ELECTRONIC TOLL COLLECTION (ETC) ON HIGHWAYS:

Global trends, Vietnam's experience, and policy lessons

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Electronic Toll Collection (ETC) on Highways: Global Trends, Vietnam's Experience, and Policy Lessons

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Abstract

This paper explores the transformative shift to Electronic Toll Collection (ETC) systems in highway management, focusing on deployment patterns and the realized benefits. By analyzing global ETC trends and taking a deep dive into Vietnam's experience, it offers practical policy insights for developing countries facing this critical transition.

A key feature of the paper is its in-depth analysis of Vietnam's shift from manual toll collection (MTC) to ETC, demonstrating significant improvements in emissions reduction, operational ef- ficiency, and cost and time savings.

Based on its findings, the paper emphasizes the role of ETC in enhancing productivity, pro- moting sustainable development, reducing pollution, and advancing towards a smart economy and society. It highlights the crucial importance of government leadership and private sector collaboration in achieving successful ETC implementation. Additionally, the paper underscores the urgency and substantial benefits of investing in digital transformation for toll facilities like metros, tunnels, and skyways to alleviate traffic congestion in megacities and on inter-city roads, potentially saving millions of people and vehicles hours of travel time.

Key words: Electronic Toll Collection (ETC); Manual Toll Collection (MTC); Highways; Estimation; Policy.

1. Introduction

The world has undergone profound changes in recent decades, driven by powerful forces shaping development and transformation across nations. Globalization, the digital revolution, and the urgent need to address sustainability challenges have emerged as key drivers of this shift (OECD, 2019; WEF, 2021; World Bank, 2024). In the developing world, these forces have accelerated rapid modernization and spurred the adoption of the latest international policy practices and digital transformation. These initiatives have enabled developing countries to

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boost productivity and sustainable development, helping them catch up with more advanced nations (Vu & Asongu, 2020).

The transition from manual toll collection (MTC) to electronic toll collection (ETC) systems[2] on existing highways, and the immediate deployment of ETC systems on newly developed highways in developing countries, serve as notable examples of this catching-up dynamism. Previous studies have provided robust evidence of the significant gains achieved by transitioning from MTC to ETC systems in various countries across both developed and developing regions (see Shahrier et al., 2024; for a comprehensive review).

Although transitioning to ETC systems can significantly improve efficiency and reduce social costs, the implementation process is complex, involving technical and political challenges that can delay the transition or result in suboptimal outcomes (OECD, 2010; Shahrier et al., 2024; Tseng et al., 2014; Tseng & Pilcher, 2022). Therefore, studies on global ETC deployment trends and the latest successful experiences from developing countries that have made the MTC-to-ETC transition a notable success would be valuable. Such studies could provide insights into the practical, technological, and political challenges of transitioning from MTC to ETC and offer guidance for transportation agencies considering similar developments.

This paper addresses a critical gap in the literature by examining the intersection of infrastructure development and digital transformation, particularly in the context of Electronic Toll Collection (ETC) deployment in developing countries. While existing research largely focuses on ETC systems in developed nations with advanced infrastructure, there is limited literature exploring the unique challenges and opportunities faced by rapidly developing countries like Vietnam. This paper fills that gap by analyzing how infrastructure growth and digital innovations can occur concurrently, reinforcing one another in terms of both efficiency and effectiveness.

Our central research questions are: Why and how should developing countries leverage ETC deployment on highways to enhance infrastructure development and digital transformation? These questions are crucial for understanding the role ETC systems can play in modernizing road infrastructure while advancing digital capabilities, ultimately improving productivity, reducing costs, and pro- moting sustainability. By focusing on these key issues, this paper provides valuable insights for policymakers and practitioners in other developing economies seeking to balance infrastructure expansion with digital transformation.

This paper aims to contribute meaningfully to the literature in this area by reviewing current global ETC deployment trends and examining in depth the case of Vietnam's transition to full ETC implementation on its highway networks. Vietnam's experience and the tangible gains realized from this endeavor provide valuable policy insights and lessons applicable to other developing countries.

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[2] In the MTC system, tolls are collected from drivers at toll booths by human operators or automated machines, requiring vehicles to stop or slow down to make payments, often leading to delays and increased fuel consumption. In contrast, the ETC system allows vehicles to pass through toll points without stopping, using wireless technology to automatically charge tolls, thereby reducing traffic congestion, saving time, and lowering fuel consumption.

The paper is organized as follows: Section 2 details the research methods employed in this study. Section 3 outlines global trends in ETC adoption, with a focus on the MTC-to-ETC transition on highways in China and India. Section 4 elaborates on Vietnam's ongoing efforts to deploy ETC on highways. Section 5 estimates the tangible gains from this deployment in recent years and projects expected gains for the period from 2024 to 2030. Policy lessons are discussed in Section 6, followed by the conclusion in Section 7.

2. Research method

2.1. Research Design

The primary focus of this study is to estimate the gains from deploying ETC systems compared to MTC on highways in Vietnam. To achieve this, the study employs a mixed-methods approach, combining quantitative and qualitative data collection and analysis techniques. The research design aims to assess both the direct and indirect benefits of ETC deployment, including time savings, fuel savings, reductions in CO2-equivalent emissions, and improvements in toll collection efficiency. Additionally, a perception survey of drivers provides complementary insights into the benefits of transitioning from MTC to ETC on Vietnam's highways.

