Appendix 13.32).

2.2.3.1 5.8GHz ETC OBU

The functional specifications for 5.8GHz OBU should comply with [2], with detailed parameters described in the following pages.

(1) Security requirement of OBU:

- Provide security module (OBE-SAM) which is used to save ETC information
- Support SM4 encryption algorithm to transmit and save information
- Have ICC interface

If the OBU is removed from the matched vehicle, the information would be written into the OBE-SAM module. All the ETC information in the OBU would be omitted and the OBU rendered invalid. This mechanism could prevent the OBU from being incorrectly used by others.

(2) Power supply:

- For two-piece type OBU: solar power supply/battery power supply
- For single-piece type OBU: on-board power supply

(3) OBU functions:

- Remote online application update
- Fault warning
- Low-power warning (battery-powered)

(4) Optional functions:

- Bluetooth module
- ISO/IEC 14443 protocol
- RS232 port
- USB port
- Loudspeaker
- Buzzer

(5) Lifespan:

The average lifespan of an OBU is about five years. After that time, an OBU usually has to be replaced.

Note*: As the PC5 OBU product type is greatly different from current 5.8GHz ETC OBU offerings, the function of PC5 OBU is more powerful. Therefore, there is no comparison between the functional specifications of PC5 OBU and 5.8GHz ETC OBU. The detailed description of PC5 OBU is in Chapter 4 and Chapter 5 of this report.*

Figure 10 5.8GHz ETC OBU

2.2.3.2 5.8GHz ETC RSU

The functional specification for RSU also complies with [2].

(1) Security requirement of RSU:

- PSAM card equipped in RSU is responsible for access permission to OBU, and information encryption (it ensures the security of ETC transactions)

Note: *There is a need for PC5 RSU to be equipped with a security module.*

(2) RSU functions:

- Online program update
- Support of simultaneous transaction
- Status monitoring
- Remote setting adjustment

Note*: PC5 RSU shall have these functions.*

(3) Ports on RSU:

- PC serial port supporting Ethernet
- Network monitoring serial port
- Isolated port supporting TTL level
- Internet serial ports supporting two IP addresses
- PCI-E 1X port

Note: *Through the analysis on porters, the backhaul system of 5.8 GHz RSU could be kept for a PC5 RSU.*

(4) Power supply:

- Both DC (24V±10%) and AC power supply (220V±20%)
- The power request is less than 60W/unit

Note*: The power supply of 5.8GHz RSU could be kept for a PC5 RSU.*

(5) Lifespan:

- The average lifespan of an RSU is about eight years

Note: *In the following investment analysis, it is assumed that the lifespan of a 5.8GHz RSU could be longer (up to ten years) owing to the yearly maintenance. The lifespan of a PC5 RSU is around eight years due to its higher power consumption.*

Figure 11 5.8GHz ETC RSU

2.2.3.3 Enforcement control

Since 2019, due to the roll-out of free-flow tolling the enforcement control system has changed. At the entrance of a tolling plaza, the ETC system could check the information of the ETC users. This includes:

1) Whether the ETC user is on the blacklist, and
2) Whether the information (vehicle type, ID) in the OBU is correct (comparing information in OBU and recorded by ANPR).

If there is no problem, the geolocation of the entrance would be recorded in the OBU and uploaded to the toll centre. On the expressway, a payment is settled once the tolled vehicle passes through a gantry. The ANPR and 5.8GHz ETC RSU on the gantry could record the ETC user's travel information. At the exit tolling plaza, the ETC system could double-check the information of the ETC user, which includes:

- Whether the OBU is removed,
- Whether information at the entrance point exists, and
- Whether the payment is successful.

If the tolled vehicle does not pass the checking at the exit tolling plaza, it would be intercepted, and a road operator (Local Highway Group) could conduct further processing to the ETC user.

If the ETC user has not paid a toll for a long time, the bank would inform the ETC card issuer to put the relevant user on a blacklist and instruct the national toll centre to limit or block his/her passage.

In the current study, this enforcement control strategy is reused for C-V2X/PC5-based tolling.

2.2.4 General Challenges in 5.8GHz DSRC-based Free-flow Tolling

As stated, 5.8GHz DSRC-based free-flow tolling has been rolled out in China. The average vehicle speed on an expressway has increased (from 61km/h to 71km/h) and the traffic capacity at the provincial boundary has been improved by three to five times[5]. However, there are also many challenges or shortcomings in 5.8GHz DSRC-based free-flow tolling. These challenges are listed in the following tables.

Table 4 The challenge of congestion at entrance/exit of expressway

No.	Challenge	Benefits of PC5 (C-V2X dedicated short-range) communication
1	**Low pass-through speed at entrance and exit:** The communication range of 5.8GHz ETC RSUs at the tolling plaza is short, therefore the vehicle speed has to be reduced for a successful transaction (20km/h). Yet speed-reduction measures could reduce the traffic efficiency at the entrance/exit and also increase CO2 emissions.	Larger communication range thanks to the big bandwidth of PC5 means vehicles could complete the transaction at a certain distance from the toll booth. Once the vehicle enters the specified lane, the barrier would rise. The vehicle does not need to slow down to pass through the tolling plaza.
2	**Truck weighing at the entrance of the expressway:** Trucks must be weighed at the entrance of the expressway. The speed limit of weigh-in-motion (WIM) is only 5km/h. Weighing is often inaccurate, and drivers may need to weigh their vehicles again, which can impact traffic efficiency and causes congestion.	The additional weighing machines could be deployed at on-ramps or rest areas. PC5 trucks could send their geolocation and actual weight to the traffic management platform. According to queue lengths and waiting times at each weighing point, the platform could send an advised weighing point to the truck via an RSU. At the weighing point, in addition to checking for 'overweight' vehicles, the weighing system could compare the weight with the one recorded by the PC5 OBU for accuracy.
3	**MTC+ETC mode:** Thanks to the MTC+ETC mode, some non-ETC vehicles in China could enter the ETC lane by mistake. This can cause congestion.	A specified lane could be advised to the vehicle via C-V2X manoeuvre coordination service.

The charge loss in China is €380km/year and is mainly from the change of toll rates and driving path. The detailed reasons are listed in following table [6].

Table 5 The challenge of charge loss

No.	Challenge	Benefits of PC5 (C-V2X dedicated short-range) communication
1	**Communication interference:** This occurs between adjacent lanes, including the lanes running in the same direction as well as those in the opposite direction. This problem could result in the driving path not being correctly recorded.	The PC5-based tolling solution is called 'one RSU for all lanes'. The position and driving direction messages could be uploaded via PC5 to identify the vehicle's accurate geolocation and keep track of its exact path.
2	**Vehicle type disinformation**: ETC users may introduce false vehicle types into ETC OBUs to reduce the toll rate (some pretend to be toll-free vehicles). This problem is mainly seen in trucks and heavy vehicles.	PC5-based tolling could promote line-fitted OBUs. If an OBU is line fitted (i.e. a T-Box), the vehicle type could be introduced in the OBU before the vehicle enters the market, and vehicle type disinformation could be effectively prevented.
3	**Cover up real driving path** (RSU errors or malicious interference): • Entrance information is not recorded in the OBU. • Toll information at the gantry is not recorded in the OBU due to RSU error. • Driver interferes with the 5.8GHz communication. It could result in a transaction failure at the gantry. If these problems arise, the real driving path might not be recorded and restored. The toll has to be calculated at exit according to the shortest path principle, resulting in lost tolling.	Thanks to its larger communication range, PC5 RSUs could initiate the transaction and read the OBU information (in loop) until the charge is successful. It could increase the success rate of the transaction. High-density C-ITS RSUs could be used for tolling. This means that drivers have to pass more transaction points. C-ITS RSUs could help keep track of a vehicle's exact driving path and accurately calculate the charge.

2.3 Next-generation Free-flow Tolling

2.3.1 Motivation of Chinese Government

Although the national standard GB/T20851 'ETC – dedicated short-range communication' is still used, it is limited to a recommendation rather than a forced tolling solution.

In addition to solving the aforementioned problems listed in Section 3.2.4, the Chinese government has higher-level motivations to develop a next-generation free-flow tolling solution. These include developing an ITS industrial chain, achieving dynamic tolling and promoting emerging industries. In recent years, the government has released some policies to describe these targets in detail.

交通强国建设纲要 (Outlook on Building National Strength in Transportation) [7]

Key information:

i) Establish a 'National 123 Transportation Circle' to implement shorter transits nationwide: one-hour commute in urban areas, two-hour travel between cities/conurbations, and three-hour links between major cities.

ii) Improved transport efficiency and decreased logistics costs for expressway tolls.

iii) On a national scale, the infrastructure for alternative energy vehicles (AEV) is to be improved, and intelligent transportation infrastructure further deployed.

iv) Intelligent vehicle technologies (including connected vehicles, automated vehicles, and connected infrastructure) is also to be further developed.

v) New technologies and digital developments are to be further integrated into the transportation sector.

Items i) and ii) foresee ambitious requirements for efficient and effective traffic in the future, but congestion at the entrance/exit of the expressway still severely impacts traffic efficiency. Item ii) also infers that, if dynamic tolling could further optimise traffic flow, dynamic toll users such as trucks could enjoy discounts and reduced logistics cost. Items iii)-v) imply the development of new industries, such as AEV, an accelerated path for the ITS industry.

Source: http://jtyst.jl.gov.cn/glj/ncgl_7609/ncgzzc/201911/P020191120479018602471.pdf

关于加快道路货运行业转型升级促进高质量发展意见 (Opinions on Accelerating the Transformation and Upgrading of the Road Freight Transport Industry) [8]

Key information: Dynamic tolling to be rolled out in China.

Source: http://www.360che.com/news/190508/110664.html

关于进一步降低物流成本的实施意见 (Opinions on Further Reducing Logistics Cost) [9]

Key information: The toll on the expressway is to be reduced and dynamic tolling further improved to guide traffic flow and reduce congested road segments.

Source: https://www.sohu.com/a/399464883_267106

Since 2018, many provincial governments have proposed to promote dynamic tolling [10][12].

Key information:

i) Sichuan: Trucks within Sichuan province could enjoy a 20-62% discount on tolls.

ii) Tianjin: AEVs could enjoy free toll use on the expressway in Tianjin and IV standard vehicles[1] could enjoy a 30% discount.

iii) Shanxi: The maximum toll discount for trucks in Shanxi province is 50%.

Source: http://www.gov.cn/xinwen/2019-03/25/content_5376511.htm

http://www.sc.gov.cn/10462/10464/10797/2019/3/28/5f1a94b32c37412c8223e5956b812411.shtml

http://www.gov.cn/xinwen/2019-01/02/content_5354285.htm

To summarise, the Chinese government aims to promote:

1. Efficient use of roads,
2. Optimisation of the transportation system (especially for heavy vehicle transportation),
3. Further development of the ITS industrial chain and its deployment,
4. Implementation of the green-energy (electric) automotive industry, and
5. New transportation business models (e.g. ride-sourcing-vehicle).

Tolling is a very important way to implement government policies in certain transportation businesses. This is the reason why China's government wants to implement dynamic tolling for future free-flow tolling.

2.3.2 Most Popular Technologies for Next-generation Free-flow Tolling

According to a detailed review of EU and Chinese policies, dynamic tolling has some special requirements that differ to the current ETC model:

1. On the vehicle side, the tolling device needs to provide more information about its motion states (in real time), including data on vehicle positioning, speed, lane, etc.,
2. Road operators could send dynamic tolling/price information to the vehicle, and
3. More intelligent information exchange and cooperation between the vehicle and road operator; road operators could send manoeuvre coordination messages to the vehicle in particular cases and environments (i.e. toll station/highway exit), and the vehicle could follow these recommendations/commands.

However, several challenges in 5.8GHz DSRC-based tolling hold back the achievement of these three targets. Therefore, there is a great need for the Chinese government to find alternative tolling technologies and to develop the next generation of free-flow tolling solutions.

Currently the most popular technologies are:

1. C-V2X (dedicated short-range communication: PC5)-based tolling solution,
2. C-V2X (cellular communication) + GNSS-based tolling solution, and
3. Satellite (Beidou)-based tolling solution (i.e. satellite also provides bi-directional communication services).

Since European Directive (2004/52/EC) of 29 April 2004 on the interoperability of electronic road toll systems came out and the Commission Decision of 6 October 2009 defining the European electronic toll service and its technical elements, cellular communication combined GNSS-based tolling solutions have been widely used in Europe for commercial transport (heavy goods vehicles). There are over ten 'cellular + GNSS' operators providing regional European electronic toll services (REETS).

In China, Beidou 'GNSS + 5G/4G' is also a very popular candidate technology for next-generation tolling services.

[1] This standard is determined according to emission.

EETS	Service Providers														
EU members states	Axxès	BroBizz	Eurotoll	Eurowag	Telepass	TMS (Total)	Toll4Europe	DKV	Egis Easytrip	Satellic NV	Shell	tolltickets GmbH	Trafineo	UTA	Via Verde
Austria	1st Priority	Operation (SP OBU)	1st Priority	1st Priority	Operation (SP OBU)	1st Priority	1st Priority	Operation (SP OBU)	2nd Priority		1st Priority	1st Priority	1st Priority	1st Priority	
Belgium	Operation (SP OBU)		Operation (SP OBU)	1st Priority	1st Priority	1st Priority	1st Priority		1st Priority	Operation (SP OBU)	2nd Priority	1st Priority	1st Priority		
Bulgaria															
Croatia	1st Priority							1st Priority							
Czech Republic	1st Priority		2nd Priority	2nd Priority	2nd Priority	2nd Priority	2nd Priority		2nd Priority		2nd Priority	2nd Priority	2nd Priority	2nd Priority	
Denmark	1st Priority	Operation (SP OBU)	2nd Priority	1st Priority	Operation (SP OBU)	1st Priority	2nd Priority	Operation (SP OBU)	2nd Priority		2nd Priority	2nd Priority	2nd Priority		
Estonia															
Finland															
France	Operation (SP OBU)	1st Priority	Operation (SP OBU)	2nd Priority	Operation (SP OBU)	Operation (SP OBU)	1st Priority	Operation (SP OBU)	1st Priority			1st Priority	1st Priority		1st Priority
Germany	1st Priority	2nd Priority	1st Priority	1st Priority	1st Priority	1st Priority	1st Priority		1st Priority		1st Priority	1st Priority	1st Priority	1st Priority	
Greece															
Hungary	1st Priority		1st Priority	1st Priority	1st Priority		2nd Priority		2nd Priority			1st Priority		1st Priority	
Ireland															
Italy	1st Priority			2nd Priority	Operation (SP OBU)	2nd Priority	2nd Priority	1st Priority	1st Priority			1st Priority	2nd Priority		
Latvia															
Luxembourg															
Malta															
Netherlands															
Poland	1st Priority	2nd Priority	1st Priority	1st Priority	1st Priority	1st Priority	2nd Priority	1st Priority	1st Priority		2nd Priority	2nd Priority	2nd Priority	1st Priority	
Portugal	Operation (SP OBU)		Operation (SP OBU)	2nd Priority	Operation (SP OBU)	Operation (SP OBU)	1st Priority	Operation (SP OBU)	2nd Priority			1st Priority	1st Priority		Operation (SP OBU)
Romania															
Slovakia															
Slovenia	1st Priority	2nd Priority	1st Priority	1st Priority	1st Priority	1st Priority	2nd Priority	1st Priority	2nd Priority		1st Priority	2nd Priority		1st Priority	
Spain	Operation (SP OBU)		Operation (SP OBU)	2nd Priority	Operation (SP OBU)	Operation (SP OBU)	1st Priority	Operation (SP OBU)	1st Priority			1st Priority	1st Priority		1st Priority
Sweden															
Switzerland															
United Kingdom															

LEGEND
1st Priority
2nd Priority
Operation (SP

Figure 12 Current EETS deployment status in EU (most technology is based on cellular + GNSS), Source: REETS

In reality, both cellular (Uu) and PC5 could meet the general requirements of 'dynamic tolling' and ITS services very well. But regarding ETC infrastructure investment over the past three years, greater focus has been on technology that manages to re-use current tolling infrastructure, and promote further C-ITS infrastructure deployment.

This idea of re-using C-ITS infrastructure is addressed in both Chinese and EU policies, such as the EU Directive (2019/520) of 19 March 2019 on the interoperability of electronic road toll systems and facilitating cross-border exchange of information and failure to pay road fees in the Union:

(44) Electronic tolling and other services, such as cooperative ITS (C-ITS) applications use similar technologies and neighbouring frequency bands for short range vehicle-to-vehicle and vehicle-to-infrastructure communication. In the future, the potential for applying other emerging technologies to electronic tolling merits exploration, after a thorough assessment of the costs, benefits, technical barriers and possible solutions thereto. It is important that measures are implemented to protect existing investments in the 5,8 GHz microwave technology from the interference of other technologies.

Views from industry also reflect the current challenges and needs in terms of free-flowing and ITS and tolling systems. Malika Seddi, VP of industry body IBTTA, Director of International Affairs at ASFA France, and current CEO of ASECAP captures this view in an interview:

"From the point of view of concessions and users, tolls or the 'user pays' principle are efficient tools to enhance sustainable mobility, and road infrastructure is a key pillar to boost our economy. Governments are responsible for providing a reliable road network that guarantees safe and efficient mobility for passengers and goods. From that perspective, France has financed, developed and equipped its motorway network of approx. 9,170km by resorting to the 'toll concession model', hence structuring the country with high levels of service and safety without recourse to public budgets. The concessionaires collect the tolls based on the 'user pays' principle which makes all users - French and foreign - contribute to the financing, instead of taxpayers. The new European legislative dispositions for concessionaires, fixed by the 2014/23/EU Directive and transposed into French law by Order 2016-65, admit the opportunity of implementing more flexibility in the use of the concessionary tool in future. Thus, concessionaires suggest the use of the assets of the toll concession model by unfolding new services to increase the efficiency of road infrastructure, and also for investments into the future mobility ecosystem. Examples of this include reserved lanes for collective use (e.g. buses, taxis, shared vehicles); penetrating multimodal exchange points between public transport and road transport; fostering the deployment of electric and autonomous vehicles; supporting the European C-ITS initiative as part of the way towards cooperative, connected and automated mobility; envisioning the transformation of toll collection into fully free-flow mode without gates, without the need for stopping; and moving forward overall modernization. European cities are increasing in size and the population is concentrated in urban and peri-urban areas. Also, time spent commuting, congestion, air pollution and noise are all increasing in our cities. Fostered by digitalisation, new mobility needs are emerging with new services: better co-modality with public transport, shared services like car-pooling or car-sharing, electromobility or autonomous vehicles. Tolls, road user charging or mobility pricing schemes may be similarly applied as well to foster and manage mobility in cities. It is also useful to recall the principles that have made the 'French-style' concession model successful to answer the double call for more sustainable mobility, thanks to clear earmarks on transportation improvements and to support the economic restart." ITS

IBTTA: The International Bridge, Tunnel & Turnpike Association which representing the worldwide tolling industry.

ASECAP: European Association of Operators of Toll Road Infrastructures

Source:

Link

Figure 13 Screenshot of interview with Malika Seddi,

The Road tolling service is also written in as efficiency information service in many 'C-V2X application layer standards', e.g. by the China Society of Automotive Engineers (C-SAE), by China Industry Innovation Alliance for the Intelligent and Connected Vehicles (CAICV) and by China Communications Standards Association (CCSA). The protocol is proposed in pre-standard T/CSAE 53-2017 by C-SAE (Table 34). Based on this technical background, In this study, the focus remains only on the investment analysis of PC5-based tolling.

Table 6 Road Tolling service as efficiency informations service in C-V2X application layer standards by CCSA

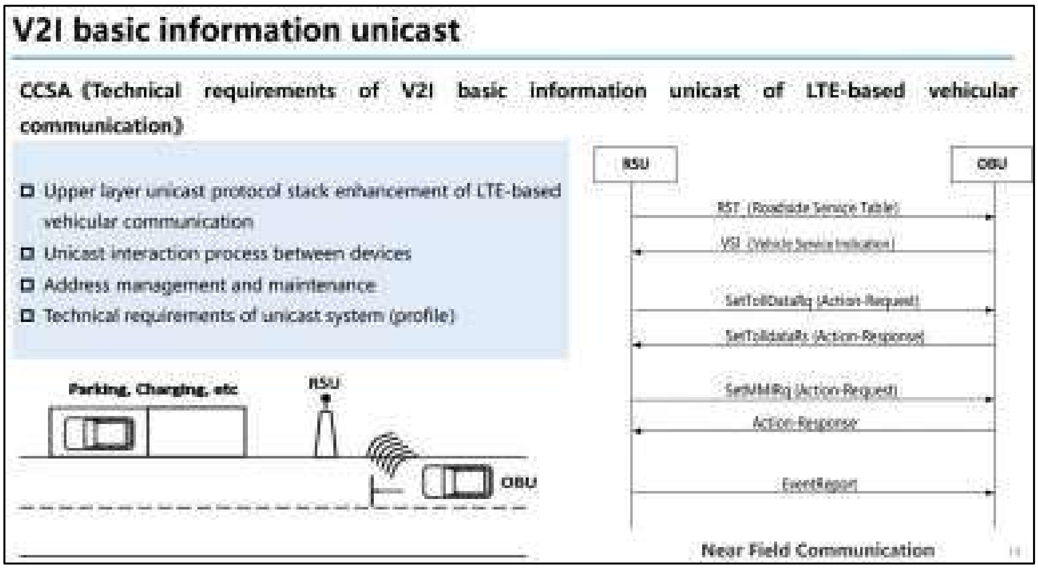


Figure source: Standardization of CCSA

Reference: 《C-V2X 产业化路径和时间表研究 2019》by CAICV

2.3.3 Key Stakeholders in Next-generation Free-flow Tolling

For a new tolling solution, there are many key influencers. The National Development and Reform Commission (NDRC) and Ministry of Transport (MOT) are the main actors. Other government institutes cooperate with the NDRC and MOT on various matters. The responsibilities of various departments are described in the table below.