2.2. Data Collection

2.2.1. Primary Data:

The primary data were obtained from two main sources: (i) surveillance camera systems installed on various highways before and after ETC implementation, and (ii) a survey conducted among drivers using both Manual Toll Collection (MTC) and ETC systems on highways. The surveillance data provided detailed transaction times for both ETC and MTC, while the survey captured drivers' per- ceptions of waiting times and their overall experience with the two systems.

2.2.2. Secondary Data:

Secondary data were sourced from the Ministry of Transport (MOT) and ETC operators, which included statistics on highway traffic volumes, vehicle population distribution, and fuel consumption rates. Additionally, international benchmarks were used to estimate the CO2-equivalent emissions associated with fuel consumption by idling vehicles.

2.3. Estimating the potential gains of ETC deployment on highways

Previous studies have examined and evidenced the potential benefits of replacing manual toll collection (MTC) with ECT systems on toll facilities, particularly highways (e.g., Andani et al., 2019; Gillen, Li, Dahlgren, & Chang, 1999a, 1999b; Huang et al., 2020; Karsaman et al., 2015; Lin et al., 2020; Parmar et al., 2018; Shahrier et al., 2024). The anticipated benefits from highway ETC deployment could be categorized into four groups of beneficiaries: the ETC user, the toll agency, society and the environment, and the economy and government. The salient benefits potentially gained by each of these four stakeholders are elaborated in Table 1.

The estimation exercise involves several steps, including the following:

(i) Estimation of time savings: Core data for time savings were derived by comparing the transaction times between ETC and MTC systems. The average time saved per vehicle was calculated and further refined through a simulation model that estimated waiting times at toll gates during different traffic conditions.

(ii) Fuel and emissions savings: Fuel savings were estimated based on the reduction in idling time for vehicles using ETC lanes compared to MTC systems. The corresponding reduction in CO2-equivalent emissions was calculated using standard emission factors for gasoline and diesel consumption.

(iii) Cost-Benefit Analysis: The monetary equivalent of time, fuel, and emissions savings was estimated using conservative as- sumptions based on average hourly labor productivity and vehicle rental costs in Vietnam. The overall benefits were then projected for the period from 2019 to 2030, considering anticipated growth in ETC transactions and highway expansions.

2.3.1. Estimation models

The study used a set of estimation equations adapted from previous research on toll collection systems. These models were cali- brated to the specific context of Vietnam using input data such as the distribution of vehicle types, fuel consumption rates, and emission factors. The models allowed for the calculation of annual benefits in terms of manpower time savings, fuel savings, CO2- equivalent emissions reduction, and toll collection efficiency improvements.

The study acknowledges certain limitations, including potential biases in the survey sample due to the convenience sampling method and the assumption of stable traffic patterns and vehicle population distributions over the examined period. Despite these limitations, the study provides robust estimates of the benefits of ETC deployment, supported by rigorous data analysis and inter- national benchmarking.

Table 1. Potential benefits from ECT deployment by stakeholder

Beneficiary	Salient benefits
ETC users	• Time savings • Improved travel planning • Reduced travel fatigue • Fuel savings • Extended service life of vehicles • Overall satisfaction
Toll Agency	• Elimination of costs associated with MTC (tolling booths, additional lanes, staff, paper receipts). • Enhancement of management efficiency and effectiveness.

	• Reinforcement of efforts to embrace digital transformation and innovation
Society and the environment	• Reduction in emissions and associated health effects on the community involved. • Decrease inroad accidents (rear-end collisions, side-swipe accidents, aggressive driving; driver confusion,..). • Equity and fairness
Economy and Government	• Increased resources for infrastructure development. • Reduced corruption by tolls collectors. • Increased traffic capacity and reduced congestion • Provision of real-time, reliable data on vehicle movement such as vehicle counts by type, passage time, and travel speed. This data not only enhances the operational management and transparency of toll collection but also provides essential information for better traffic management and economic analyses.[a] • Acceleration of the development of the digital economy, the integration of autonomous vehicles into the transport system and transition towards a cashless society. • Fostering coordination and synergistic value creation within the involved ecosystem.

[a] Kim et al. (2014) and Chen et al. (2024) show that real-time data collected from highway ETC systems provide valuable insights into trans- portation demand and economic activity by region.

3. Overview of global ETC deployment

This section provides an overview of global ETC deployment from three perspectives. First, it highlights the importance of toll infrastructure development in building prosperity and the transition from MTC to ETC systems. Second, it outlines prominent trends in global ETC deployment by analyzing the ETC market, including expenditures on ETC hardware, back-office management, and asso- ciated services. Finally, it explores significant patterns in recent ETC deployment on highways in developing countries by examining the cases of China and India – the two largest emerging economies with rapidly expanding highway networks.