Table 7 Responsibility of various departments in tolling solution

Work	Main departments	Cooperative departments
Overall tolling scheme (Objectives, KPIs, basic requirements)	NDRC, MOT	N/A
Development of roadmap	MOT	N/A
Development of industrial technology and requirements	MOT	N/A
Development of new technologies on tolling	MOT	MPS, MIIT
Construction and operation of tolling system	MOT	MOF, local government
Development of tolling regulations	MOJ, MOT	N/A
Development of charge standard	NDRC, MOT	MOF
Enforcement control	NDRC, MOT	MPS, PBOC, CBRIC
Upgrade of on-board equipment	MOT	MIIT, local government
Development of tolling market	MOT	Local government, PBOC
Analysis and evaluation of tolling service	MOT	N/A

In terms of standards development, the MOT is the leading department, and within that the Research Institute of Highways (RIOH) is responsible for setting industrial technology standards and specifications. Regarding national technology standards on tolling, such as GB/T 20851, they are developed by the whole industry, including research institutes such as RIOH, test organisations and equipment manufacturers. The Central Administration for Standards (SAC) is responsible for leading and coordinating the work.

In terms of equipment manufacturers (OBU and RSU), this includes aftermarket equipment manufacturers as well as original equipment manufacturers (OEMs):

- Aftermarket equipment manufacturers: Jinyi Tech, Wanji Tech, Juli Tech et al.
- Original equipment manufacturers: SAIC, FAW, BAIC et al.

3 Proposal of C-V2X Dedicated Short-range (PC5)-based Tolling

3.1 Policy Background

The introduction of PC5-based tolling depends on China's proposals in its C-V2X development plan. In recent years, the government and some other groups, including China-SAE, have released many relevant documents and roadmaps about the C-V2X industry. These documents specify the timeline of C-V2X evolution in China and define some C-V2X application scenarios, including tolling. More detailed information about these documents is listed below:

智能汽车创新发展战略 (Innovation and Development Strategy for Intelligent Vehicle) [13]

Key information: By 2025, LTE-V2X infrastructure should cover most areas, and 5G-V2X should be gradually implemented in some major cities and expressways.

Analysis: By 2025, C-V2X RSUs could cover most areas and provide high-density ITS services.

Source: https://www.ndrc.gov.cn/xxgk/zcfb/tz/202002/P020200224573058971435.pdf

节能与新能源汽车技术路线图 2.0 (Roadmap 2.0 for Energy-saving and Alternative Energy Vehicle) [14]

Key information: By 2025, 50% of new vehicles will be equipped with a C-V2X OBU. By 2030, almost all new vehicles will be equipped with a C-V2X OBU.

Analysis: A high penetration rate of C-V2X OBU could be reached in 2030 and almost all vehicles could be served by C-ITS services.

Source: http://img.evpartner.com/uploads/ueditor/file/202010/2863739499479020100733672800.pdf

C-V2X 产业化路径及时间表研究白皮书 (Technical Report on C-V2X Industrialisation Path and Schedule) [15]

Key information: i) The technical report defines C-V2X application scenarios in which tolling is included. ii) The technical report develops the timeline of C-V2X deployment on both the infrastructure and vehicle sides (Section 13.4).

Analysis: Government and some stakeholders in the C-V2X industry support that C-V2X is applied to tolling, and agree that PC5-based tolling has great potential for development in China.

Source: http://www.zj5glm.com/Public/headphotob/2019-11-01/5dbbe2e2755d9.pdf

C-V2X 业务演进白皮书 (Technical Report on C-V2X Business Evolution) [16]

Key information: This technical report proposes to establish C-V2X-based tolling in other scenarios as well, including expressway, parking lots, petrol stations, traffic fine issuing etc. The report also suggests that C-V2X-based tolling could be deployed and tested within three years.

Analysis: This technical report establishes that C-V2X-based tolling would have broader application potential in the future. Furthermore, it could be tested within three years and then rolled out in China. It is inferred that C-V2X-based tolling might be deployed region by region.

Source: http://www.caict.ac.cn/kxyj/qwfb/bps/201911/P020191104336556097939.pdf

3.2 Roadmap of PC5-based Tolling

Based on the aforementioned documents and roadmap related to C-V2X and tolling, 5GAA believes that PC5/C-V2X-based tolling has great potential in China, and could produce benefits in the short term. Above all, 5GAA thinks PC5-based tolling could promote the development of ITS and accelerate C-V2X deployment in China.

Therefore, according to the development plan of the C-V2X industry in China, 5GAA and Tongji University jointly propose a targeted 'development vision' for PC5-based tolling in which the roadmap and migration path are included.

In this section, a roadmap for PC5-based tolling in each phase is described in detail, including where and how to deploy PC5 RSU, how to use PC5 OBU to make charges, and what functional requirements PC5 OBU and RSU need. More details about this roadmap are described below.

Firstly, based on the aforementioned development plan, some key assumptions about the roadmap are proposed:

- There is no interference problem between 5.9GHz PC5 and 5.8GHz ETC radio network.
- PC5-based tolling is ready for application (as of 2021).
- Starting 2025, all C-ITS RSUs will achieve full coverage of the entire road network, C-ITS RSUs will support both tolling applications with ITS messages and new ITS-based tolling applications (as per ETSI TR 103 579).
- By 2030, penetration rate of PC5 OBUs (including both line-fitted and aftermarket) will be over 90%. (see Roadmap 2.0 for Energy-saving and Alternative Energy Vehicles, released by MIIT, C-SAE et al. in Oct 2020)
- In the years to come, 3GPP will define the LTE-sidelink (PC5) and 5G sidelink (NR-V) for reduced power consumption. Furthermore, ITS systems will be developed for vulnerable road users (VRUs), so it could be assumed that starting in 2030, PC5 mobile phones will be widespread and could be used for tolling.
- In 2019, there was a huge investment in ETC RSUs, which built the complete Tolling Infrastructure for today. With an estimated lifespan of 8-10 years, a large investment in replacement costs is anticipated. Therefore, it is assumed that it is the best time window to evolve C-V2X direct communication based Tolling until 2029 during the first lifespan of ETC RSU.
- The roadmap of PC5-based tolling is summarised in following figure.

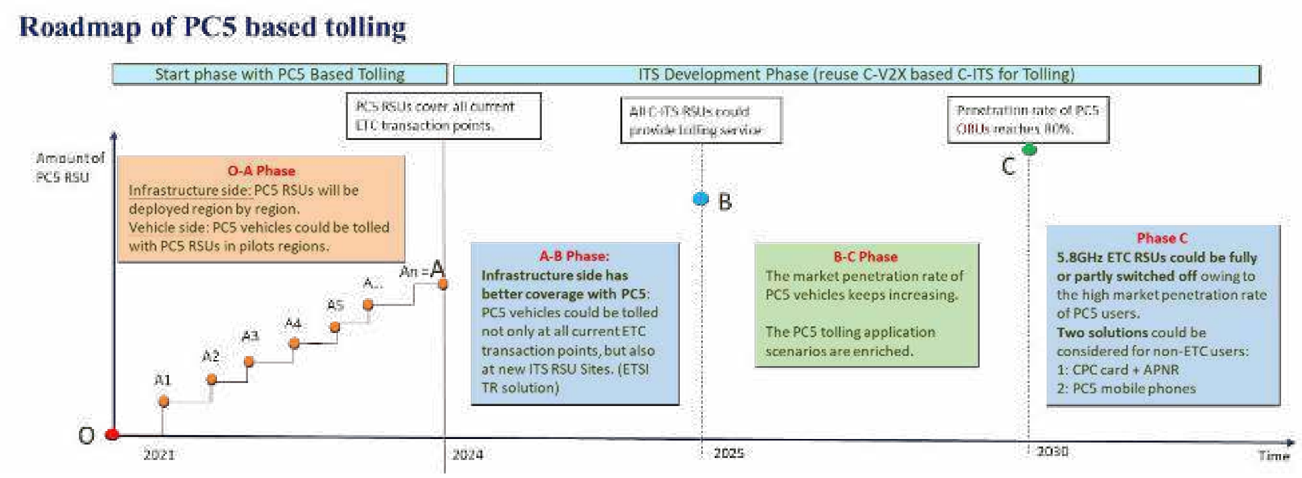


Figure 14 Proposal for the Roadmap of PC5-based Tolling

Phase O-A (2021-2024):

Key business	Description
Tolling-PC5 RSU	- The objective of this phase is to achieve a 100% penetration rate of PC5 RSUs at current 5.8GHz ETC transaction points (gantry and tolling plaza). - From 2021 to 2024, PC5 tolling RSUs will be deployed region by region. Some provinces have detailed development plans for ITS, including tolling, thus PC5 RSUs could first be deployed at current transaction points within these provinces. - Then the deployment of PC5 RSUs could be expanded to adjacent provinces. By 2024 (point A), PC5 RSUs would cover all transaction points in China and coexist with 5.8GHz ETC RSU.
ETC RSU	- In normal operation.
Vehicle	- PC5 vehicle: could use PC5 for tolling at all ETC transaction points. What kind of vehicle will use PC5 OBU? This question will be clarified in Section 4.2.1, with the proposed use case and statistical forecasts for certain vehicles. - ETC vehicle: 5.8GHz ETC could be kept and used at all ETC transaction points. - MTC vehicle: CPC card (5.8GHz ETC) could still be used for tolling at all ETC transaction points.
Tolling	- Transaction: All kinds of tolling solutions would follow the current ETC transaction strategy and workflow. PC5 just changes the radio network layer. - Enforcement control: All kinds of tolling follow the current ETC enforcement control strategy and workflow.

Phase A-B (2024-2025):

Key business	Description
Tolling-PC5 RSU	- C-ITS RSU: According to relevant documents and roadmaps about C-V2X deployment, C-ITS RSUs should cover most areas and provide high-density ITS services by 2025. - Based on relevant development plans, it is assumed that C-ITS RSUs could increase tolling functions. By 2025, all C-ITS RSUs could provide tolling services.
ETC RSU	- In normal operation.
Vehicle	- PC5 vehicle: PC5 vehicles could achieve the transaction not only at gantries, but also at new C-ITS RSU sites (poles). - ETC vehicle: ETC vehicles could achieve the transaction at all gantries with 5.8GHz DSRC OBU. - MTC vehicle: MTC vehicles could achieve the transaction at all gantries with a CPC card.
Tolling	- Transaction: • All tolling solutions at gantries (PC5 and ETC) will follow the current ETC transaction strategy and work flow. PC5 just changes the radio network layer. • All C-ITS RSU will provide the transaction with ITS standard messages and new ITS applications (the work flow reference as ETSI TR 103 579). - Enforcement control: All kinds of tolling follow the current ETC enforcement control strategy and work flow.

Phase B-C: (2025-2030)

Key business	Description
Tolling-PC5 RSU	- Same as Phase A-B.
ETC RSU	- In normal operation.
Vehicle	- PC5 vehicle: • OBU (line-fitted and aftermarket OBU): In this phase, the number of PC5 OBUs keep increasing. According to the C-V2X roadmap, the penetration rate of line-fitted PC5 OBUs would reach 100% by 2030 and PC5 tolling application scenarios will be enriched. Therefore, it is assumed that by 2030, the penetration rate of PC5 OBUs (including line-fitted and aftermarket) would be over 90%. • PC5 mobile phone: It is assumed all phones will be equipped with a PC5 module by 2030. It is suggested that PC5 mobile phones integrated with security modules could be used for tolling. - ETC vehicle: Same as Phase A-B. - MTC vehicle: Same as Phase A-B.
Tolling	- Transaction: Same as Phase A-B. - Enforcement control: Same as Phase A-B.

Phase C-Future: (After 2030)

Key business	Description
Tolling- PC5 RSU	- In normal operation.
ETC RSU	- Switch off, or partly switch off (keep the ETC RSU operation at the exit/entrance for non-ETC users).
Vehicle	- PC5 vehicle (line-fitted OBU, aftermarket OBU, PC5 mobile phone): Tolled at gantries (main tolling system), and C-ITS RSU sites (as redundancy tolling). - ETC vehicle: Operation is stopped. - MTC vehicle: There are two proposals: 1. PC5 mobile phone is used for tolling. 2. CPC card is kept in use for tolling, but the transaction (only recording) at each gantry uses the APNR solution.
Tolling	- Transaction: PC5 is used for tolling at gantries and C-ITS RSU is used for redundancy tolling. Non-ETC users could use PC5 mobile phone or CPC card + APNR. - Enforcement control: Same as Phase A-B.

4 Vision of Tolling Infrastructure – Deployment Proposal

Based on the proposed roadmap and transaction application for different kinds of vehicles, in this section the study discusses how the tolling environment will look in order to understand what units and services will be needed on the roadside. The function and key components of the equipment will also be summarised. Certain information will be used as input for next-step cost estimation and infrastructure-side investment analysis.

Notes: As our assumption, the ETC enforcement control system will be reused for PC5-based tolling applications, therefore the enforcement control hardware will not be considered extra in this analysis.

4.1 Tolling Environments for Phase O-A

In this phase O-A, PC5 tolling RSUs are deployed at existing gantries and tolling plazas, region by region. Based on the advantages of PC5, such as bigger communication range and bandwidth, the PC5-based tolling scenario is quite different from the current 5.8GHz ETC scenario.

At gantry:

The tolling scenario is shown in the following figure. A PC5 RSU could cover all lanes to avoid communication interference between adjacent lanes, with the communication distance of an RSU reaching up to 500m. In this large communication range, PC5 RSUs could initiate multiple tolling operations at once. In this tolling course, an RSU could take advantage of greater bandwidth to achieve these simultaneous transactions with multiple PC5 vehicles. The vehicle's ID, position, speed, type, and payment status could be read and recorded 'in loop' by the PC5 RSU (see Figure 15, 16). With the support of more vehicle trajectory data, the driving path of a vehicle could be more accurately recorded, and evidence could be provided for speeding checking. PC5 RSUs could also send speed advice to PC5 vehicles and play a key role in traffic management (i.e. manoeuvre coordination services). With the support of 'transaction in loop', the success rate could also be effectively improved.

For enforcement control, the existing ANPR continues to be used. The information collected by the ANPR could be uploaded to a backhaul system and compared with the data collected by the PC5 RSU. The result of this comparison could be used for enforcement control.

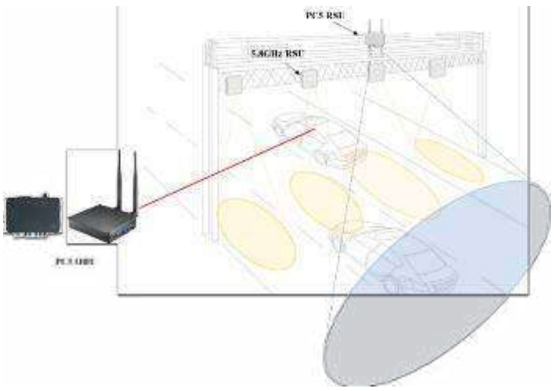


Figure 15 PC5-based tolling scenario at gantry (a)

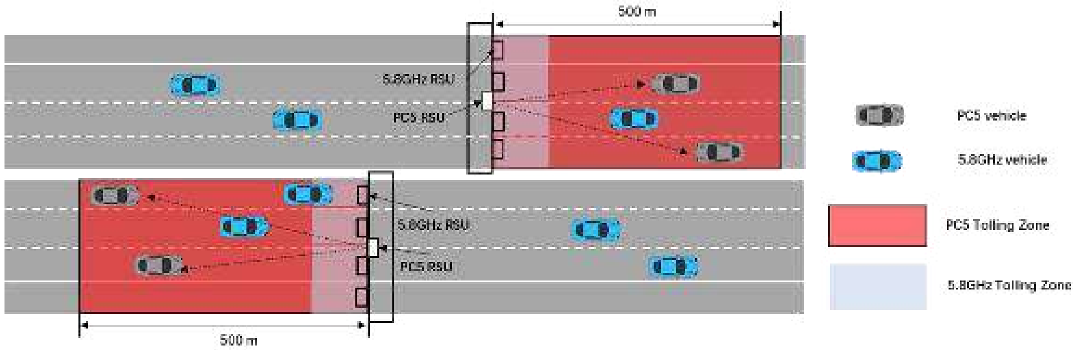


Figure 16 PC5-based tolling scenario at gantry (b)

At tolling plaza (entrance/exit):

The tolling scenario is shown in the following figure. Similar to the deployment of PC5 RSUs at the gantry, a PC5 RSU is deployed at a tolling plaza and covers all lanes. The communication range could also reach up to 500m.

Dedicated PC5 toll lanes are deployed at the tolling plaza, in order to enable PC5 vehicles to pass through the exit/entrance at a higher speed. In this large PC5 communication range, PC5 RSUs could also conduct transactions in the loop until the charge is successful. In the tolling course, PC5 RSUs could not only keep reading vehicle information, but also send speed recommendations and lane ID to PC5 vehicles via the manoeuvre coordination service. This ITS service could be beneficial in handling congestion at the entrance/exit. When the charge is completed and the PC5 vehicle enters a specified lane, the barrier would rise and the vehicle could pass through the entrance/exit at a higher speed.

For enforcement control, an ANPR is deployed at each toll lane and used for checking the vehicle and lane ID. If the information is identical to the one collected by the RSU, the physical barrier would rise. Otherwise, the vehicle would be intercepted by the barrier.

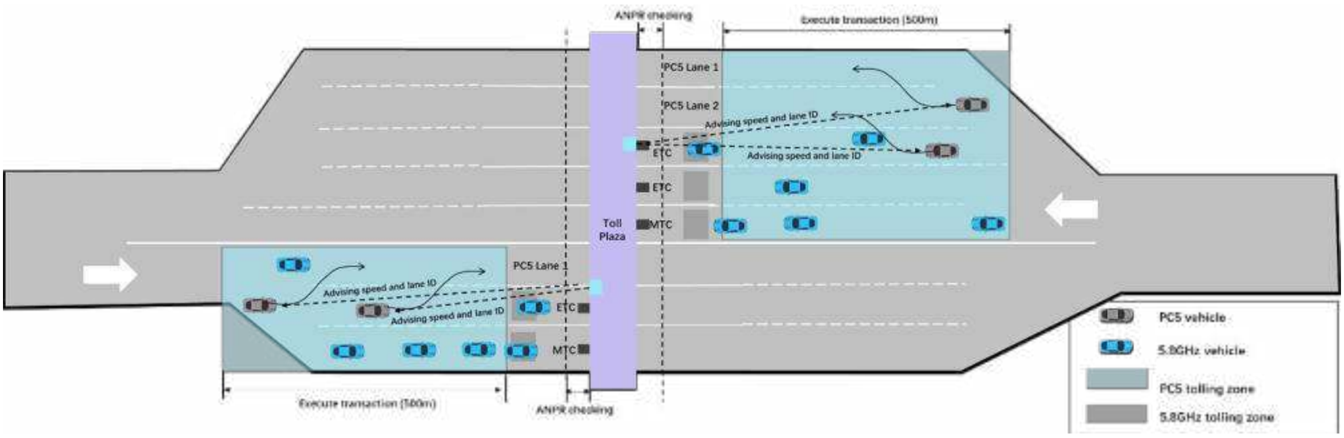


Figure 17 PC5-based tolling scenario at toll plaza

For achieving the aforementioned PC5 tolling function, and additional ITS functions such as manoeuvre coordination services, PC5 OBU and RSU must have the following general capacities:

Table 8 General capacity for PC5 RSU

Product type	Function
• PC5 Module and antenna • GNSS antenna • CAN/USB/UART/Ethernet module • Security module • Backhaul network • WIFI • AC-DC power supply • CPU + FPGA/GPU	Basic tolling function: • Restore vehicle's driving path • Send command to PC5 OBU • Calculate toll • Record vehicle information (ID, geo-location, speed…)
	Upgrade and maintenance: • OTA service • Fault diagnosis • RSU status monitoring and diagnosis • Remote operation and maintenance
	ITS service: • Manoeuvre coordination service (send advising speed and lane to PC5 OBU) • Path guiding at tolling plaza
	High-precision positioning

Table 9 General capacity for PC5 OBU

Product type	Function
Line-fitted (T-Box)/aftermarket (intelligent rear-view mirror) • **Communication module (4G + PC5)** • **GNSS module** • **MPU** • **Additional MCU** • **Memory module** • **Security module** • **PC5 antenna** • **GNSS antenna** • **Various physical porters** • **Security access module for tolling**	Basic tolling function: • Send multiple vehicle data to RSU • Receive command from RSU • Store payment status
	Upgrade and maintenance: • OTA service • Fault diagnosis • OBU status monitoring • Remote operation and maintenance
	ITS service: • Manoeuvre coordination service • Path navigation • Entertainment service • Vehicle status monitoring and diagnosis • Accident alarming
	High-precision positioning

4.2 Tolling Environments for Phase A-B

In the phases A-B, as described in Section 3.2, PC5 tolling RSUs have been deployed at all existing ETC transaction points, and C-ITS RSUs cover most areas and roads. C-ITS RSUs handles the tolling function in this phase. This means that C-ITS RSUs would provide redundancy tolling services, thus the density of transaction points would rapidly increase. This tolling scenario is referred to in [17] and has been tested in practice in France. The additional algorithm and logic are added to the C-ITS RSUs in order to achieve the tolling function, and C-ITS RSUs would have the following benefits for tolling:

1) C-ITS RSUs could cover bi-directional lanes and obtain reliable and accurate geo-location of the PC5 vehicles via BSM. This means that C-ITS RSUs would help keep track of the exact driving path of the vehicle and accurately calculate the charge. In addition, the accurate driving path information could also be uploaded to a backend system for enforcement control.
2) C-ITS RSUs are not only deployed on expressways, but also on arterial roads and in cities. Firstly, this means that if the vehicle does not effectively pay the toll on the expressway, it would be checked in other places. Additionally, this means the tolling application scenario is enriched because PC5 vehicles could perform tolling functions at petrol stations, parking lots, and other places.

In this phase, since C-ITS RSUs are used for redundancy tolling, there is no need to deploy additional PC5 tolling RSUs, therefore costs of PC5 RSUs could be saved.

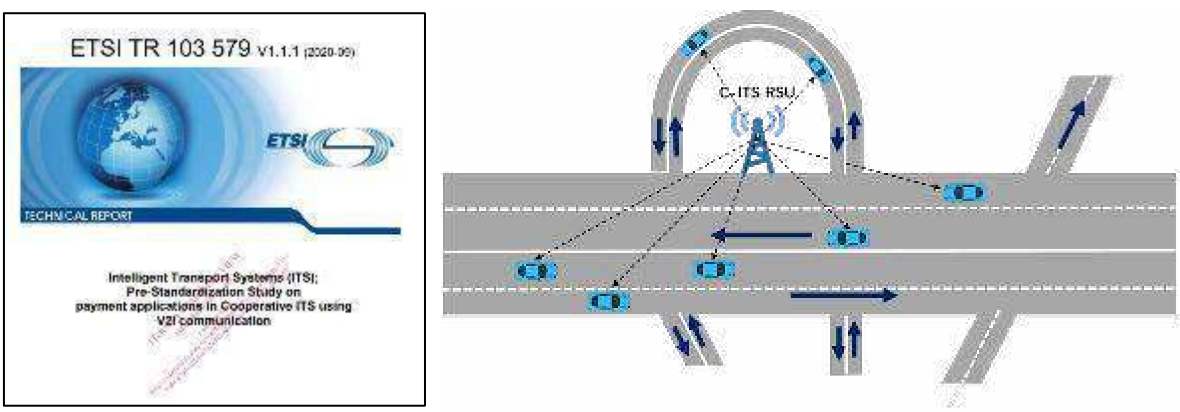


Figure 18 Tolling scenario proposed by ETSI

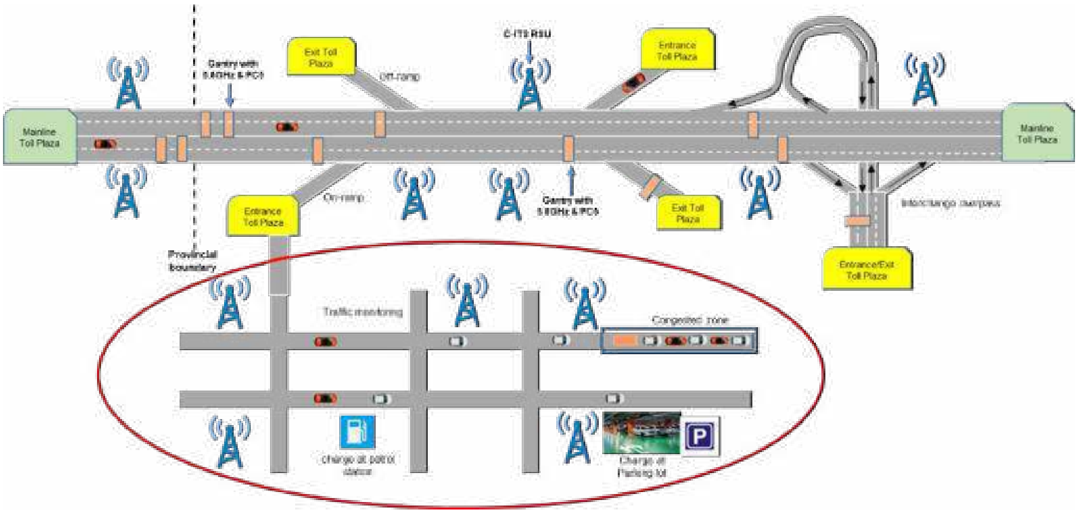


Figure 19 PC5-based tolling scenario in phase A-B

In the phases B-C, the deployment of PC5 devices on the infrastructure side have been completed. On the vehicle side, the number of PC5 vehicles would keep increasing. By 2030 (point C), the penetration rate of PC5 vehicles would be over 90%. This means that by 2030 almost all vehicles could enjoy PC5-based tolling and 5.8GHz RSUs will have reached their expected lifespan. Because of cost savings, it is suggested that 5.8GHz ETC systems are switched off instead of being replaced at that point.

4.3 Tolling Environments for Phase C to Future

Since the 5.8GHz ETC systems would be scheduled to be shut down in 2030, the CPC card supporting 5.8GHz ETC network would the no longer function at the gantries. Our proposed solutions to this eventuality are described in the following:

1. Solution 1: CPC cards will continue to be used for tolling at exit/entrance, but an ANPR solution used for the transaction (only recording) at each gantry. This means that the tolling backend system needs to be upgraded. The information recorded by the ANPR, such as vehicle type, could be rapidly checked at exit/entrance. This proposed solution means that the function/capability of the ANPR is shifted (enforcement control→transaction), and the cost of further investment saved or directed elsewhere. This ANPR solution has been applied on some highways in Austria, such as the second tube/tunnel Gleinalm on motorway A9.

Figure 20 Toll station at Austria’s Gleinalm tunnel on the A9

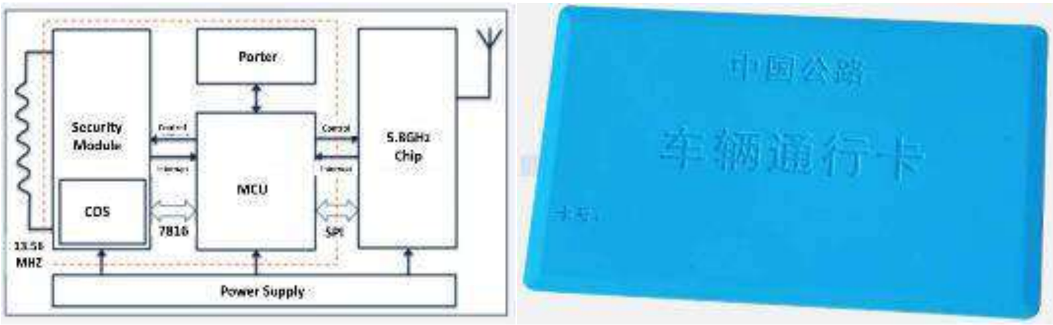


Figure 21 CPC card is a simple 5.8GHz OBU without transaction function and supports two frequency bands (5.8GHz for gantry/13.56MHz for MTC lanes at entrance/exit)

2. Solution 2: PC5 mobile phones could be equipped with an ETC security module and utilised for tolling via ITS messaging. The reasons behind this proposal:

1) ITS industry: safety requirements could not be met by solely using V2V or V2I. VRUs such as pedestrians and cyclists must be taken into consideration. PC5 could effectively ensure the safety of VRUs using mobile phones which are more portable and people normally carry them at all times. Therefore, PC5-based mobile phones must be developed.
2) Power consumption: PC5 could consume a lot of power, so the next-generation communication standard needs to solve this problem. For 3GPP Release 17, the power saving (sidelink DRX) in RAN2 is being defined, which addresses the problem of high power consumption.
3) Market: If the problem of high power consumption is solved, PC5 mobile phones could be used for VRUs and would enjoy a large market share. Furthermore, if PC5 mobile phones could support tolling, market competition could be further improved.
4) Tolling scenario: The methods to reduce power consumption include sleeping or sending/receiving messages at low frequency. 3GPP has held some discussions about how to 'wake up' PC5 when needed. For example, when PC5 mobile phone users approach the gantry, the base stations near the gantry would use Uu to activate PC5 communication for tolling purposes.

***Note**: The hardware and its cost on the vehicle side (for MTCs) will be discussed in the next section on vehicle-side investment analysis.*

4.4 Summary of the Roadside Hardware in Each Phase

Table 10 Deployment status of roadside Hardware in each phase

Phase	Location	RSU	Deployment	The changes
O-A	Gantry	PC5	- Newly deployed on gantries. - Cover all ETC gantries. - Each gantry with one PC5 RSU.	= Gantry number
		ETC	Remain to be used at ETC Gantries.	= 0, not changed
	Toll plaza	PC5	- Newly deployed on Gantries. - Cover all ETC Gantries. - Each Gantry with one PC5 RSU.	= Plaza number
		ETC	Remain to be used at ETC gantries.	= 0, not changed
	ITS pole/RSU	PC5	NA	= 0
		ETC	NA	= 0
A-B	Gantry	PC5	Unchanged (coexistence).	= 0, not changed
		ETC	Unchanged (coexistence).	= 0, not changed
	Toll plaza	PC5	Unchanged (coexistence).	= 0, not changed
		ETC	Unchanged (coexistence).	= 0, not changed
	ITS pole/RSU	PC5	Newly deployed ITS RSUs on poles, could also support the tolling application (budget from ITS investment).	= 0, cannot be estimated, and not considered
		ETC	NA	= 0
B-C	Gantry	PC5	Unchanged (coexistence).	= 0, not changed
		ETC	Unchanged (coexistence).	= 0, not changed
	Toll plaza	PC5	Unchanged (coexistence).	= 0, not changed
		ETC	Unchanged (coexistence).	= 0, not changed
	ITS pole/RSU	PC5	Newly deployed ITS RSU on poles, could also support the tolling application (budget from ITS investment).	= 0, not considered
		ETC	NA	= 0
C to future	Gantry	PC5	Newly deployed = renewed RSUs in 2031, or not changed.	= Gantry number
		ETC	Remove all ETC RSU at gantries.	= - Gantries x 4 (4 is average lane number)
	Toll Plaza	PC5	Newly deployed = renewed RSU in 2031, or not changed.	= Plaza number
		ETC	Remove ETC RSU for ETC lane. Only keep ETC RSU at MTC lane.	= MTC lane Number at toll plaza.
	ITS Pole/RSU	PC5	New deployed ITS RSUs on poles, could also support the tolling application (budget from ITS investment).	= 0, not considered
		ETC	NA	= 0

The amount of lanes/plazas/gantries is described in ‘Table 1 Tolling infrastructure statistical data covering the past seven years’.

5 The Evaluation Logic and Scope

Based on the description laid out for PC5 tolling, a clearer picture of the environment of PC5-based tolling for the next ten years is revealed, especially during the period when it coexists with current ETC solutions. This section will focus on a deeper and more concrete investment calculation, to learn about the cost comparison between ETC and PC5 tolling technology directly, about how the investment could grow and when we could reach a critical point of investment parity. This could help C-V2X stakeholders and authorities to define relevant policies for tolling applications while establishing the roll-out of C-V2X infrastructure.

The first step is to detail the PC5-based tolling model for the next decade. Through studying the current (Chinese) ETC system and transportation policies, this study proposes a rough roadmap, deployment plan (considering coexistence with ETC), tolling environment, and valuable use cases for the starting phase, as the most practical way to achieve large-scale deployment of PC5-based tolling.

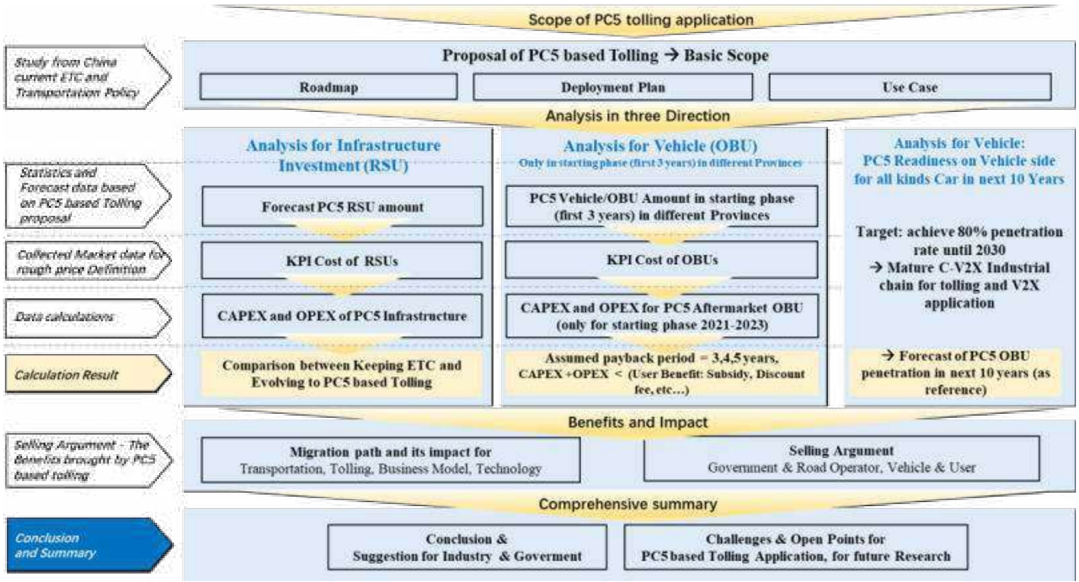


Figure 22 The logic of investment evaluation

The study then collects market data for each tolling system to create a rough estimate of KPI costs and forecast of the annual number/distribution of vehicles (including OBUs) from 2020-2030 as a basic input for next-step analysis. The data calculation is focused on three topics, which present the key factors about PC5 tolling deployment:

1	Analysis for infrastructure investment	1) Overview cost of building PC5-based tolling RSUs, including coexistence with the ETC system until 2030. 2) Comprehension of the investment cost difference between the PC5 and ETC tolling system. 3) Critical point when the investment balance/parity could be achieved.
2	Analysis for vehicle (PC5 OBU) in the starting phase (2021-2023)	1) Explores in which region and for what kind of vehicle the roll out of the PC5-based tolling application could work. 2) Potential valuable use cases for special vehicles, and the related transportation policy/benefits. 3) Investment cost for PC5 OBUs, and the possible back-to-back model, such as government subsidies (especially for AEV), tolling fee discounts and other ITS benefits (i.e. manoeuvre coordination at the toll plaza, benefits from ITS Day 1 services, etc.). 4) Rough payback model for the user in starting phase, as a reference case for the government.
3	Analysis and forecast of the PC5 OBU penetration distribution in the next decade	1) Key target: PC5 industrial chain readiness for all kinds of cars in the next ten years → achieve 80%+ penetration. 2) Forecast the penetration distribution from 2021-2030, as a reference for governments and PC5 industrial stakeholders.

Finally, based on the detailed analysis, this study provides a comprehensive summary covering the migration path and selling arguments, including how many and what sort of subsidies the government could provide to AEVs, and how to develop dynamic tolling. These quantified benefits could help the Chinese government to develop polices related to PC5-based tolling:

1	Selling argument	1) Migration path and its impact for transportation, tolling, business models, and technologies. 2) Selling argument with perspectives from the government and road operators, vehicles, and users.
2	Summary of this study	1) Challenges and open points for PC5-based tolling applications, and for future research. 2) Suggestions and conclusions.

6 Investment Evaluation for Infrastructure

6.1 KPIs on Infrastructure Side

In this section, according to the product type and functions described in Section 4, the cost KPIs of PC5 RSUs and OBUs are summarised as a proxy investment evaluation of PC5-based tolling. It is assumed that the capital and operating expenses (CAPEX and OPEX) of 5.8GHz OBUs and RSUs would remain constant in the future, and that the costs of PC5 OBUs (line-fitted and aftermarket) and RSUs would gradually decline year by year. The annual growth rate is based on Chinese market data and on a previous 5GAA technical report 'C-ITS Vehicle-to-Infrastructure Service: How C-V2X Technology Completely Changes the Cost Equation for Road Operators'. The cost of RSU, line-fitted OBU and aftermarket OBU are thus summarised in the following tables.

Cost KPIs on infrastructure side:

Table 11 CAPEX and OPEX of 5.8GHz ETC RSU and PC5 RSU

CAPEX (one-off-cost)	5.8GHz DSRC	PC5	Lifespan (years)	Annual growth	Source
RSU equipment	￥20,000/ €2,500	￥27,000/ €3,500	8-10	Constant (5.8GHz)/ -2% (PC5)	5.8GHz RSU equipment cost is from Chinese market[56], while PC5 RSU equipment cost and the annual growth rate is from 5GAA technical report[58]
Hardware installation	￥7800/ €1,000	￥7,800/ €1,000	8-10	-2%	[58]
Total CAPEX	￥27,800/ €3,500	￥34,800/ €4,500	8-10		
OPEX (annual cost)	**5.8GHz DSRC**	**PC5**	**Lifespan (years)**	**Annual growth**	**Source**
Power consumption	￥160/€20	￥160/€20	N/A	+2%	[58]
Maintenance	￥1,400/€175	￥1,800/€225	N/A	+2%	5% of RSU equipment and installation, as in[58]
Security certificated licence	￥310/€40	￥310/€40	N/A	-2%	[58]
Total OPEX	￥5370/€685	￥2270/€285	N/A		
Replacement	￥3500/€450	￥3500/€450	8	-2%	Based cost equivalent to hardware and installation [58]

Note: *According to the assumption in our proposed roadmap, the lifespan of 5.8GHz RSU is ten years and the lifespan of PC5 RSU is eight years. It makes sense that 5.8GHz RSU has longer lifespan due to the yearly maintenance, but the lifespan of a PC5 RSU is shorter due to its high-power consumption.*

6.2 Calculation of Total Investment on Infrastructure Side

There are mainly three tolling options to be considered:

1) Continuing to use previous ETC tolling solution.
- Starting phase – transition phase (O-A-C): Only ETC
- In and after 2030: Only ETC RSU
2) Change to PC5-based tolling solution (CPC card + ANPR).
- Starting phase – transition phase (O-A-C): ETC + PC5 (coexistence)
- In and after 2030: On the highway, only PC5 RSU, At tolling plaza, only MTC lane keep to use ETC RSU (for this case, ETC RSU Amount = MTC Lanes)
3) Change to PC5-based tolling solution (PC5 mobile phone).
- Starting phase – transition phase (O-A-C): ETC + PC5 (coexistence)
- In and after 2030: On the highway, only PC5 RSU; At tolling plaza, only PC5 RSU

Calculation of current 5.8GHz ETC:

The CAPEX is calculated in Table 10, the number of 5.8GHz RSUs detail the new deployed ETC RSUs each year. As the lifespan of 5.8GHz RSU is a decade, the replacement number (2021-2031) equals the number of 5.8GHz RSUs deployed in period 2010-2020 (all data from Table 1). Starting in 2032, the replacement of 5.8GHz RSUs will enter the next cycle. Regarding OPEX costs, the overall figure is the total number of 5.8GHz RSUs listed in Table 13. It is assumed that starting in 2021, there are no additional 5.8GHz RSUs deployed and the total number remains constant.

Table 12 The calculation of current 5.8GHz ETC solution

	Year	Number of 5.8GHz RSUs (data from Table 1)	Formula
CAPEX (2021-2035)	2021	0	(5.8GHz RSU replacement cost + 5.8GHz RSU equipment cost + 5.8GHz RSU installation cost) * the replaced number of 5.8GHz RSU per year (per year)
	2022	0	
	2023	0	
	2024	2,300	
	2025	2,783	
	2026	6,444	
	2027	4,505	
	2028	7,484	
	2029	6,234	
	2030	170,459	
	2031	8,000	
	2032	0	
	2033	0	
	2034	2,300	
	2035	2,783	
OPEX (2021-2035)	2021-2035	208,208	Total number of 5.8GHz RSU*5.8GHz RSU OPEX cost per unit

Calculation for PC5-based tolling with solution 1 (CPC card + ANPR):

For PC5-based tolling with solution 1, in 2021-2029, PC5 RSUs will coexist with 5.8GHz RSUs. Starting in 2030, 5.8GHz RSUs will be partly switched off. Only 5.8GHz RSUs at MTC lanes and mixed lanes (Table 1: old toll lanes in 2013-2018, new MTC lanes in 2019, and new mixed lanes in 2019) will be kept for CPC card users. ANPR could be upgraded and used for tolling at gantries. For CAPEX, the calculation of 5.8GHz RSUs is the same as the description in **Error! Reference source not found.**12. The calculation of PC5 RSUs follows the proposed roadmap. The PC5 RSUs are deployed region by region:

- In 2021, PC5 RSUs will be deployed in Jiangsu Province and Zhejiang Province.
- In 2022, PC5 RSUs will be deployed in Guangdong, Jiangxi and Hebei Provinces.
- In 2023, PC5 RSUs will cover two-fifths of the country.
- In 2024, PC5 RSUs will cover all the transaction points in China.
- Starting 2025, there will be no additional PC5 RSUs to be deployed.

The following table shows the number of gantries and tolling plazas in these five provinces:

Table 13 The number of gantries and tolling plazas in five provinces

Province	Gantry	Tolling plaza
Jiangsu	1,277 [47]	1,515 [42]
Zhejiang	2,015 [47]	1,434 [43]
Guangdong	2,177 [47]	4,749 [44]
Hebei	1,334 [47]	1,228 [45]
Jiangxi	958 [47]	499 [46]
Nation	25,594 [50]	24,612 [49]

Since a single PC5 RSU is deployed in each gantry or each tolling plaza, the number of PC5 RSUs equals the sum of gantries and tolling plazas.

As the lifespan of PC5 RSUs is eight years, the replacement of PC5 RSUs will begin in 2029.

Since the number of PC5 RSUs will keep increasing, the OPEX 2021-2024 will be cumulative. Starting in 2025, the number of PC5 RSUs will remain constant, thus there is no need to accumulate the OPEX.

Table 14 The calculation of PC5-based tolling with solution 1 (CPC card + ANPR)

	Year	Forecasted Number of PC5 RSU(calculated from 13)	Number of 5.8GHz RSU (Table 1)	Formula
CAPEX (2021-2035)	2021	6,241	0	**In 2021-2024**: (5.8GHz RSU replacement cost + 5.8GHz RSU equipment cost + 5.8GHz RSU installation cost) * the replaced number of 5.8GHz RSU per year + (PC5 RSU equipment cost + PC5 RSU installation cost) * number of newly deployed PC5 RSU per year **In 2025-2035** (5.8GHz RSU replacement cost + 5.8GHz RSU equipment cost + 5.8GHz RSU installation cost) * the replaced number of 5.8GHz RSU per year + (PC5 RSU equipment cost + PC5 RSU installation cost + PC5 RSU replacement cost) * the replaced number of PC5 RSU per year
	2022	10,945	0	
	2023	13,208	0	
	2024	19,812	2,300	
	2025	0	2,783	
	2026	0	6,444	
	2027	0	4,505	
	2028	0	7,484	
	2029	6,241	6,234	
	2030	10,945	37,577	
	2031	13,208	0	
	2032	19,812	0	
	2033	0	0	
	2034	0	2,300	
	2035	0	2,783	
OPEX (2021-2029)	2021	6,241	208,208	Total number of 5.8GHz RSU*5.8GHz RSU OPEX cost per unit + number of PC5 RSU * PC5 RSU OPEX cost per unit **Note: OPEX accumulates from 2021-2024**
	2022	17,086		
	2023	30,294		
	2024-2029	50,106		
OPEX (2030-2035)	2030-2035	50,106	67,326	Number of 5.8GHz RSU*5.8GHz RSU OPEX cost per unit + number of PC5 RSU * PC5 RSU OPEX cost per unit

Calculation of PC5-based tolling with Solution 2 (PC5 mobile phone):

The calculation of PC5-based tolling with solution 2 is similar to the PC5-based tolling with solution 1. The only difference is that in this solution, the 5.8GHz ETC will be fully switched off starting in 2030. Instead of CPC cards, PC5 mobile phones would be used for tolling.