3.1. Toll highway infrastructure and transition to ETC systems

Highway development is crucial for economic prosperity and societal well-being, providing efficient and faster routes for trade, tourism, and access to essential services. By connecting urban centers, rural areas, and industrial zones, highways improve market access, job opportunities, and overall quality of life. The strategic importance of highway development, coupled with private sector growth and global integration in developing nations, has stimulated innovation and partnerships in transportation infrastructure. Toll roads have emerged as a vital solution within this framework.[3]

It's important to note that toll roads, unlike traditional government-funded highways, operate on a user-pays principle, ensuring that those who directly benefit bear a share of the costs. This development model provides a dedicated revenue stream for construction, maintenance, and operation. Globally, there has been a surge in toll road adoption as governments and private investors increasingly recognize tolling as a sustainable funding mechanism, especially in rapidly urbanizing regions with growing mobility needs.

Toll highway projects often involve public-private partnerships (PPPs), leveraging expertise and resources from the private sector to efficiently deliver high-quality infrastructure. Consequently, toll highways have become integral to comprehensive transportation strategies, fostering economic growth, connectivity, and sustainable development. Additionally, implementing usage pricing and toll collection for highways has been a key management priority to ensure sustainable financing for their development.

Over the past three decades, methods of collecting usage fees on tolled facilities have undergone significant transformation, transitioning from MTC to ETC systems. The rapid progress and penetration of digital technologies have facilitated the adoption of ETC, enabling it to generate substantial gains for all stakeholders.

However, it is important to note that the transition from MTC to ETC systems over the past three decades has been an evolution with incremental advancements from simple cash-based MTC models to full-speed ETC systems.

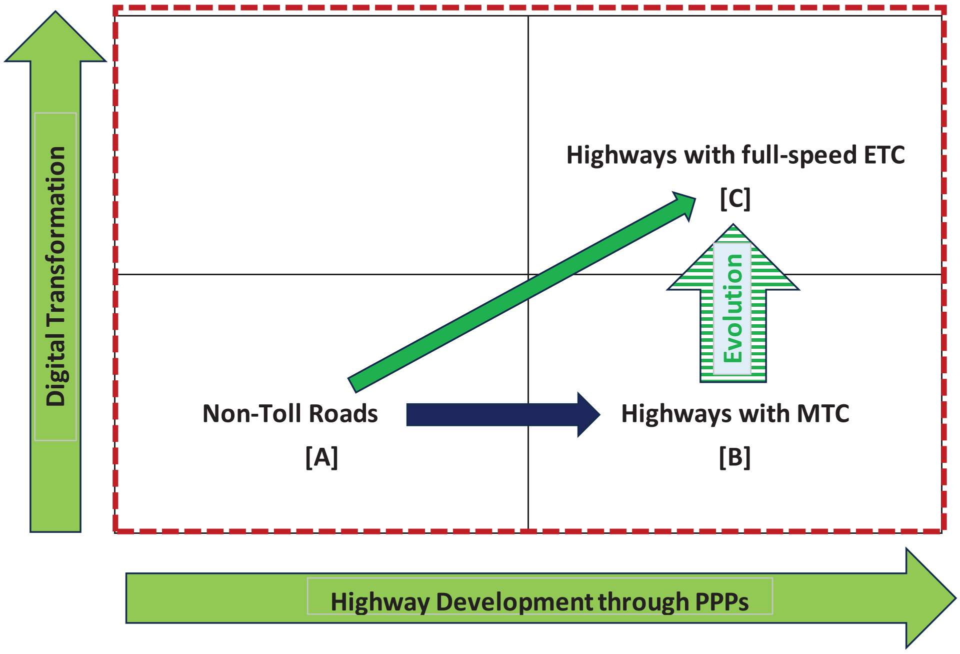
For example, in the mid-1990s, the toll plazas in the US featured up to five types of toll collection lanes: (i) Manual toll lane, where transactions are handled by a toll collector; (ii) Automatic toll lane, operated through coin machines; (iii) Mixed automatic vehicle identification (AVI) lane, where AVI – an early version of ETC - is installed on a manual lane, or an automatic lane, or both; (iv) Dedicated AVI lane that permits AVI patrons only; and (v) Express AVI lane that permits free-flow speeds up to 88 km/h (Al-Deek et al., 1997). Furthermore, as of the mid-2000s, only 85 (59.4%) out of 143 tolled highways in the US had adopted some form of ETC system (Holguin-Veras et al., 2006).

The rapid improvements in ETC solutions in the last two decades, particularly in performance and investment cost, have made their deployment much more feasible and cost-effective. Consequently, the deployment of ETC on tolled facilities, especially on highways, has accelerated. This acceleration is evident in the transition from MTC to ETC on existing highways and the immediate deployment of ETC systems on newly developed highways without the installation of MTC. This is illustrated in diagram 1 below.

[3] As an illustrative example, the Cipularang toll road, connecting Jakarta and Bandung, not only reduced travel time between these two major Indonesian cities from around 5 h to about 2 h but also greatly stimulated urbanization, industrial growth, upgrading, and tourism in the region (Andani et al., 2021; Anas et al., 2017.

The diagram in Fig. 1 illustrates three possible scenarios for modernizing a country's road networks: (i) investing in a new highway with MTC systems (from point A to point B), (ii) replacing MTC with ETC on an existing highway (from point B to point C), and (iii) building a new highway with ETC systems without the installation of MTC (directly from point A to point C).