Table 15 The calculation of PC5-based tolling with solution 2 (PC5 mobile phone)

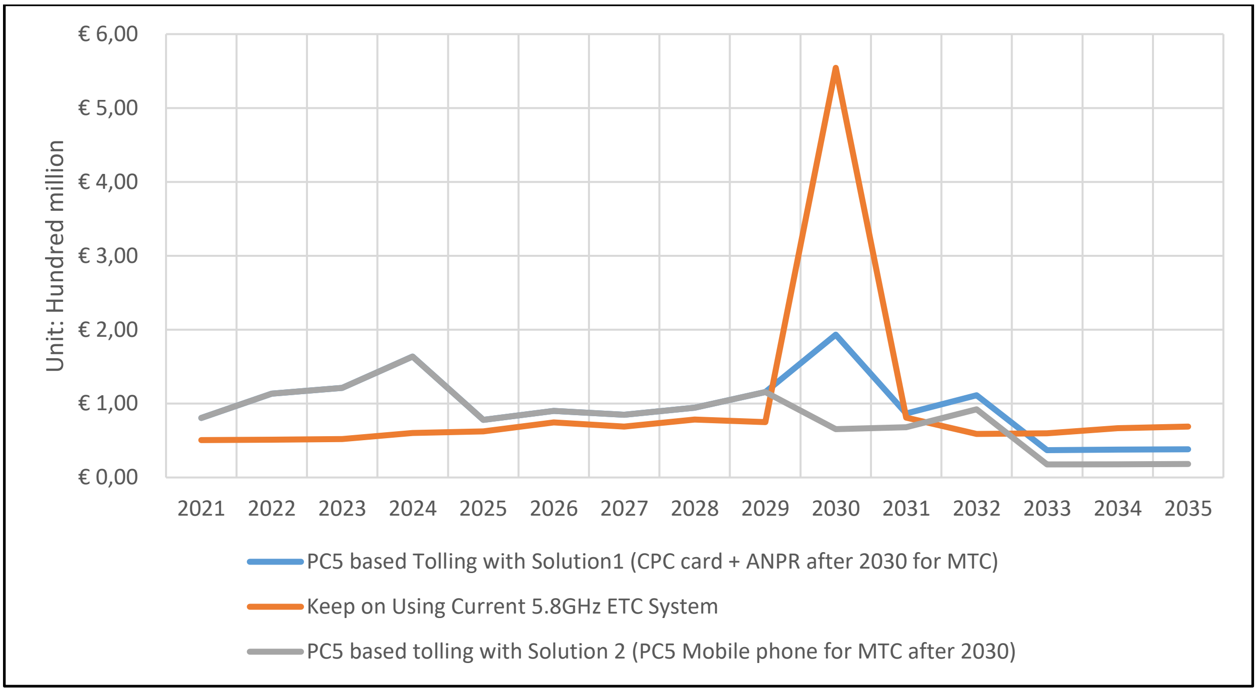
	Year	Forecasted Number of PC5 RSU(calculated from 13)	Number of 5.8GHz RSU (Table 1)	Formula
CAPEX (2021-2035)	2021	6,241	0	**In 2021-2024**: (5.8GHz RSU replacement cost + 5.8GHz RSU equipment cost + 5.8GHz RSU installation cost) * the replaced number of 5.8GHz RSU per year + (PC5 RSU equipment cost + PC5 RSU installation cost) * number of newly deployed PC5 RSU per year **In 2025-2035** (5.8GHz RSU replacement cost + 5.8GHz RSU equipment cost + 5.8GHz RSU installation cost) * the replaced number of 5.8GHz RSU per year + (PC5 RSU equipment cost + PC5 RSU installation cost + PC5 RSU replacement cost) * the replaced number of PC5 RSU per year
	2022	10,945	0	
	2023	13,208	0	
	2024	19,812	2,300	
	2025	0	2,783	
	2026	0	6,444	
	2027	0	4,505	
	2028	0	7,484	
	2029	6,241	6,234	
	2030	10,945	0	
	2031	13,208	0	
	2032	19,812	0	
	2033	0	0	
	2034	0	0	
	2035	0	0	
OPEX (2021-2029)	2021	6,241	208,208	Total number of 5.8GHz RSU*5.8GHz RSU OPEX cost per unit + number of PC5 RSU * PC5 RSU OPEX cost per unit **Note: OPEX accumulates from 2021-2024**
	2022	17,086		
	2023	30,294		
	2024-2029	50,106		
OPEX (2030-2035)	2030-2035	50,106	0	Number of PC5 RSU * PC5 RSU OPEX cost per unit

6.3 The Result of Investment Evaluation on Roadside

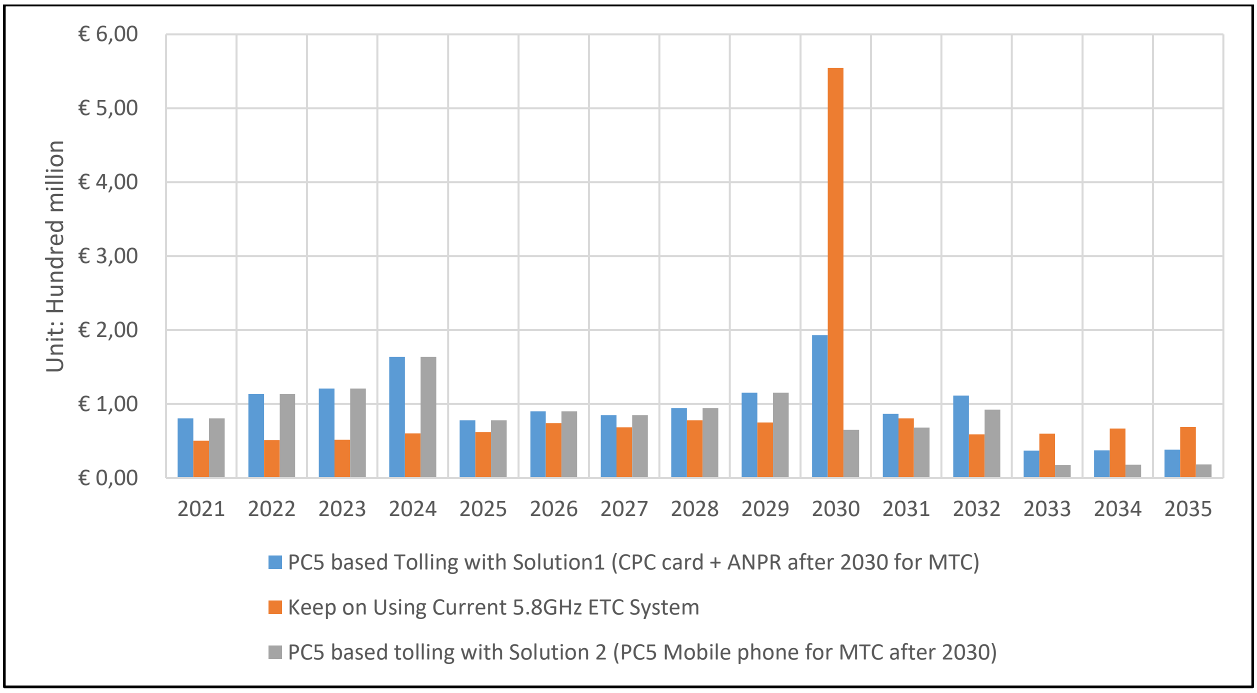
Based on Chapter 5, the investment volume of PC5 RSUs and PC5 aftermarket OBUs are respectively calculated. The results are shown in the following figures.

As shown in **Error! Reference source not found.**23, there is an investment comparison among current 5.8GHz ETC, P C5-based tolling with solution 1 (CPC card + ANPR), and PC5-based tolling with solution 2 (PC5 mobile phone). By 2035, the total investment in PC5-based tolling with either solution is lower than the total investment in 5.8GHz ETC. In the early stage, the investment in PC5-based tolling is higher due to the new deployment of PC5 RSUs at all transaction points, but starting in 2030 PC5-based tolling calls for less investment than 5.8GHz ETC, owing to the fact that the number of PC5 RSUs is lower and 5.8GHz ETC RSUs are switched off or partly switched off. Therefore, PC5-based tolling could contribute to cost-savings on infrastructure investment.

In terms of PC5-based tolling investment, it is indicated that during the period 2021-2029, the costs of PC5-based tolling with both solutions 1 and 2 are higher. On the one hand, this is because in phase O-A (2021-2024), new PC5 RSUs will be deployed in each year. On the other hand, based on the proposed roadmap, PC5 RSUs are expected to coexist with all 5.8GHz RSUs before 2030. This means that in this phase, the cost of both types of RSUs should be calculated. However, starting 2030, as 5.8GHz RSUs are switched off/partly switched off investment in PC5-based tolling would be much less demanding. Importantly, after 2029, the cost of PC5-based tolling with solution 1 is shown to be higher than the cost on PC5-based tolling with solution 2. The reason is that in solution 1, 5.8GHz RSUs would be partly switched off (5.8GHz RSUs at MTC lanes/mixed lanes would still be in operation for CPC card users), but in solution 2, all 5.8GHz RSUs would be switched off (PC5 mobile phones could be utilised for tolling). Therefore, PC5-based tolling with solution 2 could save more money compared to PC5-based tolling with solution 1:



(a)



(b)

Figure 23 Comparison of current 5.8GHz ETC, PC5-based tolling with solution 1 (CPC card + ANPR), and PC5-based tolling with solution 2 (investment on infrastructure side)

In terms of investment needed for 5.8GHz ETCs, there will be no additional deployment of new 5.8GHz RSUs. Replacement costs and OPEX are already factored into investment calculations. Therefore, the cost of 5.8GHz ETC in the period 2021-2029 would be lower than the cost of PC5-based tolling. However, in 2030, a peak in the total investment in 5.8GHz ETC would be expected, because in 2019 the Chinese government established 5.8GHz-based free-flow ETC and deployed huge numbers of 5.8GHz RSUs on ETC gantries. After a decade (the product lifespan) has passed, these 5.8GHz RSUs would need to be replaced. Therefore, in 2030, anticipated replacement costs would demand more investment in 5.8GHz ETC on the infrastructure side. In contrast, for PC5-based tolling, as 5.8GHz ETC could be switched off/partly switched off, the replacement of 5.8GHz RSUs could be avoided with corresponding savings.

7 Evaluation on Vehicle side – How to Roll Out PC5-based Tolling Application in Starting Phase

Although the infrastructure could be ready within the next three years (for tolling applications), there needs to be valuable use cases and enough users to support the rollout of a PC5-based tolling system.

On the user/vehicle side, the starting phase is the most complex. In this section of the study we discuss how to roll out the PC5-based tolling application in vehicles for each of the phases, especially in the starting Phase 'O-A'. The study also looks into what the possible use cases for PC5-based tolling are, and how to create market value in the short term in order to roll out PC5 tolling applications.

7.1 Phase O-A: Proposed Rollout for PC5 Tolling Application, Province by Province

The first step is always difficult, especially as in 2019 when the Chinese government invested heavily in building ETC infrastructure. This section is based on a study of the Chinese policy behind this, and on the concrete challenges/developments observed in the transportation sector. The aim is to analyse what kind of vehicles and which regions could implement C-V2X dedicated PC5-based tolling solutions, and to explore the motivations and benefits.

The following questions were addressed during the study:

- In which regions might PC5 RSUs first be deployed?
- What types of vehicles might be equipped with PC5 OBUs first?
- What industries might PC5-based tolling promote?
- What problems could PC5-based tolling solve for various types of equipped vehicles?
- What additional benefits could PC5-based tolling bring to relevant stakeholders?
- How might the number of PC5 RSUs and OBUs change over time?

To answer these questions, 5GAA and Tongji University conducted an analysis based on relevant policies, and predicted that PC5-based tolling could be firstly applied in the following provinces and on the following vehicles.

The first provinces to deploy PC5 RSU:

1) Jiangsu, 2) Zhejiang, 3) Guangdong, 4) Jiangxi, 5) Hebei

The first vehicles to deploy PC5 OBU:

1) New alternative energy vehicle (new AEVs),

2) Ride-sharing vehicles (including taxis),

3) Truck,

4) Liang Ke Yi Wei (LKYW)

Proposed deployment plan (for infrastructure and vehicles):

Table 16 Proposed priority provinces to roll out PC5-based tolling infrastructure

Year	RSU cover all tolling transactions point
2021	Jiangsu, Zhejiang
2022	Guangdong, Hebei, Jiangxi
2023	Remaining provinces

7.2 Phase O-A1: Starting PC5 Tolling Application in Top Priority Provinces for Special Vehicles

In phase 0-A1, PC5-based tolling would be first deployed in certain provinces. In 2018, the Chinese government started the 'pilot programme for intelligent expressways'[18] covering nine provinces and focusing on:

i) construction of C-V2X-based infrastructure on expressways,
ii) development of connected vehicle technology, and
iii) development of new technical solutions for tolling without changing current systems.

Both C-V2X technology and new tolling solutions were proposed and the central government also pointed out that Guangdong, Jiangxi and Hebei should mainly focus on exploring new tolling solutions and improving the current tolling technology. In response to this policy, Guangdong, Jiangxi and Hebei provinces invested time and energy into the issue of tolling. In addition, Jiangsu-Zhejiang provinces issued detailed documents [19][20] in which the development of a new tolling solutions is mentioned. These provinces thus have related **key objectives for tolling**:

1) Create new technologies, including but not limited to C-V2X, with Beidou integral to new tolling solutions and developments.
2) Implement free-flow tolling at expressway entry and exit points.
3) Develop more effective enforcement controls.

Based on the pilot programme proposed by the central government and the development plan for tolling, Jiangxi, Guangdong, Hebei, Jiangsu, and Zhejiang are the most likely provinces to pioneer PC5 tolling RSUs.

In these provinces, new AEVs, ride-sharing operators, trucks, and LKYW would be first vehicle types to be equipped with PC5 OBU. This assumption is explained and described in the following subsection.

7.3 Proposed Use Cases and PC5 Vehicles

7.3.1 Case 1: Alternative energy vehicle

1) Current Challenge:
As the abovementioned transportation policy describes, Chinese road operators believe that expressways could attract more vehicles, especially AEVs with dynamic tolling, because of the existing discounts and subsidies for these. From an operational perspective, they could also boost the traffic load to increase toll revenue, and finally achieve the goal of promoting more 'green and efficient transport'. However, the policies which could support dynamic tolling for AEVs are few. The reason is that there are still very few charging stations on expressways, and that many are occupied or obstructed by fossil fuel-consuming vehicles. According to statistics, 35.94% of charging parking lots are occupied and 20.65% of charging stations are non-functional[22]. The new AEV drivers could not travel on expressways until this problem is solved.

Notes: AEVs include all-electric, plug-in hybrid, and hydrogen fuel-cell vehicles.

2) Policy:
新能源汽车产业发展规划（2021-2035）(Development Plan for Alternative Energy Vehicle Industry)[21]

Key information: Technology for intelligent and connected vehicles to be applied to AEVs first. Technology and products for C-V2X to be further promoted and applied.

Analysis: It means that AEVs would be the first equipped with PC5 OBUs, as supported by government policies. C-V2X OBUs would be line-fitted on all newly-manufactured AEVs. For existing AEVs, it is suggested that if new AEV users purchase aftermarket PC5 OBUs, the government could provide subsidies, and therefore new AEV users could enjoy discounts for the purchase of a PC5 OBU.

Source: http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm

3) Application scenario:
i) PC5 parking lot barriers are deployed at charging points, AEVs could use PC5 to communicate with the parking lot. After a PC5-powered new AEV is authenticated, the parking lot barrier would open and the vehicle could park there to charge. This solution could prevent other vehicle types from occupying the designated charging spots.

ii) PC5 OBUs could send vehicle status (speed, path, remaining power etc.) to a RSU. The RSU could broadcast speed advice and recommend suitable charging points to a PC5 OBU (ITS service). It could help vehicles drive in an ecological way and remove concerns about running out of charge along the expressway.

4) Travel range:
AEVs drive within the province.

5) Benefits:

Stakeholder	Benefits
Government	• Develop dynamic tolling for AEVs • Improve the AEV industry • Achieve 'green and efficient transport' goals proposed in[7]
Road operator	• Increase toll revenue due to more AEVs driving on expressways • Reduce congestion at entrances/exits • Enhance enforcement control and prevent toll evasion (Section 4.3.1) • ITS management
New AEV owner	• Enjoy lower tolls on expressways due to dynamic tolling • Enjoy discounts on the purchase of aftermarket PC5 OBUs • Enjoy better charging services • First to enjoy free-flow tolling at entrances/exits • Reduce charging cost via driving in an ecological way (eco-speed advice from RSU)

6) Additional capacity for PC5 OBU

Product type:

- Line-fitted (T-Box): for newly manufactured AEVs
- Aftermarket (intelligent rear-view mirror): for existing AEVs

Function:
- Manoeuvre coordination service: RSU sends eco-speed, and advice on charging point to vehicles
- Record and upload battery status
- Conduct vehicle authentication at charging stations

7.3.2 Case 2: Ride-sharing Vehicles and Taxis

1) Current Challenge:

Tolling:

i) Toll via ETC is not recorded in billing systems and cannot be displayed on a taximeter, thus the passenger and the driver could disagree over a taxi fare.

ii) If the ride-sharing vehicle driver uses ETC, the toll receipt could not be issued and a passenger's demand for reimbursement could not be satisfied.

These problems have hindered the penetration of ETC in ride-sharing vehicles/taxis.

Security concerns:

In recent years, there have been reported crimes related to online ride-sharing vehicles. Passengers have been murdered by ride-sharing vehicle drivers[23]. These incidents indicate that there is a security problem that needs addressing in the operation and management of online ride-sharing vehicles in China.

2) Policy:

i) 关于深化改革推进出租汽车行业健康发展的指导意见 (Guide for Reforming and Promoting Healthy Development of Taxi Industry)[24]

Key information: Ride-sharing vehicle companies to use connected technology to enhance supervision over the operation of ride-sharing vehicle. In addition, the accuracy of billing is guaranteed.

Source: http://www.gov.cn/zhengce/content/2016-07/28/content_5095567.htm

ii) 网络预约出租汽车监管信息交互平台运行管理办法 (Operation and Management Measures for Supervision Platform of Online Ride-sharing Vehicle Information)[25]

Key information: The ride-sharing vehicle company to ensure the quality of data transmitted from operating the vehicle, including data integrity, standardisation, and authenticity.

Source: http://www.gov.cn/zhengce/zhengceku/2020-01/15/content_5469168.htm

Analysis: These policies propose requirements for ride-sharing vehicle operation. One is that ride-sharing vehicle companies enhance the supervision of drivers operating vehicles. The other is that the tolls of ride-sharing vehicles be accurately calculated, and accessible/open to passengers.

3) Operational requirement of relevant company:

Didi is the largest company in the ride-sharing industry in China, they require drivers to purchase and install its self-developed dashcam for €76 [26]. Other ride-sharing vehicle companies do not have such supervision requirements. This means that aftermarket PC5 OBUs have a large potential market in ride-sharing vehicles.

Figure 24 Dashcam developed by Didi

4) Application scenario:

i) PC5 OBU could be connected to the taxi billing system, thus taxi fares and tolls could be settled together. The toll could also be displayed on the screen of the PC5 OBU, and any potential disputes over bills eliminated. In addition, PC5 OBU could issue electronic receipts to meet passenger's demand for reimbursement. This application scenario of PC5-based tolling could help ride-sharing vehicles solve the problems faced with 5.8GHz ETCs.

ii) PC5 OBUs could connect to in-car monitoring, OBD, and dashcams. PC5 could send real-time vehicle status (geolocation), and driver condition to the backhaul system. Based on this data, a traffic management platform could monitor the ride-sharing vehicle in real time. PC5 OBUs could also have an emergency alarm function, and in case of emergency, the driver or passenger could send a distress signal via the PC5 OBU.

5) Travel range:
Ride-sharing vehicle drives within provinces.

6) Benefits:

Stakeholder	Benefits
Government	• Encourage ride-sharing vehicle drivers to purchase AEVs equipped with a PC5 OBU. • Commercial vehicles become among the first to use intelligent and connected driving systems [14]. • Promote the AEV industry and dynamic tolling.
Road operator	• Improve traffic efficiency at entrances/exits due to more ride-sharing vehicles equipped with PC5 OBU (thus no longer using MTC). • Accurately record the driving path of ride-sharing vehicles, and prevent the driver increasing fares by taking detours.
Drivers and passengers	• Avoid disputes between the driver and passenger based on the payment of a toll. • Improve users' experience thanks to free-flow tolling at entrances/exits. • Improve the security via C-V2X certification and applications by service provider. • If ride-sharing vehicle is an AEV, the owner could enjoy additional benefits.

7) Additional capacity for PC5 OBU:

Product type

- Line-fitted (T-Box): for newly manufactured AEV ride-sharing vehicles
- Aftermarket (intelligent rear-view mirror): for existing AEV ride-sharing vehicles

Function

- Connected to the dashcam for uploading real-time vehicle and driver status to the traffic management platform.
- Connected to the taximeter for calculating taxi fares and tolls.
- Display driving path and taxi fare in real-time via visual interface.

7.3.3 Case 3: Trucks

1) Current Challenge:

Trucks are the main cause of congestion at the entrance/exit to expressways. In the following figures we provide some relevant data on certain entrances/exits of tolling plazas. While there are fewer trucks than passenger vehicles at the plazas, trucks take longer and spend more time en route which translates into a greater negative impact on traffic efficiency especially at the entrance/exit to expressways.

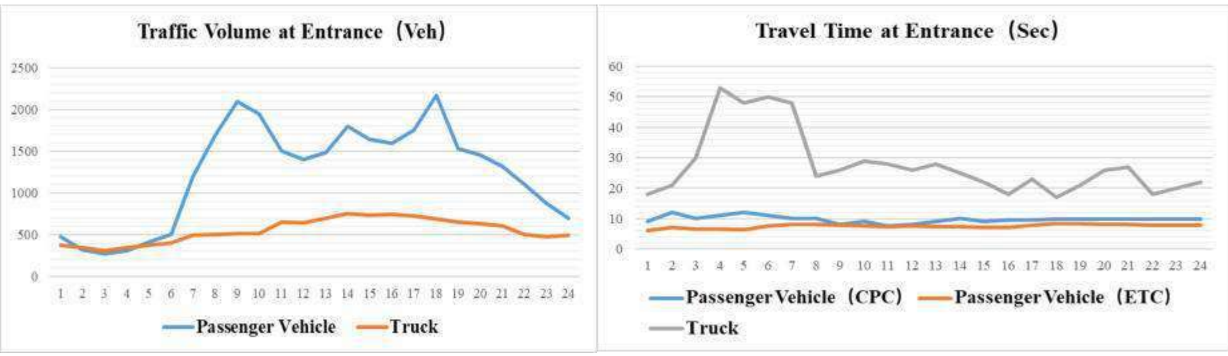


Figure 25 Traffic volume and travel time at certain entrance of the expressway

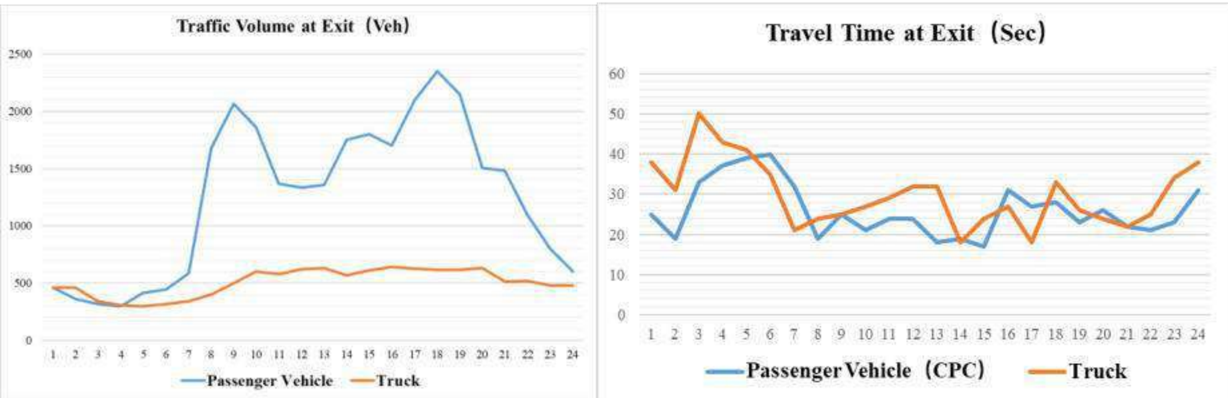


Figure 26 Traffic volume and travel time at certain exit of the expressway

The reasons why trucks could cause severe congestion at entrances/exits are listed below:

i) Starting January 2020, the toll for trucks has been calculated with its axle dimensions and weight, so all trucks must be weighed at the entrance of the expressway. For the overweight trucks, it is not allowed to enter the expressway. This weighing of trucks at the entrance causes severe congestion.

Figure 27 Truck weighing at entrance to expressway

The speed limit of weigh-in-motion facilities is only 5km/h. This means that most trucks have to pass through the machine at a very low speed. Also, this weighing is not very accurate, and trucks sometimes have to be weighed again. Repeated weighing could further impact traffic efficiency and cause congestion.

ii) The ETC penetration rate for trucks is low. By the end of 2020, 53% were equipped with ETC OBUs in China[27]. In Jiangsu province, only 22.5% trucks were equipped with ETC OBU[28]. The low ETC penetration rate in trucks means that most truck drivers still pay a toll via MTC. This leads to inefficient flows at the expressway exits.

Truck driver safety issues are also a major concern in China. Traffic incidents involving trucks account for 80% of the total number of accidents [29]. High accident rates are also a huge burden on logistics companies. Therefore, new technologies can be used to radically improve safety issues involving trucks.

2) Policy:

深化收费公路制度改革取消高速公路省界收费站实施方案 (Implementation Plan for Deepening the Reform of Toll Road and Removing Provincial Tolling Plaza)[30]

Key information: Dynamic tolling promoted to guide traffic, reduce congestion and further improve traffic efficiency. The charge to trucks to remain the same.

Source: http://www.gov.cn/zhengce/content/2019-05/21/content_5393377.htm

In addition, in May 2020, the MOT held a forum in Henan province. At the forum, it proposed that dynamic tolling should be promoted for trucks, something that could lead to reduced freight logistics costs and improved road network efficiency.

Analysis: The government's main targets are i) the promotion of dynamic tolling; ii) the reduction of freight logistics costs/tolls for trucks; iii) the improvement of road network efficiency. This means the congestion at entrances/exits caused by trucks needs to be tackled, and their operating costs need to be reduced through smarter tolling thanks to wider ETC penetration in the sector.

3) Application scenarios:

i) Pre-weighing: Additional weighing machines could be deployed at on-ramp or rest areas. Trucks equipped with PC5 OBUs could send their geolocation and actual weight to the traffic management platform. According to a real-time queue at each weighing point, platforms could send an advised weighing point to the truck via an RSU. At the weighing point, the system could compare the weight with the one recorded by the PC5 OBU. This measure could not only determine whether the truck is overweight, but also improve the accuracy of weighing (comparison between the weight recorded by the PC5 OBU and the one measured by the weighing machine). If the truck completes the weighing at the pre-weighing point, it could enter the expressway through the dedicated PC5 lane and the traffic efficiency would be greatly improved.

Currently, 5.8GHZ ETC OBUs cannot carry out this pre-weighing operation. This is because 5.8GHz ETC OBUs only record the scheduled weight of the truck and cannot record the actual weight. In addition, 5.8GHz ETC OBUs cannot have manoeuvre coordinated services. However, in these aspects, PC5 would bring great advantages.

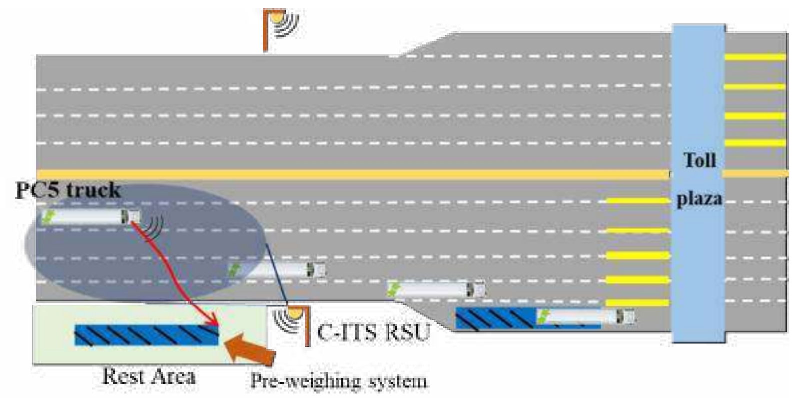


Figure 28 Pre-weighing scenario

ii) PC5 OBU could be connected with in-car monitoring. The OBU could send real-time driver status updates to traffic management platforms. According to the driver's status, the platform could determine whether the driver has fatigue and could send him/her an alarm or warning. This measure could effectively help prevent traffic accidents caused by trucks.

4) Travel range:
Trucks travelling within the pilot provinces could use PC5 OBU.

Trucks travelling across the provinces would continue using 5.8GHz ETC or MTC.

5) Benefits:

Stakeholder	Benefits
Government	• Achieve dynamic tolling in trucks (provide toll discount for PC5 trucks) • Enhance the development of intelligent trucks • Reduce freight logistics cost (improve efficiency and safety) • Increase the traffic efficiency of the road network • Commercial vehicles become the first to be intelligent and connected [14]
Road operator	• Increase ETC penetration rate in trucks • Reduce congestion at entrances/exits • Increase toll revenue due to improved traffic efficiency • Reduce traffic accidents • Solve tolling-related problems (see Section 2.2.4)
Truck owner	• Reduce operating costs from tolling, safety etc. • Improve transport efficiency • Improve safety • Save travel time

6) Additional capacity for PC5 OBU:
Product type

- Line-fitted (T-Box): For newly manufactured trucks
- Aftermarket (intelligent rear-view mirror): For existing trucks

Function

- Manoeuvre coordination service: RSU sends speed advice, toll lane, and the geolocation of the weighing point to the truck
- Integrate the on-board weighing system and read real weight
- Connect to in-car monitoring/dashcam for recording vehicle and driver status

Lastly, the government has high requirements for the supervision of LKYW.

Since 2011, it has proposed that these vehicles must be equipped with an OEM on-board positioning system[31]. Nowadays, in addition to the positioning system, most LKYWs are equipped with in-car monitoring systems and dashcams. However, these devices cannot achieve real-time supervision of the vehicle status. This shortcoming could be overcome by PC5. PC5 could send real-time vehicle status to a traffic management platform. In addition, the government also proposed that commercial vehicles should be the first to be equipped with intelligent and connected driving systems. Therefore, based on this requirement, it is predicted that LKYW could be first to be equipped with PC5. Newly manufactured vehicles could be equipped with a PC5 T-Box. For existing vehicles, the on-board devices could be integrated with PC5 modules and augmented functions.

7.4 Calculation of Total Investment on Vehicle Side in Starting Phase

The investment on the vehicle side falls upon each vehicle owner. This value depends on the payback period. The detailed formulation is shown as follow:

Total investment= $CAPEX_t + OPEX_t + OPEX_{(t+1)} + \cdots + OPEX_{(t+i)}$ (i=payback period)

Based on the investment volume calculated by this formula, the vehicle owner decides the best time when he/she could purchase a PC5 OBU and how much to spend on it in order to enjoy more ITS services and PC5-based tolling.

KPI Cost

Regarding the PC5 line-fitted OBU, the product type is a T-Box. The visual interface, speaker and any other porters on the T-Box could be reused. The additional devices for tolling are listed in the following table.

Table 17 CAPEX and OPEX of PC5 line-fitted OBU

CAPEX (one-off cost)	PC5	Annual growth	Source
T-Box equipment	￥200/€25		Consult
Communication module (4G + PC5)	￥350/€45		Consult
GNSS module	￥750/€96		Consult
MPU	￥300/€38		Consult
Additional MCU	￥30/€4		Consult
Memory module	￥20/€3		Consult
Security module	￥200/€25		Consult
PC5 antenna	￥25/€3		Chinese market data[57]
GNSS antenna	￥15/€2		Chinese market data[57]
Various physical porter	￥25/€3		Chinese market data[57]
Security access module for tolling	￥50/€6		Chinese market data[57]
CAN connector	￥12/€1.5		Chinese market data[57]
CAN chip	￥10/€1.2		Chinese market data[57]
CAN-capable control unit	￥6/€0.8		Chinese market data[57]
Total CAPEX	￥1993/€253	-2%	[58]
OPEX (annual cost)	PC5	Annual Growth	Source
Power consumption	￥24/€3	+2%	Chinese market data[57] Annual growth rate is from [46]
Maintenance cost	￥100/€13	+2%	5% of total CAPEX[58]
OTA cost	￥24/€3	-2%	[58]
Total OPEX	￥148/€19		

For the PC5 aftermarket OBU, the product type is an intelligent rear-view mirror, this is an aftermarket on-board product integrated with an android system. Its functions include in-car monitoring, GPS positioning, over speed warning, entertainment, Bluetooth hands-free phone, and support for third-party software. The cost KPIs of this product are listed in the following table.

Figure 29 Intelligent rea-view mirror

For vehicles equipped with a dashcam (like ride-sharing vehicle, truck, "LKYW"), they could repeat the installation of the following devices. For vehicles without a dashcam, the following devices could cover the function of the dashcam, but the devices shall be integrated with the monitoring platform.

Table 18 CAPEX and OPEX of Aftermarket PC5 OBU (Intelligent rear-view mirror)

CAPEX (one-off cost)	PC5	Lifespan (years)	Annual growth	Source
Proposed product type: Integrated intelligent rear-view mirror **Including key component** • **GNSS module/antenna** • **CPU** • **Dashcam** • **Visual interface** • **Speaker** • **Memory module** • **Power supply** • **Bluetooth**	¥1500/€190	5		Chinese market data[57]
Communication module (4G+PC5)	¥350/€45	5		Consult
Security module	¥200/€25	5		Consult
PC5 Antenna	¥25/€3	5		Chinese market data[57]
Various physical porter	¥25/€3	5		Chinese market data[57]
Security access module for tolling	¥50/€6	5		Chinese market data[57]
Total CAPEX	¥2150/€272	5	-2%	[58]
OPEX (annual cost)	**PC5**	**Lifespan (years)**	**Annual growth**	**Source**
Power consumption	¥24 /€3	N/A	+2%	Chinese market data[57] Annual growth rate is from[46]
Maintenance cost	¥108/€14	N/A	+2%	5% of total CAPEX[58]
OTA cost	¥24 /€3	N/A	-2%	[58]
Total OPEX	¥156 /€20			
Replacement cost	¥430/€54	5	-2%	20% of total CAPEX[56]

7.5 The Invest-and-Return in Different Payback Options for Starting Phase (0-A)

The following figure shows the investment volume on the vehicle side. This result could help the vehicle owner to decide the best time to purchase a PC5 OBU.

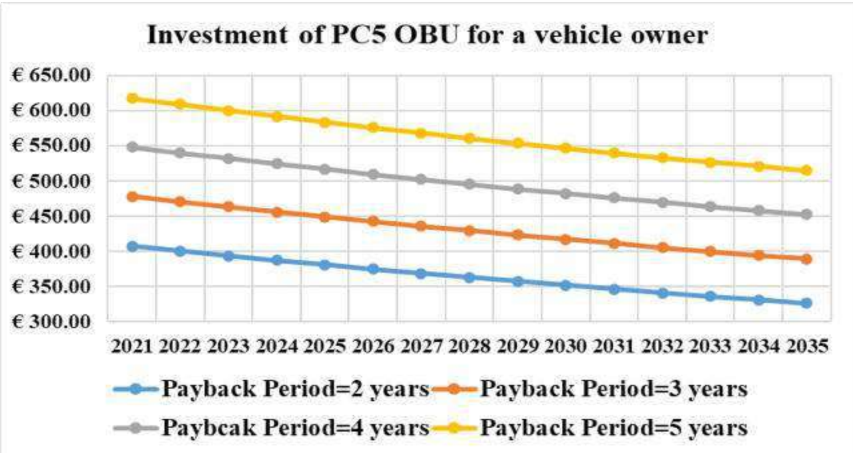


Figure 30 Total Cost of PC5 Aftermarket OBU per Vehicle

This describes the total cost of PC5 aftermarket OBUs for the proposed vehicle types:

1) As the PC5 market grows, the cost would keep reducing
2) The longer the payback period, the more OPEX costs
3) The early adopters will pay the highest CAPEX and OPEX cost. For the pay-back model we therefore only take into account the cost of the first-round PC5 users as a reference.

The cost change curve of the PC5 aftermarket OBU could help vehicle owners make a reasonable decision on investment. Furthermore, the Chinese government could refer to the cost curve for the development of discounts or dynamic tolling policies.

Therefore, the government and vehicle owners could take into account the short payback period, and thus vehicle owners spend less on PC5 OBUs and fewer discounts would be needed. However, when the government establishes a discount, the investment of the first/early PC5 users should be considered because they bore the highest cost.

After calculating investment volume, according to the proposed evaluation scheme, the next step is to analyse the benefits brought by PC5-based tolling on a quantitative level. Among these benefits, calculation of dynamic tolling/discount is then based on:

- CAPEX+OPEX-Benefits<0
- Payback period=2,3,4,5 years
- The mileage of different types of vehicles

CAPEX+OPEX-Benefit<0 is the basis for calculating the dynamic tolling/discount. To encourage first/early PC5 users, the benefit from dynamic tolling/discounts should ideally be the maximum value of the PC5 OBU investment. In addition, the benefit differs according to the different payback periods. Most importantly, the mileage of different types of vehicles could influence the discount developed by the Chinese government (i.e. favouring PC5 users with lower mileage). Therefore, the mileage factor is introduced to ensure that PC5 users with lower mileage could also enjoy dynamic tolling discounts developed by the government.

There are other additional benefits brought by PC5-based tolling, including the use of ITS Day 1 services, manoeuvre coordination services, and subsidies on new vehicle purchases. These benefits should also be considered.

All these benefits have been summarised in the following table, which could help the Chinese government develop new relevant policies for PC5-based tolling:

Table 19 Benefits brought by PC5-based tolling

Vehicle type: Mileage per year :	AEVs 18,000km/year	Ride-sharing vehicles 75,000km/year	Trucks 100,000km/year	LKYW 100,000km/year
Mileage factor	8	4	1	1
Saving from dynamic tolling or discount **(per kilometre)** **Saving=maximum investment/mileage *mileage factor**	• ￥1.4/€0.18 (payback period=2 years) • ￥1.7/€0.21 (payback period =3 years) • ￥1.9/€0.24 (payback period=4 years) • ￥2.2/€0.27 (payback period=5 years)	• ￥0.74/€0.09 (payback period=2 years) • ￥0.86/€0.11 (payback period =3 years) • ￥0.96/€0.12 (payback period=4 years) • ￥1.1/€0.14 (payback period=5 years)	• ￥0.18/€0.023 (payback period=2 years) • ￥0.21/€0.027 (payback period =3 years) • ￥0.24/€0.03 (payback period=4 years) • ￥0.27/€0.034 (payback period=5 years)	• ￥0.18/€0.023 (payback period=2 years) • ￥0.21/€0.027 (payback period =3 years) • ￥0.24/€0.03 (payback period=4 years) • ￥0.27/€0.034 (payback period=5 years)
Additional benefits from ITS Day1 service (avoidable insurance cost) **This benefit is not calculated in the investment analysis**	￥4,000/€520 [60]	￥4,000/€520 [60]	￥70,000/€9,000 [29]	￥70,000/€9,000 [29]
Benefits from ITS manoeuvre coordination services **This benefit is not calculated in the investment analysis**	Speed: +16%~+62% Travel time: -13%~-48% at tolling plaza Throughput: +8%~+25% Emission: -1.5%~-33% [61][62]	Speed: +16%~+62% Travel time: -13%~-48% at tolling plaza Throughput: +8%~+25% Emission: -1.5%~-33% [61][62]	Speed: +16%~+62% Travel time: -13%~-48% at tolling plaza Throughput: +8%~+25% Emission: -6%~-55% [61][62]	Speed: +16%~+62% Travel time: -13%~-48% at tolling plaza Throughput: +8%~+25% Emission: -6%~-55% [61][62]
Subsidy by Chinese government to encourage PC5 vehicle sales **(per vehicle)** **Note: It is the general subsidy for AEV (the percent of the subsidy could to be used for PC5 is not defined)** **This subsidy is not calculated in the investment analysis**	￥18,000/€2,300 (2021) ￥13,000/€1,600 (2022) [59]	N/A	N/A	N/A

The quantified benefits are mainly divided into three categories: i) Tolling; ii) ITS services; iii) Subsidies for purchasing new vehicles. Among these, the benefits from ITS services, such as ITS Day 1 services and manoeuvre coordination services, not only refer to cost saving, but also include quantified benefits related to speed improvement, emission reduction, travel time saving and so on. Regarding subsidies for purchasing new vehicles, the Chinese Government has released relevant policies and proposed subsidies for AEVs, but this subsidy would gradually decline year by year (-10% in 2020, -20% in 2021, -30% in 2022). In terms of saving from dynamic tolling, this benefit would change over the payback period. It is a reference for the Chinese Government to develop relevant polices on dynamic tolling (adjusting tolling to various types of vehicles at different road segments or at different times). Dynamic tolling could improve traffic efficiency, and help achieve the objective proposed in [7]. Additionally, dynamic tolling could reduce the costs at expressways, and encourage more people to purchase PC5 tolling devices.

In summary, these benefits could help PC5 users reduce the toll and enjoy useful ITS services. On top of that, the benefits brought by PC5-based tolling could improve traffic efficiency, enhance safety and reduce emissions. **It is indeed greatly beneficial for the development of sustainable transport in China**.

8 Vision for Vehicle: How to Leverage C-V2X Direct Communication Technology in the Automotive Industry

After the introduction of the starting phase, another question arises: If we want to set in motion a real evolution for tolling technology, how could the new technology largely and widely be used so that we could close most ETC systems after their lifecycle is over (in 2030)?

For this question, it is difficult to propose an intuitive analysis in terms of cost perspectives. It reflects a problem with industrial-chain maturity. So, how should the penetration rate of PC5 OBUs evolve in order to ensure that PC5 applications become widespread in vehicles? (**Here, we assume that an 80% penetration rate by 2030 should be the minimum value to ensure enough PC5 terminal coverage on the vehicle side**).

This analysis will be divided into three main steps, as the figure shows below:

Figure 31 Three steps for PC5 OBU estimation

In the future, we hope the forecasted penetration growth could be used as a key reference for future PC5-based C-V2X industrial-chain developments, also as a guideline for C-V2X stakeholders (especially policy-makers) and their investment plans.

8.1 The Product Form of PC5 OBU

Before forecasting PC5 OBU deployment, the OBU type should first be defined. For line-fitted OBUs, there is no need to discuss them because the performance of the on-board unit is normally high enough, but for aftermarket OBUs there will be various solutions on the market.