Fig. 1. PPP-Driven Highway Development and Evolution of Toll Road Payment Methods



Source: Author

The transition to ETC deployment on highways in developing countries, however, is not without its challenges. The case of Indonesia serves as an illustrative example of this evolving process. According to the Ministry of Public Works and Housing, I. T. R. A. (2017), as of the end of 2016, 77% of toll transactions on Indonesia's highway system, spanning 987 km with 261 toll plazas and 1,484 toll booths, were cash-based. Meanwhile, 23% utilized electronic cards, either by tapping the card on a reader device (requiring the vehicle to stop) or using an e-card plugged into an onboard unit (OBU), which necessitates the vehicle to slow down. To address this issue, the Indonesian government aimed to accelerate the penetration of e-payment to 100% by the end of 2017 (Ministry of Public Works and Housing, I. T. R. A. (2017)). However, despite achieving this goal, congestion during rush hour remained a problem, as toll users still needed to stop their vehicles to tap the card to the reader device (Kamiliah & Wijaya, 2023). Consequently, the Indonesian government introduced an initiative, later embodied in a regulation issued by the Minister of Public Works and Public Housing in 2020, to foster the deployment of full-speed ETC systems on its toll roads.

3.2. Global trends of ECT deployment

This subsection draws insights on the global trends of ETC deployment by examining the global ETC market, which captures ex- penditures on ETC hardware, back-office support, and related services. As illustrated in Table 2, the global ETC market can be segmented based on application, technology, and geographic region. Several noteworthy observations emerge from this analysis.

First, the total market size of the global ETC market reached US$9.2 billion in 2023 from US$7.05 billion in 2020, reflecting a compound annual growth rate (CAGR) of 9.4%. The market is projected to sustain this high growth trajectory with a CAGR of 8.1% over the next five years, reaching US$14.7 billion by 2029.

Second, the Highway application constitutes approximately 90% of the global ETC market, with its share increasing from 88.8% in 2020 to 89.6% in 2023 and projected to reach 91.1% by 2029. The remaining application, Urban Areas, which provides urban so- lutions for congestion reduction, parking access, and environmental management, accounts for approximately 10% of the market. While it exhibits healthy growth rates, they are lower than those of the highway application in both periods: 6.9% compared to 9.7% during 2020–2023 and 5.3% compared to 8.4% for 2023–2029.

Third, among three key ECT (Electronic Toll Collection) technologies, namely ‘Radio Frequency Identification’ (RFID), ‘Dedicated Short-Range Communications’ (DSRC), and ‘Others’, RFID commands a majority share of the global ECT market. Its share has seen a slight increase from 63.2% in 2020 to 63.5% in 2023, and it is projected to reach 63.9% by 2029. Conversely, the share of DSRC is experiencing a declining trend, decreasing from 31.6% in 2020 to 30.5% in 2023 and is expected to further reduce to 28.4% by 2029. Meanwhile, the share of other technologies is witnessing rapid expansion, indicating a transition away from DSRC technology, which has been widely adopted in Europe, towards either RFID or emerging new ECT technologies.

Table 2. Global ETC market

	Market Size (US$ million)			Share in Total Global ETC Market			Growth Rate by Period (CAGR)	
	2020	**2023**	**2029**	**2020**	**2023**	**2029**	***2020-23***	***2023-29***
Total Market	**7,050**	**9,222**	**14,741**	**100**	**100**	**100**	***9.4%***	***8.1%***
Breakdown by Application								
Highways	6,262	8,259	13,428	**88.8**	**89.6**	**91.1**	*9.7%*	*8.4%*
Urban Areas	788	963	1,313	**11.2**	**10.4**	**8.9**	*6.9%*	*5.3%*
Breakdown by Technology								
RFID	4,455	5,856	9,422	**63.2**	**63.5**	**63.9**	*9.5%*	*8.2%*
DSRC	2,225	2,810	4,186	**31.6**	**30.5**	**28.4**	*8.1%*	*6.9%*
Other Technologies	370	555	1,133	**5.3**	**6.0**	**7.7**	*14.5%*	*12.6%*
Breakdown by Geography								
North America	2,468	3,083	4,496	**35.0**	**33.4**	**30.5**	*7.7%*	*6.5%*

Europe	2,115	2,704	4,127	**30.0**	**29.3**	**28.0**	*8.5%*	*7.3%*
Asia Pacific	1,833	2,570	4,717	**26.0**	**27.9**	**32.0**	*11.9%*	*10.7%*
Rest of world	635	866	1,400	**9.0**	**9.4**	**9.5**	*10.9%*	*8.3%*

Source: Author's calculation with data from M&M (2024)

Similarly, Table 3 summarizes the development of the ETC market in Asia-Pacific countries. The following observations stand out from Table 2.

First, the highway application accounts for more than 90% of the Asia Pacific ETC market, with its share expanding from 91.4% in 2020 to 92.2% in 2023 and is projected to reach 93.8% by 2029. Compared to the global ETC market shown in Table 1, the Asia Pacific ECT market experienced significantly faster growth in this highway segment, witnessing growth rates of 12.2% versus 9.7% during 2020–2023 and 11.0% versus 8.4% for 2023–2029.