To simplify the analysis model, in this study we will select only one type PC5 OBU and consider it as the most relevant aftermarket solution for the forecasting work. For that, we need to first understand what the most popular features are for future OBUs. In the following table we list the most relevant applications for future vehicles, and the most popular functions.

Table 20 Most popular applications for vehicles in next 10 years

Capacity/application	Most popular function
C-ITS (V2X)	Safety driving perspective
Enhance AD (V2X)	Collective perception
Tolling	Dynamic tolling
Dash Cam	Video record
Autonomous driving (AI computing)	1) For line-fitted product: support diverse AD function 2) For aftermarket product: support few easy ADAS function like lane departure warning
Comfortable driving functions, such as parking camera	1) For Line-fitted product: as market trends 2) For aftermarket product: some advanced OBUs support certain retrofit work, such as smart rear-view mirror
Navigation	Online service, HD MAP, local dynamic map information
Infotainment	Integrated with virtual assistant, such as Siri, Alexa, and Car-play

We have listed the most popular features in the following table (from a communication perspective). This is the same idea as the proposed use cases in the previous chapter. Here, we think the advanced rear-view mirror dash cam is the best candidate.

Table 21 the possible Products support future functions

Market Oriented:	Feature								
	Voluntary Approach	Regulatory Measures	Governmental Action	Voluntary Approach	Hope: Governmental Action	Voluntary Approach	Voluntary Approach	Voluntary Approach	Voluntary Approach
Possible Technology in Product	Dash Cam	Basic Tolling	ITS Day1 (safety)	Advanced ITS Service (ISAD), V2X Perception	Tolling + C-ITS	simple retrofitted ADAS function (Lane Departure warning)	Retrofitted comfortable Drivign: Parking Camera	HD MAP, Dynamic map (integrated with Navi)	Infortaiment with virtual assistant (integrate with Mobile Phone)
line-fitted PC5 OBU + Board Computer									
smart dash CAM (smart Rear view mirror) - with PC5									
PC5 Mobile Phone User									

Meet most requirements | Support part of function | Doesn't support this feature

About PC5 mobile phone and portable PC5 devices:

PC5 mobile phones and portable PC5 devices are also very important OBU types, and could enable higher penetration of PC5 in the future. To achieve this tolling function with software application is quite easy. But because the maturity of PC5 mobile phones is currently not high enough and difficult to forecast, **mobile phone distribution (amount) is not therefore include in the final calculation.**

8.2 Forecast of PC5 Vehicle Growth to Achieve Sufficient Penetration for Tolling and C-V2X Applications

8.2.1 The Mathematical Model for the Forecast

Purpose:

For a better description of the vision on how to deploy C-V2X direct communication technology (PC5), we try to incorporate the most relevant parameters in the 'group function' in order to build a representative mathematical model for the annual penetration rate over the next ten years.

Forecasted penetration of from 2021-2030												
	Penetration of both type of PC5 OBU	Year (y)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		Percentation of PC5 OBU in each catatory in (y) year	Starting Phase									
1	a (y) line-fitted PC5 OBU	$a(y) = \frac{annual\ sales\ of\ PC5\ Vehicle\ (new\ line fitted\ PC5\ OBU)}{annual\ sales\ of\ vehicle}$	a2021	a2022	a2023	a2024	a2025	a2026	a2027	a2028	a2029	a2030
2	b (y) PC5 smart dash CAM (smart Rear view mirro)	$b(y) = \frac{Total\ new\ increased\ aftermarket\ PC5\ OBU)}{the\ total\ vehicle\ with\ any\ PC5\ OBU\ in\ (y)\ year}$	b2021	b2022	b2023	b2024	b2025	b2026	b2027	b2028	b2029	b2030

Figure 32 Nationwide PC5 OBU penetration rate a(y) and b(y) for annual PC5 vehicle growth and annual increased PC5 aftermarket OBUs

Because the starting phase presents only a regional forecast of PC5 tolling deployment, it uses as(y) and bs(y) to describe the percentage of PC5 OBUs.

Table 22 The Parameter and its formula for PC5 OBU penetration rate estimation analysis

Parameter	Definition	Database or formula
a (2021-2023) **a(y)**	Penetration rate of line-fitted PC5 OBU in starting phase	$$a(y) = \frac{annual\ sales\ of\ PC5\ Vehicle\ (new\ linefitted\ PC5\ OBU)\ in\ pilot\ provinces}{annual\ sales\ of\ vehicle\ (nationwide)}$$ $$\text{annual sales of PC5 Vehicle in pilot province} = \text{as(y)} \cdot \text{total number of 4type vehicle in pilot provinces}$$ as(y): The percentage of vehicle, which is newly equipped with line-fitted PC5 OBU in proposed 4types vehicles in year XXXX in pilot provinces
b (2021-2023) **b(y)**	Penetration rate of aftermarket PC5 OBU in starting phase	$$b(y) = \frac{annual\ increased\ PC5\ smart\ rear\ view\ mirror\ in\ pilot\ provinces}{Total\ vehicle\ without\ PC5\ linefitted\ OBU\ (national\ wide)}$$ $$annual\ increased\ PC5\ smart\ rearview\ mirror\ in\ pilot\ provinces = bs(y) \cdot total\ number\ of\ 4type\ vehicle\ in\ pilot\ provinces$$ bs(y): The percentage of vehicle, which is newly equipped with aftermarket PC5 OBU (for 4types vehicle) in year （y） in pilot province
V (year)	Total number of vehicles in China	Statistic data, estimated data
N (year)	Annual sales vehicle	Statistic data, data from strategic plan, estimated data
Npc5 (year)	the Number of new vehicle with line-fitted PC5 OBU in year (y)	Estimated/forecasted data $$\text{Npc5}(y) = \text{N(y)} \cdot \text{a(y)}$$
Sum Npc5	Sum of PC5 line-fitted vehicle from 2021-2023	$$\text{sum Npc5} = \sum_{2021}^{2030} Npc5(y)$$
DC (year)	Total number of vehicle without line-fitted PC5 OBU = Total Potential user of smart rear-view mirror	**1. Assumption: the total number of dash cams and vehicles has approximately equal value in 2020.** Reason: The annual sales of dash cams **in 2020** is nearly RMB55.92 billion. There are different prices for dash cams on the market. According to 2019 figures, the cheapest model (under RMB500) dominated market. We take the **average level TMB200** as a reference for the single price, when the 2020 total sales are divided by the single price (RMB200), we could get the **rough total number of dash cams in 2020: RMB2.796 billion**, and with vehicle numbers in 2021 at nearly 2.92 billion. Considering that some people still use the old dash cam, **we could assume that the total number of dash cams and vehicles is approximately equal in 2020.** ➔ It means, every vehicle has been equipped with one dash cam in 2021. **2. Formula** $$\text{DC}(y) = \text{V(y)} - \sum_{2020}^{2030}(new\ increased\ linefitted\ PC5\ Vehicle) = V(y) - \sum_{2020}^{2030}(annual\ increased\ Vehicle \cdot linefitted\ PC5\ OBU\ peneration\ in\ new\ vehicle) = V(y) - \sum_{2020}^{2030}[N(y) \cdot a(y)]$$

		For example: $D(2021) = V(2021) - N(2021) \cdot a(2021)$ $D\ (2022) = V(2022) - N(2022) \cdot a(2022) - N(2021) \cdot a(2021)$ Reason: 1. We have the total number of vehicles in each year, and the total number of annual sales (increased new vehicles). But the total number of scrapped cars is still missing. 2. Therefore the total number of vehicles without PC5 OBUs: total number of vehicles in 202X minus all the PC5 line-fitted vehicles in past years.
DCpc5 (year)	The number of the vehicles newly equipped with aftermarket PC5 OBU in year XXXX	$DCpc5(y) = DC(y) \cdot b(y)$
Sum DCpc5	Sum of aftermarket	$\text{sum DCpc5} = \sum_{2021}^{2030} DCpc5(y)$

8.2.2 Data Used in the Mathematical Model

The mathematical model is based on:

1) The proposed/hypothetical value of each factor in the previous chapter (especially on the description in starting phase).

2) Market data, such as statistics, Historical data, and calculated data: total vehicle volume, new vehicle sales volume and dash cam sales volume.

This section lists all the relevant data used for this mathematical model.

In the following analysis, various market data from 2020-2030 is needed for the calculation work, but we it is incomplete. Missing information includes:

1) The annual sales in next ten years (certain data is not available)
2) Target sales in 2025 from the published strategic plan by the Chinese Association of Automobile Manufacturers has been used as reference value only for analysis
3) The annual sales value in other years could only be estimated from Historical data (2015-2020), giving a reference value based on linear prediction

In the database, the character/type of every data value is indicated/marked. Thus, the total number of vehicles in China in each year can be estimated.

Table 23 Total number of vehicles in China each year

Factor	Value type	Source	Value	Source link
V (2019)	Historical data	Ministry of Public Security and sorted by Huajing institute	260 000 000	https://baijiahao.baidu.com/s?id=1657492529228702682&wfr=spider&for=pc
V (2020)	historical data	Ministry of Public Security and sorted by Huajing institute	281 000 000	https://baijiahao.baidu.com/s?id=1672183541693587443&wfr=spider&for=pc
V (2021)	forecasted data	Ministry of Public Security	292 000 000	https://baijiahao.baidu.com/s?id=1704534501347285163&wfr=spider&for=pc
V (2030)	forecasted data	Speech of Wangqing (State Council Development Research Centre)	430 000 000	
V (2022)	estimated data		304 830 480	
V (2023)	estimated data		318 224 731	
V (2024)	estimated data		332 207 526	
V (2025)	estimated data		346 804 725	
V (2026)	estimated data		362 043 324	
V (2027)	estimated data		377 951 508	
V (2028)	estimated data		394 558 697	
V (2029)	estimated data		411 895 606	

Table 24 Annual sales of vehicle

Factor	Value type	Source	Value	Source link
N (2025)	official estimated data	Speech of Fubingfeng, CAAM (Chinese Association of Automobile Manufacturers)	30 000 000	http://www.xinhuanet.com/auto/2020-12/16/c_1126865937.htm
N (2021)	official estimated data	Speech of Fubingfeng, CAAM (Chinese Association of Automobile Manufacturers)	26 300 000	http://www.xinhuanet.com/auto/2020-12/16/c_1126865937.htm
N (2022)	estimated data	NA	27 179 735	
N (2023)	estimated data	NA	28 088 897	
N (2024)	estimated data	NA	29 028 471	
N (2025)	estimated data	NA	29 999 473	
N (2026)	estimated data	NA	31 002 955	
N (2027)	estimated data	NA	32 040 004	
N (2028)	estimated data	NA	33 111 742	
N (2029)	estimated data	NA	34 219 330	

N (2030)	estimated data	NA	35 363 967	
N (2020)	history data	Ministry of Public Security, Speech of Cuidongshu, CPCA National Passenger Cars Association	24 240 600	https://baijiahao.baidu.com/s?id=1688841190671031485&wfr=spider&for=pc
N (2019)			25 780 000	https://www.chyxx.com/industry/202012/913949.html
N (2018)			26 730 000	
N (2017)			28 130 000	
N (2016)			27 520 000	
N (2015)			32 850 000	
N (2014)			21 880 000	

Table 25 Total number of vehicles without line-fitted PC5 OBU, or total potential users of smart rear-view mirrors

Factor	Value type	Source	Value	Source link
DC (2021)	estimated data	NA	291 997 917	
DC (2022)	estimated data	NA	304 812 109	
DC (2023)	estimated data	NA	318 010 875	
DC (2024)	estimated data	NA	327 639 399	
DC (2025)	estimated data	NA	327 236 862	
DC (2026)	estimated data	NA	323 873 688	
DC (2027)	estimated data	NA	318 955 869	
DC (2028)	estimated data	NA	312 384 838	
DC (2029)	estimated data	NA	304 057 250	
DC (2030)	estimated data	NA	293 870 470	

8.2.3 Statistics data and Forecast for starting phase (2021, 2022, 2023)

Part 1: Estimated annual number of proposed vehicles in pilot province (2021-2023):

To summarise, based on the aforementioned analysis, PC5-based tolling would be firstly applied in Jiangsu, Zhejiang, Guangdong, Jiangxi, and Hebei provinces. AEVs, ride-sharing vehicle, trucks and LKYW could be the first vehicles equipped with PC5 OBUs.

Deployment plan:

- 2021: Jiangsu, Zhejiang
- 2022: Guangdong, Jiangxi, Hebei
- 2023: Remaining provinces

For the evaluation on vehicle side, the number of AEVs, ride-sharing vehicles, trucks, and LKYWs are investigated and forecasted, and the details are listed in the following tables. The data in each year is the sum of the number of existing vehicles and the number of newly manufactured vehicles. The Historical data is referred to [32]-[41]. A forecast curve is matched to Historical data and used for the 2021-2023 forecasts. For the data on infrastructure side, it has been introduced in Section 3.2.1.

About the following statistic data:

- All data before 2020: real statistics
- All data after 2020: estimated from Historical data using linear predictions

Table 26 Number of AEVs in pilot provinces at starting phase (thousand vehicles)

	Historical data						Forecasted data		
Year	2015	2016	2017	2018	2019	2020	**2021**	**2022**	**2023**
Jiangsu	16.6	30.4	62.2	163.3	180.9	267.6	352.2	447.8	554.4
Zhejiang	28.5	49.3	88.2	138.7	310	475	696.5	962.7	1273.6
Guangdong	11.6	51.6	43.4	32.7	167.5	451.2	1121.4	2108.7	3504.2
Hebei	14.4	26.4	44.8	87.6	123.1	142.8	170.7	198.6	226.4
Jiangxi	11.2	15.8	29.7	37.1	46	55.2	64.3	73.4	82.5

About 26% AEVs are used in commercial vehicles. (ride-sharing vehicle, trucks “LKYW” incl.) 74% AEVs are used in passenger vehicles.

Table 27 Number of ride-sharing vehicles in pilot provinces (thousand vehicles)

	Historical data						Forecasted data		
Year	2015	2016	2017	2018	2019	2020	**2021**	**2022**	**2023**
Jiangsu	110.9	102.7	102.2	101.6	101.5	105.8	111.9	120.4	131
Zhejiang	72	72.8	73.7	74.9	75.9	76.4	77	77.6	78.3
Guangdong	136	137.3	136.7	135.8	133.5	135.8	136.4	136.9	137.6
Hebei	97.9	99.7	100.8	101.3	101.6	102.5	103	103.5	104
Jiangxi	42.2	42.4	43.3	42.6	43.2	45.8	47	48.1	49.1

Table 28 Number of trucks in pilot provinces (thousand vehicles)

	Historical data										Forecasted data		
Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	**2021**	**2022**	**2023**
Jiangsu	823.9	892.9	967.9	971.6	903.8	941.7	1056.4	1162.4	1260.2	1526.8	1865.4	2318.1	2901.7
Zhejiang	612.1	673.5	725.9	713.6	657.6	704.5	761.9	831.1	897.2	1081.4	1319.3	1640.9	2058.8
Guangdong	1599.2	1698.6	1788.9	1818.1	1749	1830.2	1960	2179.1	2375	2523.7	2741.4	2983.8	3251
Hebei	1371.5	1534.2	1500.1	1435.4	1466.4	1633.2	1743.4	1933.7	2110	2055.8	2155.9	2260.7	2370.7
Jiangxi	467.6	470.1	545.6	584	599.6	603.3	651.3	731.9	794.2	821.4	875.6	933.3	994.9

For LKYW, the number of trucks carrying dangerous goods is included in28. In Table 2929, only two types of coaches (tour coach and intercity coach) are investigated.

Table 29 Number of LKYW in pilot provinces (thousand vehicles)

	Historical data						Forecasted data		
Year	2015	2016	2017	2018	2019	2020	**2021**	**2022**	**2023**
Jiangsu	100.3	107.6	111.4	115.3	115.2	118.1	119.6	120.9	122.1
Zhejiang	62.1	66.4	70.3	73.5	75	79.3	82.6	85.9	89.2
Guangdong	153.1	163	174.7	176.7	175.1	181	183.4	185.4	187.2
Hebei	52.5	62.5	65.9	67.5	67.5	71.2	72.6	73.9	75
Jiangxi	25.6	26.6	27.9	29.4	30.3	31.6	32.8	34.1	35.3

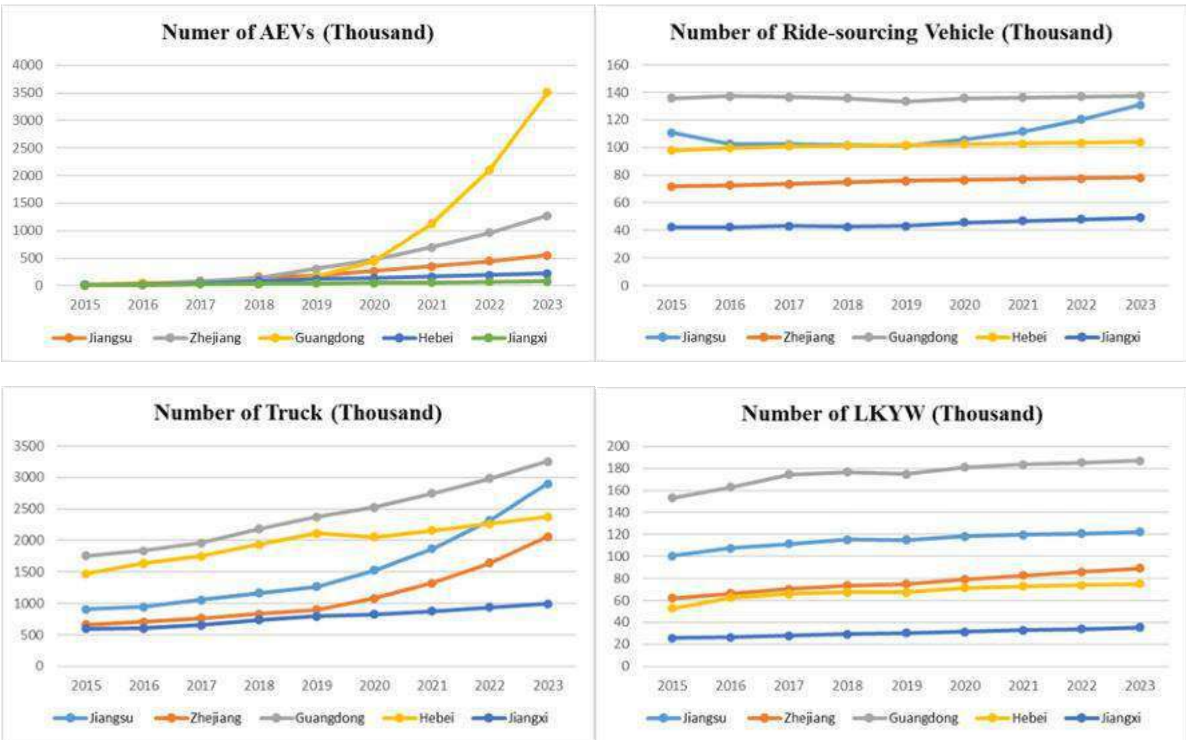


Figure 33 Statistics of four types of vehicles in aforementioned provinces (thousand)

In phase O-A1, PC5-based tolling is only promoted and tested. There will be few drivers/incentives to purchase aftermarket PC5 OBUs, which is reflected in the penetration rate of early ETC market in China (from 2013 to 2014)[48].

Part 2 - Key Parameters

The blue marked values below represent key parameters for our mathematical model, presenting the penetration rate of PC5 vehicles in the starting/roll-out phase.

These values are identical to those previously mentioned in Chapter 9, and they are considered as Hypothetical value for analysis.

Table 30 Definition and forecast of PC5 OBU (line-fitted and Aftermarket OBU) percentage for total '4types' vehicle in pilot provinces

Parameter	Year	2021	2022	2023
as(y)	The percentage of vehicles newly equipped with line-fitted PC5 OBUs for '4types' vehicles in year **XXXX** in pilot provinces.	1%	2%	5%
bs(y)	The percentage of vehicles newly equipped with aftermarket PC5 OBUs for '4types' vehicles in year **XXXX** in pilot provinces.	10%	20%	20%

Part 3 - Calculation with Mathematical Model

Table 31 Additional new PC5 OBUs (aftermarket/line-fitted) in pilot provinces at starting phase (2021-2023)

	Year	2021	2022	2023
Increased PC5 vehicles (4 type) in pilot province in each year	Value (K)	7 607	16 944,3	41 755,7
	Formula	Total number (Jiangsu, Zhejiang provinces) in 2021	Total number (Jiangsu, Zhejiang Guangdong, Jiangxi, Hebei provinces) in 2022 – Total number (Jiangsu, Zhejiang provinces) in 2021	Total number in China of (4type) vehicles in 2023 – Total number (five provinces) in 2022
Increased PC5 vehicle (4 Type) with aftermarket OBU	Value (K)	760,7	2 628,16	4 962,28
	Formula	Increased PC5 vehicles (4 type) in 2021 x bs(2021)	Increased PC5 vehicles (4 type) in 2022 x bs(2022)	Increased PC5 vehicles (4 type) in 2023 x bs(2023)
Increased PC5 Vehicle (4 Type) with line-fitted OBU	Value (K)	38,035	300,851	1 748,899
	Formula	New Increased PC5 Vehicle (4 type) in 2021 x as (2021)	New Increased PC5 Vehicle (4 type) in 2022 x as (2022)	New Increased PC5 Vehicle (4 type) in 2023 x as (2023)

Table 32 Calculation of penetration rate in national scale

		2021	2022	2023
b(2021,2022,2023): Aftermarket PC5 OBU penetration rate	Value (K)	0,002605137	0,00862171	0,015593634
	Formula	Increased PC5 vehicle (4type) with aftermarket OBU in 2021/ Total vehicles in China 2021	Increased PC5 vehicles (4type) with aftermarket OBU in 2022/ Total vehicles in China 2022	Increased PC5 vehicles (4type) with aftermarket OBUs in 2023/ Total vehicles in China 2023
a(2021,2022,2023): Line-fitted PC5 OBU penetration rate	Value (K)	0,000130257	0,000986945	0,005495798
	Formula	Increased PC5 vehicles (4type) with line-fitted OBUs 2021/ Total vehicles in China 2021	Increased PC5 vehicles (4type) with line-fitted OBUs 2021/ Total vehicles in China 2021	Increased PC5 vehicles (4type) with line-fitted OBUs 2023/ Total vehicles in China 2023

8.2.4 Forecast for the Next Ten Years

Estimated result:

Factor	Value
Npc5 (2021)	2 081
Npc5 (2022)	16 289
Npc5 (2023)	195 485
Npc5 (2024)	4 354 271
Npc5 (2025)	14 999 737
Npc5 (2026)	18 601 773
Npc5 (2027)	20 826 003
Npc5 (2028)	23 178 220
Npc5 (2029)	25 664 498
Npc5 (2030)	28 291 173

Factor	Value
DCpc5 (2021)	462 447
DCpc5 (2022)	1 595 494
DCpc5 (2023)	7 618 797
DCpc5 (2024)	9 829 182
DCpc5 (2025)	16 361 843
DCpc5 (2026)	19 432 421
DCpc5 (2027)	25 516 470
DCpc5 (2028)	31 238 484
DCpc5 (2029)	45 608 587
DCpc5 (2030)	58 774 094

Table 33 Forecasted penetration rate (one possibility) for next ten years

Penetration of both type of PC5 OBU	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	Starting phase									
a(y) line-fitted PC5 OBU	0.008%	0.06%	0.696%	15%	50%	60%	65%	70%	75%	80%
b(y) PC5 smart dash CAM (smart rear-view mirror)	0.1584%	0.5234 %	2.3958%	3%	5%	6%	8%	10%	15%	20%

One possibility to approach the target penetration rate of 80%+ in 2030:

$$\text{Final PC5 OBU penetration in 2030} = \frac{sum(aftermarekt\ PC5\ OBU) + sum(linefitted\ PC5\ OBU)}{Total\ number\ of\ vehicle\ in\ 2030}$$

$$\text{Final PC5 OBU penetration in 2030} = \frac{\sum_{2021}^{2030} Npc5(y) + \sum_{2021}^{2030} DCpc5(y)}{V(2030)} = 82\%$$

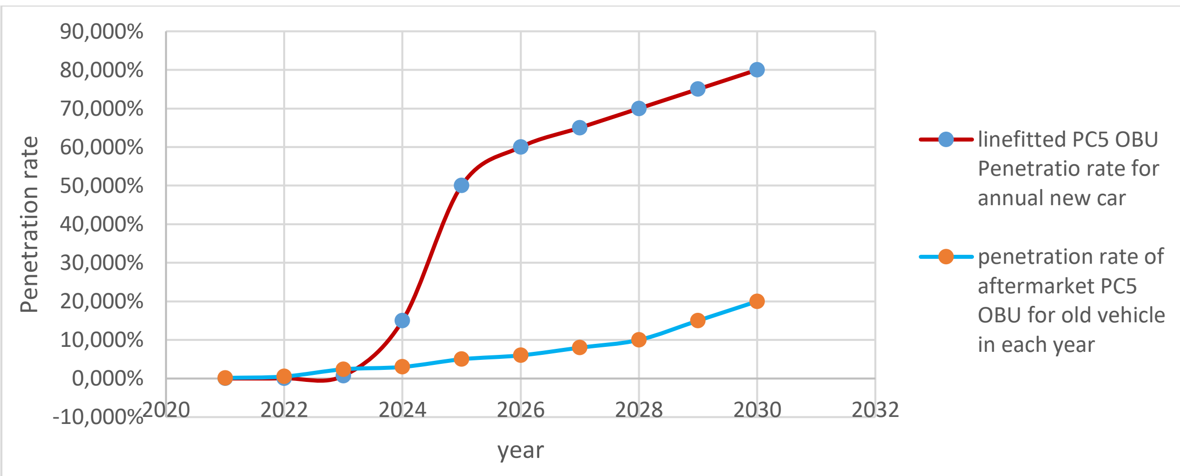


Figure 34 Penetration rate of line-fitted OBUs and aftermarket OBUs each year

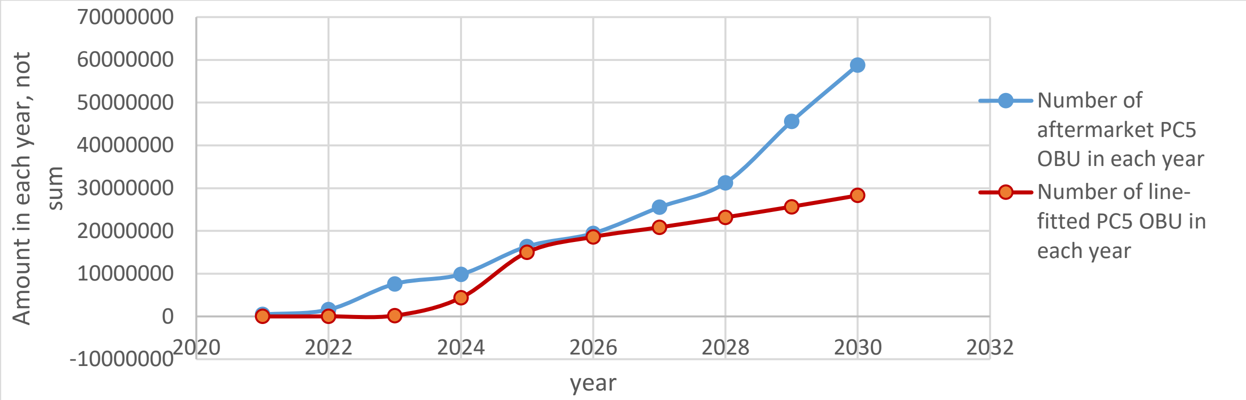


Figure 35 Forecasted annual increased number of PC5 OBUs

8.3 Conclusion of the Forecast

Key opinions reflected from this forecast diagram

1. In first diagram, both curves present the penetration rate for each year.
2. The cardinality is different: the cardinality of aftermarket OBU is ten times bigger than that of line-fitted OBUs, therefore the penetration rate of line-fitted OBUs is relatively higher than for aftermarket ones.
3. The second diagram details the annual increased number of PC5 OBUs in both categories. We can see in this forecast that both have a similar trajectory beyond 2028 because we think PC5 (or other C-V2X direct communication) will be widely used and installed in new vehicles. Before 2025, aftermarket OBUs drive the market because it is flexible and can be equipped in older vehicles. PC5-based tolling is likely to trigger a new PC5 industrial chain promoting the whole C-V2X business.
4. The year 2025 appears to be a critical point, as China's C-V2X roadmap and strategic plan calls for 50% of new vehicles to be installed with PC5 or C-V2X OBUs. To reach this target, we need to speed up PC5 pre-installation rates.

Clarification for this Mathematical Model and Outputs

In this mathematical model, the key parameters are assigned a reasonable hypothetical value to reach a penetration rate of over 80% by 2030. This means:

1) The parameter values are based as much as possible on market conditions and statistical data.
2) The forecast result from this mathematical model describes just one possibility for the PC5 industrial chain development (from a mathematical perspective there are infinite solutions in adjusting various parameters and thus too many factors that can influence PC5 OBU implementation).
3) The forecast result does not reflect real market trends, but comes from a purely mathematical model and has nothing to do with any automotive stakeholders' business plans per se.

Note: *The forecast result presents the possibility as a reference only. As a guide for industrial stakeholders, if we want to achieve 80% penetration rate in 2030, how should we promote PC5 technology in each phase?*

9 Proposal for Migration and Selling Argument

9.1 Migration Path

C-V2X is an emerging technology which could support larger communication ranges, and have the capability to transmit more data. Taking advantage of C-V2X, ITS could be further developed including manoeuvre coordination services, ITS Day 1 services, autonomous valet parking, and so on. Given the development of ITS and connected vehicle (CV) technology, the Chinese government, and other groups have released some documents related to C-V2X technology, including technical reports, policies, roadmaps and strategies. However, C-V2X applications in practice are still being slowly rolled out. There is some distance to cover before the goals proposed in the government strategy, **Outline for Building National Strength in Transportation**, can be achieved. Therefore, based on the development strategy and on C-V2X policies proposed by the government, this study is dedicated to developing a proposal for applying PC5 to tolling. Firstly, it is because there are general challenges in the existing 5.8GHz ETC system and PC5 will help to improve current tolling practices. Secondly, tolling is closely related to every vehicle owner, and could gain more attention from the government and road operators (BOT). Based on these reasons, the current study proposes PC5-based tolling solutions and conducts an investment analysis to justify this recommendation. The aim is to take full advantage of PC5, and promote the deployment of PC5 devices on both infrastructure and vehicle sides in order to accelerate the development of ITS services in China.

PC5-based tolling could usher in valuable ITS services, especially manoeuvre coordination services that enhance safety and improve traffic efficiency. In addition, PC5-based tolling could achieve the development of dynamic tolling (差异化收费) which supports various goals proposed in the above strategy. Based on these reasons, 5GAA and Tongji University have developed a detailed roadmap, deployment plan, use case and investment evaluation for PC5-based tolling. It is expected that the proposed PC5-based tolling could promote the C-V2X industry in China and bring economic benefits.

In the following, the benefits and impacts brought by PC5-based tolling are summarized from different aspects.

9.1.1 Benefits for and Impacts on Transportation

i) Infrastructure/investment savings: In 2020, the Chinese government proposed to develop ‘next-generation infrastructure’ based on emerging technologies (C-V2X, 5G, Beidou et al.). It promoted the government to invest more in the construction and operation of advanced infrastructure projects. Based on the advantages of PC5, including the wider bandwidth and larger communication range, fewer RSUs would be needed than required for equivalent coverage via 5.8GHz ETC solutions. Furthermore, the existing tolling infrastructures (ETC gantry and tolling plaza) could continue to be used for PC5-based tolling, and there will be no additional investment in the construction of new gantries and tolling plazas. Therefore, the infrastructure cost of PC5-based tolling on the infrastructure side would be lower than for 5.8GHz ETC (as analysed in Chapter 6). This means that PC5-based tolling could help to save significant sums otherwise earmarked for investment in so-called next-generation infrastructure.

ii) **Improved traffic efficiency**: PC5-based tolling ushers in new ITS services, especially manoeuvre coordination services which offer advice on optimal driving paths and speeds to PC5 vehicles. For trucks that need to be weighed at expressway entrances, this service could guide them to less congested weighing points. This mechanism could effectively reduce the severe congestion caused by trucks, thereby improving throughput, and reducing travel time. On top of that, manoeuvre coordination services could send lane ID advice to PC5 vehicles approaching the tolling plaza to avoid queuing and improve vehicle flow. Therefore, due to the aforementioned reasons, PC5-based tolling could also entail the deployment of ITS services which boost traffic efficiency as well. Based on this, the government’s goal ‘National 123 Transportation Circle, proposed in its ‘Outline for Building National Strength in Transportation’ strategy, could be achieved faster.

iii) Reduced emissions: Owing to manoeuvre coordination services, a so-called ‘advising speed’ can be issued to PC5-enabled vehicles. This speed recommendation promotes green driving and reduces emissions. In addition, as described in the use case in Section 4.3.1.1.1, PC5-based tolling is beneficial for the development and increased penetration of AEVs, which leads to more sustainable driving and energy savings. Therefore, PC5-based tolling could be conducive to achieving the government’s ‘Green Transportation’ mission also proposed in its outline strategy.

iv) Safety enhancement: PC5 technology could enhance safety, according to C-V2X group technical reports [15][16]. Taking advantage of PC5's larger communication range and manoeuvre coordination services, traffic accident information could be sent to PC5 vehicles in advance. Furthermore, PC5 OBUs integrated with dash cams could effectively monitor the status of drivers (especially truck and ride-sharing vehicle drivers) in real time to avoid traffic accidents caused by fatigue or poor driving. Thus, PC5-based tolling has great potential to enhance road safety as well.

9.1.2 Benefits and Impacts for Tolling

i) Improved tolling solutions: As described in Section 3.2.4, there are many general challenges in existing 5.8GHz DSRC-based tolling, such as congestion at expressway entrances/exits and lost or missed charges. PC5 could address these problems in an effective way. The benefits and solutions brought by PC5 have been detailed in Table 4 and Table 5. The capacity of tolling could be further promoted, and the toll revenue could be significantly increased thanks to greater PC5 use.

ii) Reasonable deployment proposal for PC5-based tolling: PC5-based tolling introduces significant savings CAPEX and OPEX). Based on this premise, this study has developed a reasonable deployment proposal which takes regional economies and industry requirements into consideration. Distinguished from the deployment of 5.8GHz free-flow tolling (the deployment beginning in 2019 was completed within the year), PC5-based tolling is deployed region by region. This deployment schedule takes national C-V2X development plans and regional policies into account. Jiangsu, Zhejiang, Guangdong, Hebei, and Jiangxi provinces have specific development plans for free-flow tolling and C-V2X technology, thus our analysis suggests that these regions could be used as pilots and PC5-based tolling could be deployed within these provinces as a priority. After that, PC5-based tolling could be gradually expanded to other corridors within the country. This deployment plan could effectively decrease potential problems and reduce investment in infrastructure. On top of that, based on the roadmap of C-V2X deployment in China, the proposal refers to [17] (EIST TR 103 579 V1.1.1), and thus confirms that the C-ITS RSUs could be used for tolling. Using C-ITS RSUs for tolling could reduce infrastructure investment needs and promote the development and application of C-V2X in China. The deployment proposal thus meets the government's expectations under the 'next-generation transportation' proposal. On the vehicle side, our research proposes some valuable use cases, namely for AEVs, ride-sharing vehicles, trucks and LKYWs. It is suggested that PC5 could be first deployed on these four types of vehicles (so-called '4types'). This emerging technology could effectively solve some of the noted problems these vehicles face. Furthermore, it would be beneficial for the development of connected vehicle technology, and promote the ITS strategy proposed by Chinese government.

iii) Dynamic tolling: Dynamic tolling is an effective method to improve traffic efficiency, reduce the logistics costs and promote the development of AEVs. These goals are also proposed under the government's 'Outline for Building National Strength in Transportation'. Due to the problems in 5.8GHz free-flow ETCs, dynamic tolling has not been promoted. However, the advantage of PC5-based tolling could make dynamic tolling more feasible. This research also develops a proposal demonstrating the savings to be gained from dynamic tolling (Table 19). Governments could refer to these savings to develop policies related to dynamic tolling.

9.1.3 Business Model

PC5-based tolling is set to trigger new business models which combine the traditional ETC tolling business and PC5 advances to bring about new product types, including PC5 line-fitted OBUs (T-Box) and PC5 aftermarket OBUs (intelligent rear-view mirror), and especially developments in PC5-enabled mobile phones and other portable devices carried by vulnerable road users. In terms of line-fitted OBUs, the existing T-Box could be upgraded, thus delivering a next-generation PC5 T-Box to market. This new line-fitted product could meet tolling requirements and provide rich ITS services offering great benefits to PC5 users. Meanwhile, OEMs such as SAIC could derive sales and market share through the sale of 'PC5 T-Boxes'. Perhaps most importantly, PC5 T-Boxes could also promote the development of intelligent and connected vehicles, and stimulate an evolution in the transportation sector. In terms of aftermarket OBUs, this type of product (i.e. intelligent rear-view mirror) also extends the benefits of ITS services to existing vehicle owners. It could be integrated with a dash cam, and various sensors to boost safety and efficiency while improving environmental performance. A large number of existing vehicles represent a huge market in PC5 aftermarket OBUs. Many equipment manufacturers and providers, including Jinyi, Wanji and Datang, could derive great economic benefits from the deployment of PC5 aftermarket OBUs.

Starting in 2030, 5.8GHz ETC systems would then be switched off, which means the CPC card supporting 5.8GHz ETC networking would no longer work at gantries. Therefore, in this proposal, two solutions are proposed for addressing this eventuality:

- In solution 1, it is suggested that 5.8GHz RSUs installed along MTC and mixed lanes could be kept in situ. ANPR can be used for transactions at gantries (only recording), which means the tolling backend system would need to be upgraded to handle rapid checks at entrances/exits.
- In solution 2, it is suggested that PC5 mobile phones with ETC security modules be used for tolling via ITS messages. This approach extends the tolling application scenarios to the likes of parking lots, petrol stations, and so on. More importantly, PC5 mobile phones with integrated tolling functions could enhance market competition benefiting mobile terminal manufacturers and providers, such as Huawei, Vivo, Apple, etc.

9.1.4 Communication Technology

PC5-based tolling can help to promote ITS services and CV technology. According to proposals in this study, PC5-based tolling could accelerate the deployment of C-ITS RSUs (EIST TR 103 579 V1.1.1) and thus expand the C-ITS network corridors. Based on notions of a 'perfect C-V2X (LTE-V) communication network', an increasing number of ITS or CV applications could thus be realised, such as cooperative vehicle-infrastructure systems (CVIS), cooperative adaptive cruise control (CACC), autonomous valet parking (AVP), and more. This means that the transportation system would enter a new era, prompting a mini-revolution towards advanced transportation services and business models. These developments also complement emerging 5G-V2X technologies; the deployment of PC5 tolling and C-ITS RSUs would further benefit the integration and upgrade of 5G communication networks, resulting in huge potential investment cost savings.

The proposed PC5-based tolling could thus deliver significant benefits and savings in the transportation telematics sector, and help to realise a rapid but stable evolution in ITS services and CV technologies.

9.2 Selling Argument

This section covers the PC5 selling arguments from the view of both government/road operator and vehicle owners with PC5 functionality, supporting their decision-making and investment plans.

9.2.1 Government/Road Operator Perspective

i) Performance:

According to our proposal, at the early stage of PC5-based tolling (PC5 tolling solution coexists with 5.8GHz ETC), PC5 RSUs and C-ITS RSUs could be utilised for redundancy tolling, therefore reducing lost charges. Once full coverage of PC5 RSUs is attained, taking advantage of the wider bandwidth and communication range, PC5-based tolling could provide high-speed, secure and accurate tolling services which are beneficial for enforcement control and avoiding toll evasion. For the government, PC5-based tolling makes dynamic tolling more feasible, and helps the development of ITS and relevant automobile industries.

ii) Timeframe:

The project timeframe is for PC5 RSUs to be deployed region by region. In addition, this deployment takes full use of the lifespan of 5.8GHz DSRC RSUs and key infrastructure (gantries and tolling plazas) in state-of-practice. Therefore, this deployment plan could effectively decrease potential problems and reduce investment on the infrastructure side. Furthermore, PC5-based tolling could lay the foundation for a stable evolution from 4G to 5G, thus reducing the investment in 5G-V2X and accelerating the promotion and application of 5G technology.

iii) Security:

C-V2X has powerful security certification mechanisms and a unified technical framework which not only reduces the investment on the infrastructure side, but also makes it easier for road operators to manage tolling devices (OBU and RSU). Under the premise of ensuing communication security, road operators could provide manoeuvre coordination services for PC5 users via C-ITS broadcasting, therefore achieving efficient tolling and traffic management.

iv) Informed decision:

A huge amount of policies, development strategies, technical reports, and roadmaps related to C-V2X deployment plans have been referenced during this study. Therefore, the proposal for PC5-based tolling is more than reasonable and well founded. The Chinese government or road operators could refer to the suggestion in the proposal to avoid over-investment, and achieve a rapid and stable evolution from current to emerging technologies (5.8GHz DSRC→PC5 (LTE-V)→Beidou+5G). In addition, the standardised cellular technology proposed by 3GPP could also provide a reasonable redundancy design basis for the reliable operation of tolling systems.

v) Added value:

The proposal foresees PC5-based tolling not only being deployed on expressways. With the increase of C-ITS RSU density, PC5-based tolling could cover arterial roads and city traffic conditions. In all settings, enforcement control features are notably enhanced. If the vehicle evades or 'escapes' a toll on the expressway, it would be checked in other places. The tolling application scenario is enriched with more tolling business applications, such as AVP), and tolling in congested zones could be realised. It means toll revenues could be increased through multiple sources. Furthermore, more PC5 application scenarios could promote the development of CV technology, and lay the foundation for connected and automated vehicle technology.

9.2.2 The Vehicle Owner (PC5 User) Perspective

i) Performance:

PC5 users could enjoy high-quality tolling and ITS services via PC5-based tolling. PC5 technology could improve the driving speed and cut travel times especially for commercial vehicles, such as trucks, LKYWs, and ride-sharing vehicles. PC5-based tolling could ensure driver and passenger safety in these different modes. On top of that, PC5-based tolling could improve dynamic tolling which could bring discounts or toll saving to PC5 users.

ii) Timeframe:

The deployment plan of PC5 devices on the vehicle side is based on the use cases explored in Section 4.3.1.1.1. Given the challenges AEVs, ride-sharing vehicles, trucks and LKYWs face and the advantages of PC5, there is great demand for these four types (4types) of vehicles to take the lead in PC5-based tolling. It means that the PC5 investment in commercial '4type' vehicles could be rapidly reduced. This is beneficial for the development of the automobile industry and transportation/logistics sector in general. On top of that, the proposed deployment plan could achieve a rapid and stable evolution from PC5 (4G) to 5G NR, thus PC5 users could invest less in 5G on-board products and enjoy the benefits from 5G technology much sooner.

iii) Security:

C-V2X has a powerful security certification mechanism which reassures PC5 users when they are conducting a transaction with the PC5 RSU. The personal information about the PC5 users could be effectively protected.

iv) Informed decision:

It is anticipated that proposal for PC5-based tolling in this study could greatly benefit the Chinese government, and that authorities and stakeholders take our suggestions into consideration by giving early adopters a discount or financial support, such as subsidies for PC5 vehicles, dynamic tolling, reduced insurance premiums, and so on. These financial incentives could prompt more vehicle owners to take up PC5 OBUs (T-Box and intelligent rear-view mirror), which ultimately encourages faster deployment of C-V2X devices on the vehicle side, and the development of an automobile industry chain, such as for AEVs.

v) Added value:

PC5-based tolling not only brings toll savings to users, but also delivers additional benefits. PC5 users could enjoy discounts when they purchase new PC5-powered vehicles. Further, ITS services within the PC5 ecosystem, such as manoeuvre coordination and ITS Day 1 services, could help PC5 users reduce insurance and logistics cost. The enriched PC5 tolling application scenarios could also provide additional value for PC5 users and stakeholders who could use PC5 OBUs to complete transactions in parking lots, petrol stations, and congested zones. PC5 applied in various scenarios could also promote faster transactions, and indirectly increase traffic efficiency.