Second, the RFID technology currently dominates the Asia Pacific ETC market, although its share is gradually declining, from 80.3% in 2020 to 79.5% in 2023 and is projected to reduce to 78.0% by 2029. This downward trend is attributed to the increasing adoption of alternative technologies compared to RFID, with growth rates of 13.4% versus 11.6% for the period 2020–2023, and 12.0% versus 10.3% for 2023–2029. This shift suggests a growing acceptance of new ETC technologies beyond RFID in the region.

Third, China is the largest adopter of ETC among Asia Pacific countries. However, its share in the region's ETC market is declining, from 32.0% in 2020 to 30.2% in 2023 and is projected to drop to 27.0% by 2029. Japan's share follows a similar pattern. Conversely, ASEAN nations and the rest of Asia Pacific, likely spearheaded by India, are experiencing faster growth rates. This shift indicates that the drive for modernization and digital transformation across the Asia Pacific region is now extending beyond China, encompassing ASEAN and other nations.

Table 3. Asia Pacific ETC market

	Market Size (US$ million)			**Share in Total Asia Pacific ETC Market**			**Growth Rate by Period (CAGR)**	
	2020	**2023**	**2029**	**2020**	**2023**	**2029**	***2020-23***	***2023-29***
Total Market	1,833	2,570	4,717	**100**	**100**	**100**	***11.9%***	***10.7%***
Breakdown by Application								
Highways	1,676	2,369	4,425	91.4	92.2	93.8	***12.2%***	***11.0%***
Urban Areas	158	200	292	8.6	7.8	6.2	***8.4%***	***6.5%***
Breakdown by Technology								
RFID	1,472	2,043	3,679	80.3	79.5	78.0	*11.6%*	*10.3%*
Other Technologies*	361	526	1,038	19.7	20.5	22.0	*13.4%*	*12.0%*
Breakdown by Geography								
China	587	777	1,274	32.0	30.2	27.0	*9.8%*	*8.6%*
Japan	220	290	472	12.0	11.3	10.0	*9.7%*	*8.4%*
ASEAN Countries	275	394	755	15.0	15.3	16.0	*12.7%*	*11.5%*
Rest of Asia Pacific	752	1,109	2,217	41.0	43.1	47.0	*13.8%*	*12.2%*

Source: Author's calculation with data from M&M (2024); Other technologies include automatic number/license plate recognition (ANPR/ALPR), automatic vehicle classification (AVC), and weigh-in-motion (WIM) tolling.

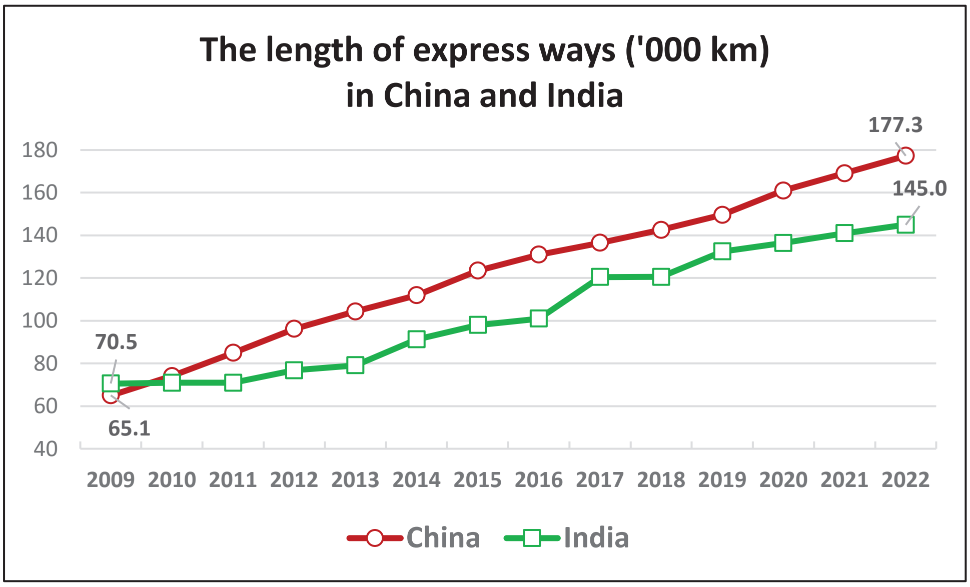
To gain further insights into ETC deployment on highways in Asia, Subsection 3.3 below examines the advancement in this front of the region's two largest nations, China and India.

3.3. Highway development and ETC deployment in China and India

3.3.1. Highway development and the importance of tolling policy in China and India

To facilitate their rapid economic growth and modernization efforts, both China and India have made significant investments in the development of highway systems. Between 2009 and 2022, the total length of highways in China increased from 65.1 to 177.3 thousand km, representing a CAGR of 8%. Meanwhile, in India, the respective figures rose from 70.5 to 145.0 thousand km, with a CAGR of 5.7% (Fig.2) during the same period.

Figure 2. The length of highways in China and India, 2009-2022



Source: Source: Author, using data from Statista (China: Statista - Total length of China's freeways; India: Statista - Length of India's national highways).