10 Challenges for C-V2X-based Tolling

In this study, we have analysed, revealed and made predictions about PC5-based tolling in various directions (technical, policy, use case, cost, deployment, investment…). However, tolling is a complex topic and involves many actors and scenarios. These include different business models and transactions, enforcement controls, the impacts of interference, stability, standardisation, verification, etc.; and the implications on investment, user installation needs and MTC. This section lists some open points, which are not discussed or not fully developed in the current study.

1. Standardization problem:

There are two standards (from different standardisation bodies) defining the UC with payment application.

Table 34 China C-ITS standards defining the UC with payment application

No.	Organisation	Standard	Phase	Contents of payment application
1	CSAE	T/CSAE 53-2017: cooperative intelligent transportation system; vehicular communication; application layer specification and data exchange standard	Day 1 UC	The 2017 version defined the basic UC description and payment environment, including highway tolling. In 2020 version, add the definition about message Protocol.
2	China ITS Industry Alliance	Cooperative intelligent transportation system: vehicular communication Application layer specification and data exchange standard Phase II	Day 2 UC	The 2020 version defined the basic UC description and message protocol. The contents are similar.

In Europe, ETSI has published TR 103 579 in 2020 with detail and complete technical design for whole Tolling system (based on DSRC technology), we hope that Chinese standardization organization could also contribute certain technical paper to guide the pilot and promote PC5 Tolling application forward.

2. Open technical problem:

There are several technical problems which need to be worked on in the coming steps, including:

- Compatibility issues: Are there unknown interference concerns between PC5 and ETC?
- Transition period issues: if one vehicle equipped with both OBUs and both tolling systems finishes the transaction at a tolling point, how can double billing and settlement be avoided?
- MTC and CPC card issues: What is the efficient and alternative solution for PC5-based tolling, or via Uu + satellite based tolling?
- Security issues: What are the requirements and what research is needed for better security? (e.g. encryption)
- Certification issues: Could the ITS certification system be reused for tolling applications?

3. Data used in this study:

- The analysis and methodology was defined at the beginning of 2021, marking that year as milestone or starting point for the ‘PC5 tolling’ roadmap. Yet the actual study was completed at the beginning of 2022, which means some data used may not be the absolute latest, but it does provide a solid basis for forecasts and recommendations provided.
- The biggest change observed in this short period of time has already been observed in the AEV market. It is growing very fast and is difficult to accurately predict. Yet AEVs are an important early adopter (4type) and one of best opportunities to speed up PC5 rollout and the development of an industrial chain on the vehicle side.

4. Industrial chain:

- A big question is how to maximise the value of C-V2X and find the best ways to quickly implement viable tolling solutions ideally built around native PC5 OBUs and/or software/application updates in smart PC5 terminals/OBUs.
- How can stakeholders leverage the value of Uu in C-V2X-based tolling?

It should nevertheless be pointed out that this study was never intended as a ‘complete picture’, but rather sought to establish the technical feasibility of PC5-based tolling developments through dedicated analysis of the investment needs and overall added value. 5GAA welcomes relevant technology developers and institutes to cooperate with us in further technical analyses and future developments in this important sector.

11 Conclusion

Study review

In China, C-V2X technology is gaining increasing interest from government and relevant industries. Many policies, development strategies, roadmaps and technical reports related to C-V2X have been released. However, C-V2X applications in practice are still being slowly rolled out. This is due to business models related to C-V2X technology not being established. Therefore, considering that tolling is a vital transportation business for every vehicle owner, and existing tolling systems face general challenges, this study seeks to clarify and underline the benefits of C-V2X-dedicated short-range communication (known as PC5), in tolling. Our work uncovers where and how PC5-based tolling can improve the transportation sector. Referring to relevant documents, this research proposes a reasonable roadmap, deployment plan and use cases for PC5-based tolling. Based on our proposal, combined with the industry developments, we conduct a detailed investment analysis and benefits case for PC5-based tolling. The Chinese government can use this information for its planning and policies focused on new-generation tolling solutions and in achieving its strategic goals according to the 'Outline for Building National Strength in Transportation' and further developing an ITS industry chain in China.

The proposal of PC5-based tolling is thus summarised in the following:

- In principle there should a positive business case in using PC5 also for tolling: PC5 OBUs fulfil ITS as well as tolling transactions, and RSUs perform both ITS and tolling services. The combined services could enhance traffic management efficiency, as illustrated in the use cases provided in this study.
- The deployment of PC5 tolling devices on the infrastructure side could be carried out region by region. Based on relevant policies, PC5 RSUs could be firstly deployed in Zhejiang, Jiangsu, Guangdong, Hebei, and Jiangxi provinces. These provinces could be used as pilots. The existing ETC gantries and tolling plazas could keep being used for the deployment of PC5 RSUs. After the success of PC5-based tolling in these pilots, the new tolling solution could be rolled out on a national scale, and cover all corridors in China.
- The timeframe and proposed roadmap in this study is merely indicative, but does align with ITS and transportation policy in China. Thus the starting phase (2021-2023) is the key period, and needs stronger promotion from the government on infrastructure stakeholder and user side. The second important milestone is 2025 when the government's ITS strategy should be much clearer during real deployment. At that time, there will be more evidence to support PC5 tolling and cases to promote related developments in the automotive industry, especially in PC5-enabled vehicle production. The last important milestone will be 2030 when most ETCs will be closed and PC5 maturity is anticipated.
- Tolling capabilities can be added to C-ITS RSUs, providing a redundancy tolling solution and increasing the density of transaction points. On top of that, using C-ITS RSUs for tolling could greatly reduce the investment on the infrastructure side. The feasibility of this proposal has been verified by [17] (EIST TR 103 579 V1.1.1). This solution is also beneficial for the rollout of tolling application scenarios. It would support PC5 transactions in parking lots, petrol stations and other locations.
- Between 2021 and 2030, PC5-based tolling could coexist with current 5.8Hz ETC. Starting in 2030, when it is assumed market penetration of PC5 OBUs would be much higher, it is suggested that 5.8GHz ETC systems could be switched off or partly switched off. Correspondingly, two solutions are proposed for non-ETC users (CPC card users):
  - Solution 1: CPC cards remain in use for tolling at exits/entrances, but an ANPR solution is used for the transaction (only recording) at each gantry.
  - Solution 2: PC5 mobile phones could be equipped with ETC security modules and used for tolling via ITS messages; 3GPP is devising strategies for decreasing the power consumption of PC5 to support the development energy efficient PC5 mobile phones.
- PC5 deployment on the vehicle side is based on benefits cases for AEVs, ride-sharing vehicles, trucks, and LKYWs. It would be beneficial for the development of the automobile industry and transportation/logistics sector as well.
- There would be a great difference between the PC5 OBUs and existing 5.8GHz DSRC OBUs. The PC5 line-fitted OBU could be a T-Box which meets the demand for tolling and richer ITS services. OEMs, such as SAIC, could develop and grow the market for PC5 T-Boxes. PC5 T-Boxes could promote the development of intelligent and connected vehicles and aftermarket OBUs could emerge in technologies such as intelligent rear-view mirrors and other enhanced ITS services designed for legacy vehicle owners. A large pool of existing vehicles offers a huge market for PC5 aftermarket OBUs. Many equipment manufacturers and providers, including Jinyi, Wanji and Datang, could enjoy a lucrative aftermarket for PC5 OBUs.

The investment evaluation indicates cost-savings on the infrastructure side. Due to better bandwidth and communications range with PCF RSUs, fewer would be needed than 5.8GHz DSRC RSUs, which means the total cost of PC5 RSUs would be lower in the long run. On the vehicle side, owners could make a reasonable investment as the cost-benefit of PC5 OBUs become clear. The Chinese government could refer to the quantified benefits brought by PC5-based tolling to develop discounts or dynamic tolling policies. Other benefits of PC5 on ITS services were revealed during the study, including enriched manoeuvre coordination and ITS Day 1 services as well as insurance savings, improved traffic efficiency, and reduced emissions. More importantly, these benefits match the goals proposed in the government's 'Outline for Building National Strength in Transportation'. Therefore, PC5-based tolling would be beneficial for the development and evolution of the transportation sector in China. Furthermore, proposed PC5-based tolling not only facilitates a rapid and stable transition from existing communication technology to 5G (5.8GHz DSRC→PC5 (4G)→5G), it also speeds up advanced ITS and tolling service deployment in more efficiency way.

Appeal to the government

For the infrastructure, the benefits of dual-use RSU (both for tolling and for other ITS services) is clear, but **there is no evidence of activities to start such dual services**. This fact prompted 5GAA to carry out this study to show how PC5 could be used for tolling purposes as well road safety and advanced Day 2 services.

From the user and vehicle point of view, we have listed various use cases involving key stakeholders, and the study confirmed that there is a positive business case. From a cost and installation (space, maintenance, operation) perspective, already existing PC5 infrastructure in vehicles can already be used for tolling with the additional of tolling software. Two boxes (one for ETC and one for PC5-based ITS services) would no longer be needed in the vehicle. But today, as communicated with automotive industry members in 5GAA during this study, the car OEMs are not actively pushing for the transition. Many seem reluctant to raise this with government authorities, and road operators foresee (incorrectly) complex changes to legacy ETCs systems with the introduction of PC5.

Therefore, we think there is need for an 'orchestrator role' to organise this migration, and to kick-start the process by setting the right investment environment and incentives, on the car OEMs side as well as on road operator's side. 5GAA thinks this role is best matched to government authorities, and the findings in this study provide guidelines and proposals for this vital starting and later transition phase.

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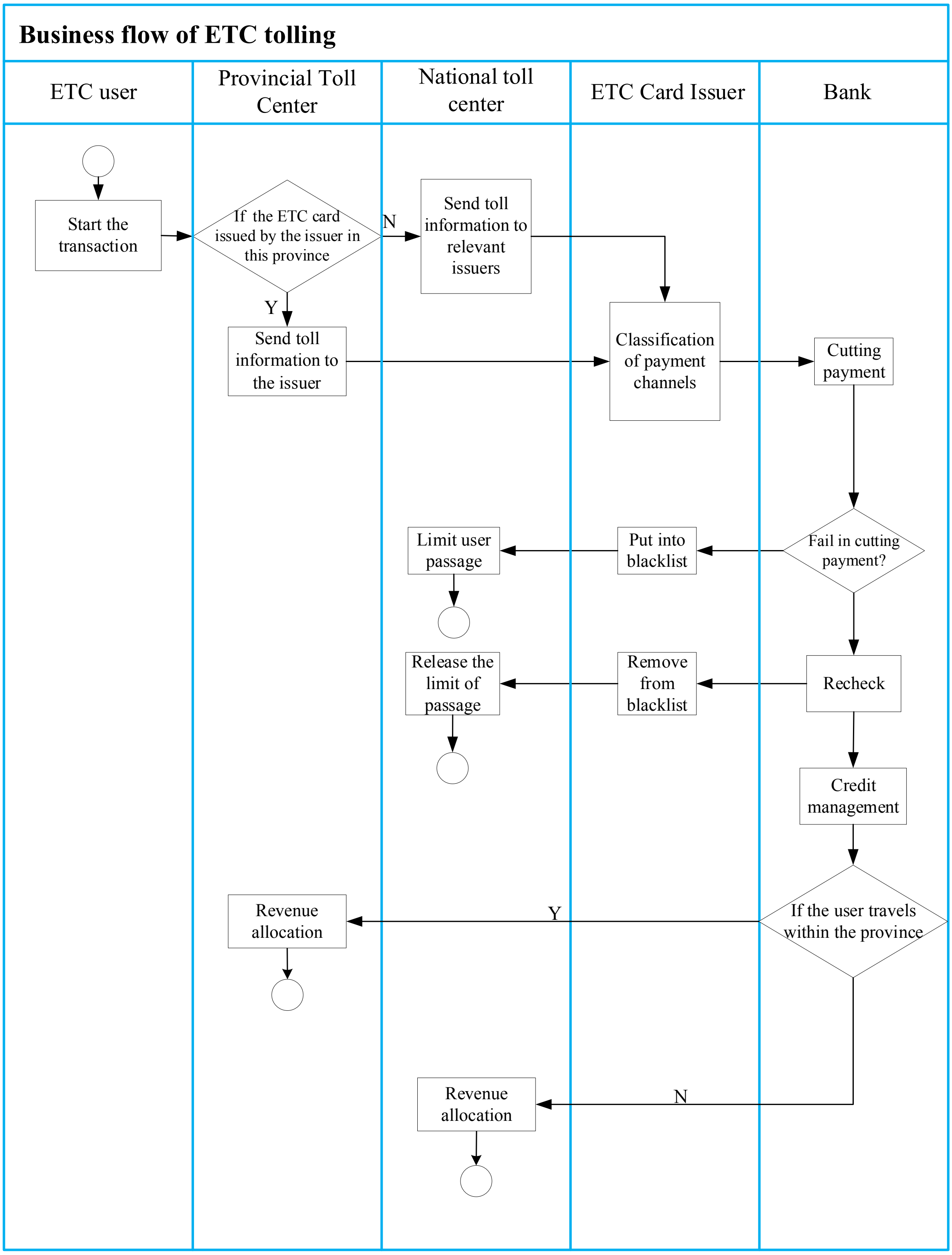
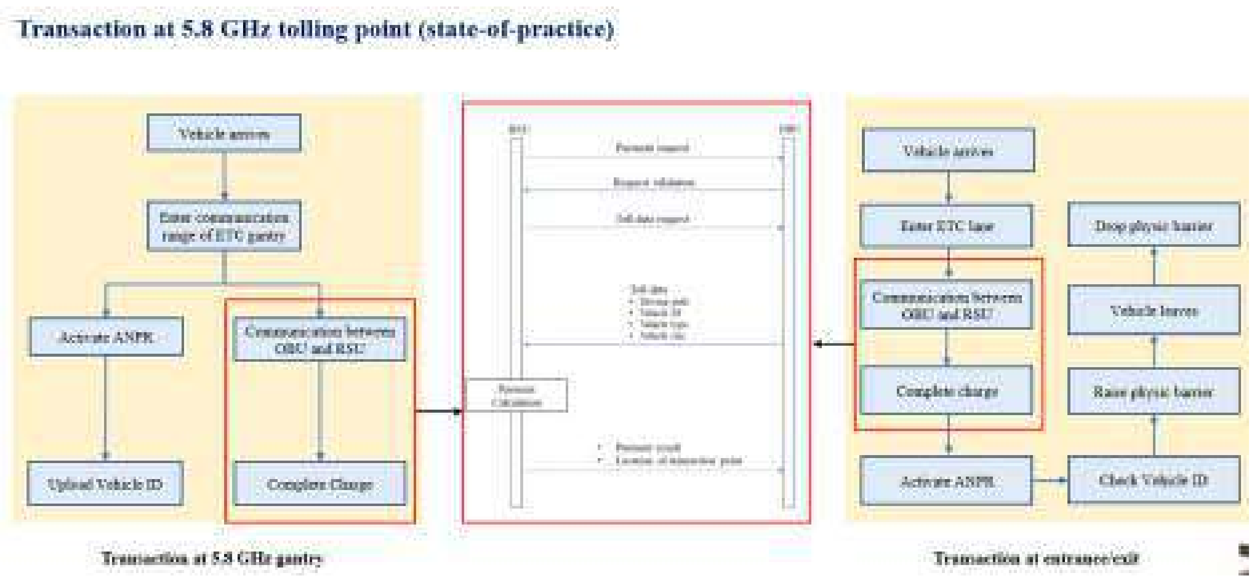
13 Appendix

13.1 Business Flow of 5.8GHz DSRC-based ETC Since 2015



13.2 Workflow of 5.8GHz ETC Transactions Between Vehicle and Toll Gantry



13.3 Technology Specification for 5.8GHz Communication (Downlink and Uplink)

Current 5.8GHz ETC system complies with GB/T20851 'ETC – dedicated short-range communication'. This document defines the communication between RSU and OBU, and proposes two-class technology requirements:

A class: The 5.8GHz communication shall meet ETC application

B class: Based on meeting ETC application, the communication shall support high-speed data transmission.

Downlink:

No.	Parameters		A class	B class
1	Carrier frequency	Channel 1	5.830GHz	5.830GHz
		Channel 2	5.840GHz	5.840GHz
2	Occupied bandwidth		≤5 MHz	≤ 5MHz
3	Frequency tolerance		$\pm 10\times 10^{-6}$	$\pm 5\times 10^{-6}$
4	e.i.r.p		≤ 33 dBm	≤ 33dBm
5	Adjacent channel leakage power ratio		≤-30 dB	≤ -30dB
6	Modulation system		ASK	FSK
7	Wake-up time of OBU		≤ 5ms	≤ 5ms
8	Wake-up sensitivity of OBU		≤ -40dBm	≤ -40dBm
9	Receive sensitivity of OBU		≤ -50dBm	≤ -70dBm
10	Maximum input signal power of OBU		≥ -20dBm	≥ -20dBm
11	Co-channel interference suppression ratio		＜ 15dB	＜ 15dB
12	Adjacent channel interference suppression ratio		＜ 15dB	＜ 15dB
13	Blocking interference suppression ratio		＜ -10dB	＜ -10dB
14	Receive bandwidth of OBU		Max: 5.825GHz-5.845GHz Min: 5.8285GHz-5.8315GHz 5.8385GHz-5.8415GHz	Max: 5.825GHz-5.845GHz Min: 5.8285GHz-5.8315GHz 5.8385GHz-5.8415GHz
15	BER		$\leq 10\times 10^{-6}$	$\leq 1\times 10^{-6}$

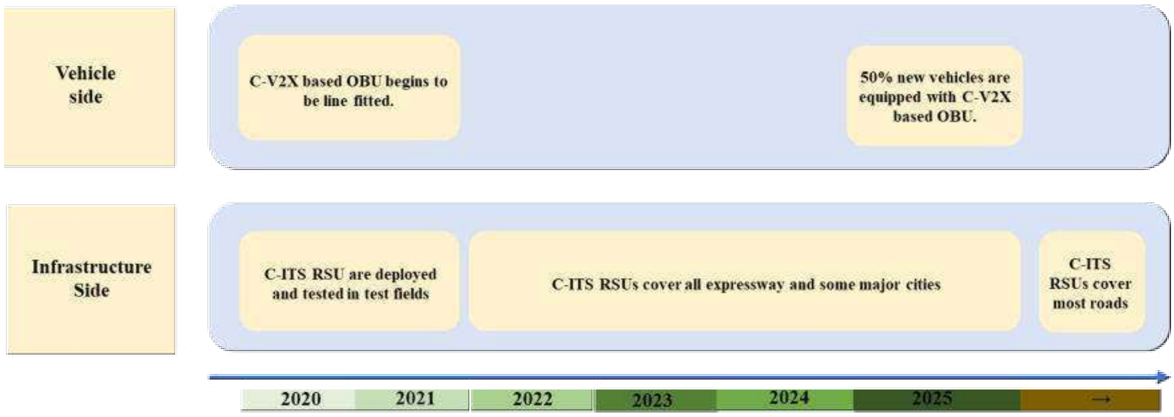
Uplink:

No.	Parameters		A class	B class
1	Carrier frequency	Channel 1	5.790GHz	5.790GHz
		Channel 2	5.800GHz	5.800GHz
2	Occupied bandwidth		≤5MHz	≤ 5MHz
3	Frequency tolerance		$\pm 200\times 10^{-6}$	$\pm 20\times 10^{-6}$

4	e.i.r.p	≤ 10dBm	≤ 10dBm
5	Adjacent channel leakage power ratio	≤-30dB	≤ -30dB
6	Modulation system	ASK	FSK
7	Receive Sensitivity of RSU	≤ -70dBm	≤ -70dBm
8	Maximum input signal power of RSU	≥ -20dBm	≥ -20dBm
9	Co-channel interference suppression ratio	＜ 10dB	＜ 10dB
10	Adjacent channel interference suppression ratio	＜ -20dB	＜ -20dB
11	Blocking interference suppression ratio	＜ -30dB	＜ -30dB
12	Receive bandwidth of RSU	Channel 1: Max: 5.7875GHz-5.7925GHz Min: 5.7885GHz-5.7915GHz Channel 2: Max: 5.7975GHz-5.8025GHz Min: 5.7985GHz-5.8015GHz	Channel 1: Max:5.7875GHz-5.7925GHz Min: 5.7885GHz-5.7915GHz Channel 2: Max: 5.7975GHz-5.8025GHz Min: 5.7985GHz-5.8015GHz
13	BER	≤ 10×10^{-6}	≤ 1×10^{-6}

13.4 Timeline of C-V2X Proposed in Technical Report on C-V2X Industrialisation Path and Schedule

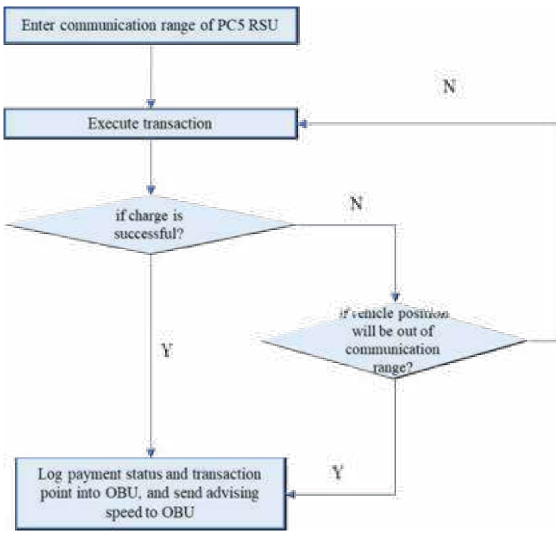
C-V2X 路侧基础设施建设、车载设备部署时间表



Timeline of C-V2X deployment on infrastructure side and vehicle side

13.5 PC5-based Tolling Logic

Tolling logic at gantry



Tolling logic at tolling plaza (entrance/exit)