In efforts to accelerate the development of highway networks, both China and India have embraced tolling strategies as major levers to stimulate investment in their highway infrastructure, with China emerging as a leading player. For instance, in 2013, China accounted for approximately 70% of global tolled roads (Reja et al., 2013). Additionally, by 2020, China had 152,900 km of toll expressways, representing around 95% of the total expressway mileage (Chinahighway.com, 2020).

Moreover, annual investment in tolled highways in China nearly doubled from CNY 6,145 billion (US$ 860 billion) in 2014 to CNY 12,118 billion (US$ 1,697 billion) in 2021 (source: Statista database). Furthermore, the annual revenue from toll road passage fees in China experienced a compound annual growth rate (CAGR) of 8.5% from 2010 to 2019 (the year prior to the Covid-19 outbreak), rising from CNY 286 billion in 2010 to CNY 594 billion (approximately US$ 88.7 billion) in 2019 (source: Statista database).

Similarly, India has also increasingly relied on tolling policies to expedite the development of its highway systems. Revenue from toll collection on national highways in India witnessed a CAGR of nearly 18% over the past six years, climbing from INR 179 billion in FY2017 to INR 480 billion (US$ 5.9 billion) in FY2023 (source: Statista database).

3.3.2. Key facts on highway ETC deployment in China

The following notable facts emerge from examining the deployment of ETC on highways in China[4], [5]:

(i) The deployment of ETC significantly trailed the rapid expansion of tolled highways. By October 2018, ETC utilization in most provinces was below 50%, with some provinces even below 30% (Baidu, 2024). Despite the considerable increase in ETC users to 270 million by the end of 2022, the adoption rate stood at only 86% out of 316 million vehicles.

(ii) The absence of effective coordination among provinces emerged as a major obstacle to ETC deployment on China's highways. Additionally, the application process was considered cumbersome, especially for infrequent highway travelers. These users found the process hindering their ability to benefit from the convenience of mobile payments, as the application procedures, which included presenting identification documents, vehicle insurance certificates, and making deposits, discouraged adoption (Shangpu Consulting, 2023).

(iii) The Chinese government's role in promoting ETC deployment has become notably effective in recent years. Decisive policy measures, such as abolishing all 487 provincial border toll stations by the end of 2019 (Shangpu Consulting, 2023), have greatly enhanced the operability of the national toll collection system. This has resulted in a significant increase in ETC users from 73 million in 2018 to 200 million in 2019 and 270 million in 2022.

(iv) The deployment of ETC on China's highways has yielded significant benefits. Vehicles equipped with ETC devices experienced a dramatic reduction in toll station passage time, from 14 s to just 3 s, with one ETC lane equivalent to the capacity of five manual toll lanes (Chinanews.com, 2015). Additionally, ETC usage resulted in fuel savings of 20%, a 50% reduction in CO2 emissions, and a 70% reduction in CO emissions per trip (Chinanews.com, 2015). Moreover, the implementation of the ETC system led to substantial cost savings,

[4] Data from: https://baijiahao.baidu.com/s?id=1779619110546160364&wfr=spider&for=pc; accessed 18th March 2024.
[5] Data from: https://baijiahao.baidu.com/s?id=1779619110546160364&wfr=spider&for=pc; accessed 18th March 2024.

including nearly 87% of toll station expansion costs and approximately 20% of labor and service costs (Central Government Portal, 2015). These savings amounted to CNY18 billion (US$2.8 billion) in investment savings over the span of two years (2019–2020) (Baidu, 2024).

3.3.3. Salient facts on highway ETC deployment in India

The deployment of ETC on highways in India exhibits the following three salient facts.

First, the government has taken a leading role in proactively coordinating the deployment of Electronic Toll Collection (ETC) systems on its rapidly expanding highway networks. Particularly, a panel was formed to select ETC technology for implementation on national highways, chaired by Shri Nandan Nilekani, Chairman of the Unique Identification Authority of India. The committee evaluated various technologies for ETC and recommended the adoption of passive Radio Frequency Identification (RFID) based on EPC, Gen-2, ISO 18000-6C Standards, considering factors such as user convenience, adoption rate, and implementation ease (Ministry of Information & Broadcasting, P. I. B. (2023, July 10)). Additionally, to facilitate ETC deployment, the government established the Highways Management Company Limited (IHMCL) in 2012, tasked with nationwide implementation of RFID-based ETC systems on India's national highways (Indian Infrastructure, 2017). IHMCL and the National Highways Authority of India (NHAI) introduced FASTag, a toll collection mechanism utilizing RFID tags on vehicles. The National Electronic Toll Collection (NETC) program developed by the National Payments Corporation of India (NPCI), has played a crucial role in driving digital transactions across the country (PWC, 2022).

Second, India has adopted an ecosystem approach to promote the deployment of Electronic Toll Collection (ETC) on highways. The ecosystem involves multiple stakeholders, including the IHMCL[6], tag-issuing and acquiring banks, concessionaire/plaza operators, the Ministry of Road Transport and Highways (MoRTH), tag manufacturers/vendors, and the National Payments Corporation of India (NPCI), and NHAI. According to PWC (2022), this approach is pivotal for the efficient and successful operation of the National Electronic Toll Collection (NETC) program. Noteworthy features of the NETC ecosystem include effective program communication through stakeholders' websites, which articulate its clear objectives[7], and transparency in the ETC development process, evidenced by timely and comprehensive annual reports published by stakeholders.

Third, India has experienced remarkable growth in its highway Electronic Toll Collection (ETC) deployment since the official launch of the National Electronic Toll Collection (NETC)

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[6] IHMCL, which is responsible for highway ETC deployment, was established in 2012 with three shareholders: NHAI (41.38%); Concessionaires (33.81%); and Financial Institutions (24.81%). Source: https://ihmcl.co.in/about-us/, accessed 20th April 2024.

[7] As outlined on the NETC website, these objectives encompass: (i) establishing an interoperable secure framework applicable nationwide; (ii) enhancing transparency and efficiency in transaction processing; (iii) promoting the electronification of retail payments; (iv) mitigating air pollution by alleviating congestion around toll plazas; (v) curbing fuel consumption; (vi) minimizing cash handling; and (vii) bolstering audit control through centralized user accounts. (Source: https://www.netc.org.in/about-netc-fastag)

program by the Ministry of Road Transport & Highways (MoRTH) in October 2014. The number of ETC FASTag transactions has surged by 162 times, from 23.6 million in FY2015-16 to 3,825.1 million in FY2023- 24. Concurrently, revenue has increased nearly 100 times over the same period, from INR6.6 billion (figures may be provided in USD also) in FY2015-16 to INR648 billion (US$8.5 billion) in FY2023-24 (IHMCL, 2024).

Fourth, while the deployment on India's highways has yielded significant benefits, there is considerable potential for India to further enhance the outcomes of its deployment initiatives. For instance, although the average waiting time per vehicle at toll plazas has notably decreased from 734 s on average MTC transaction to 47 s by 2023, with the government aiming to reduce it to 30 s soon (Mint, 2023), this waiting time is too long compared to the efficiency of toll plaza operations in other countries, such as Vietnam, as discussed in Section 4.

The rapid expansion of highway networks in China and India, along with their accelerated efforts in ETC deployment, highlights the importance of gaining a comprehensive understanding of these dynamics in the developing world, where infrastructure development and digital transformation often occur simultaneously and reinforce one another in both efficiency and effectiveness.

To address this, Section 4 examines Vietnam as a case study, focusing on the dynamics of ETC deployment on its highway networks and the potential gains from this effort. Vietnam was selected for two primary reasons. First, since its economic reforms in 1986, Vietnam has emerged as one of the fastest-growing economies globally, with rapid infrastructure development and strong efforts toward digital transformation driving much of its success Vu and Austin (2015). Second, Vietnam has made significant strides in ETC deployment on its highways, moving from no ETC systems in 2014 to achieving full deployment by 2023.

4. Vietnam's highway development and ETC adoption

4.1. The development of highways in Vietnam

Since the launch of economic reform in 1986, Vietnam has undergone a remarkable transformation from an impoverished and isolated country to one of the world's fastest-growing and most globally integrated economies (Vu and Austin, 2015).

A pivotal driver behind Vietnam's economic growth and integration into the global economy has been its substantial investment in strategic infrastructure, with the construction of highways emerging as a top priority. As a piece of evidence, Vietnam's highway network reached a length of 1,163 km in 2020, recording a CAGR of nearly 29% over the decade from 2010, which far exceeded those observed in other major economies of ASEAN countries (see Table 4).

Table 4. Total length of expressways in ASEAN by country (km)

Country	2010	2015	2020	CAGR

				(2010-2020)
Cambodia	--	--	187	--
Indonesia	758	948	2,346	12.0%
Lao PDR	--	--	109	--
Malaysia	1,666	2,021	2,016	1.9%
Myanmar	587	590	590	0.0%
Philippines	312	378	445	3.6%
Singapore	161	164	164	0.2%
Thailand	208	208	225	0.8%
Viet Nam	89	699	1,163	29.3%
Total ASEAN	**3,781**	**5,008**	**7,244**	**6.7%**

Source: ASEAN Statistics Database; available at https://data.aseanstats.org/indicator/ASE.TRP.ROD.A.004

The rapid expansion of highway networks in Vietnam has been chiefly driven by its implementation of tolling strategies, supported by significant participation from the private sector in construction and operation. Consequently, by early 2024, Vietnam's toll highway network had reached a total length of 1340 (812.5 + 528.2) km (Table 5.)

While Vietnam had previously depended on Manual Toll Collection (MTC) for its existing 812 km of toll highways, the country decisively transitioned to Electronic Toll Collection (ETC) beginning on August 1st, 2022 (See Table 5). Furthermore, it mandated direct full ETC implementation for all newly built or upgraded highways following this date. Vietnam's decisive adoption of ETC deployment on highways in August 2022 can be attributed to the following four reasons.

First, the Manual Toll Collection (MTC) systems on existing highways demonstrated notable limitations, as evident by severe traffic congestion at toll plazas during peak hours and holiday periods, owing to the influx of vehicles. The government has attempted to tackle this pressing problem with regulatory measures, but they appeared ineffective in successfully addressing these challenging situations.

Second, the rapid advancement of digital technologies has significantly enhanced the feasibility, cost-effectiveness, profitability, and operational efficiency for toll agencies in deploying ETC over MTC. Various attractive ETC solutions are offered by global leading providers such as ...

Third, Vietnam is steadfastly pursuing its goal of expanding its highway network from 1,290km in 2021 to 5,000km by 2030 (Pham, C. (2022,)). Among the policy measures to facilitate this development, the government is further leveraging the tolling approach, issuing a decree to monetize state-owned road infrastructure assets by transferring toll collection rights to private entities, aiming to boost revenue generation.[8]

[8] Pham, C. (2022, September 9). Why Vietnam's Infrastructure is Crucial for Economic Growth. Vietnam Briefing. https://www.vietnam-briefing.com/news/why-vietnams-infrastructure-crucial-for-economic-growth.html/

Fourth, private businesses are well prepared and eager to capitalize on the full deployment of ETC on highways, recognizing it as a promising avenue for cost-effectiveness, profitability, and the enhancement of their ESG (Environmental, Social, and Governance) business profile (Source: author's interviews with ETC operators in Vietnam).

Table 5. Vietnam's toll highways and the deployment of ETC

Highway	Length (km)	Commencement Date	Full ETC Implementation Date	Tolling Operator
The Highways Transitioning from MTC to ETC (A)				
Ha Noi-Hai Phong	105.0	12/5/2015	6/1/2022	VETC
Noi Bai-Lao Cai	245.0	21/9/2014	8/1/2022	VETC
Phap Van-Cau Gie	32.3	30/12/2018	8/1/2022	VETC
Cau Gie-Ninh Binh	74.0	30/6/2018	8/1/2022	VETC
Bac Giang-Lang Son	64.0	15/1/2020	8/1/2022	VDTC
Ha Noi-Bac Giang	45.8	1/3/2016	---[a]	VETC
Da Nang-Quang Ngai	139.2	9/2/2018	8/1/2022	VETC
Trung Luong-My Thuan	51.5	19/1/2022	8/9/2022	VETC
HCMC-Long Thanh-Dau Giay	55.7	T2/2015	8/1/2022	VETC
Total (A)	**812.5**			
New Highways with Direct ETC Deployment (B)				
Cam Lam-Vinh Hao	78.5	28/04/2024	5/2/2024	VETC
Phuoc An	4.5	Q4/2024 (sch.)	NA	NA
Phu Huu	2.6	5/2024 (sch.)	NA	VETC
Dau Giay-Phan Thiet	99.0	30/04/2023	30/04/2023	VETC
Ha Long-Van Don	64.0	30/12/2018	8/1/2022	VETC
Tien Yen-Mong Cai	64.0	9/1/2022	10/5/2022	VDTC
National Road N.18	30.0	13/02/2018	8/1/2022	VETC
Lao Cai-Sa Pa	29.2	22/09/2023	2/8/2024	VDTC
Nha Trang-Cam Lam	49.1	19/05/2023	26/04/2024	VDTC
Dien Chau-Bai Vot	49.3	28/04/2024	9/2/2024	NA
Ben Luc-Long Thanh	58.0	Under construction	NA	NA
Total (B)	**528.2**			

Source: Vietnam's Ministry of Transport

Note: [a] ETC was deployed on this highway on 17/10/2017 marking a gradual transition from MTC (authors' interviews).

4.2. Implementation of ETC on Vietnam's highway

Vietnam began investigating the deployment of non-stop Electronic Toll Collection (ETC) technology on its highway networks in the late 2000s, where two-stop and one-stop Manual Toll Collection (MTC) systems were predominant (Ministry of Transport, Vietnam, J. I. C. A. (JICA). (2010)). Until 2015, the only ETC technology deployed was DSRC (Dedicated Short-Range Communication) 5.8 GHz. [9] However, the adoption of this technology progressed slowly, reaching only 50,000 vehicles (approximately 1% of the total vehicle population).

To accelerate the deployment of ETC, in mid-2014, the Ministry of Transport (MOT) with the approval of the Prime Minister established an inter-agency deliberation group to identify the non-stop highway ETC technology for national adoption. The group concluded that passive RFID technology emerged from comparisons to other technologies, particularly DSRC, as a preferable choice based on three selection criteria: (i) Expected much faster penetration compared to DSRC [10]; (ii) low user adoption cost per vehicle ($1–2) compared to $30–40 for the required on-board unit (OBU) of DSRC applied in Japan, Singapore, and France; and (iii) RFID tags affixed to vehicles can serve as unique identifiers and require no internal energy, which make it more convenient for maintenance and management.

Following the conclusion, MOT issued order (Document No. 14767/BGTVT-CQLXD) dated November 21, 2014, assigning Tasco Joint Stock Company to conduct a pilot of RFID technology at three toll stations on their BOT highway projects. After more than 10 months of piloting, monitoring, and evaluation, MOT determined that passive RFID technology is the most suitable non-stop toll collection solution for Vietnam. With the pilot implementation results, MOT issued another order (Document No. 11138/BGTVT- CQLXD) on August 21, 2015, to seek the approval of the Prime Minister for the widespread adoption of RFID technology on Vietnam’s highways. This proposal was approved, and the official ETC deployment was launched, beginning with National Highway 1 and the Ho Chi Minh Road segment passing through the Central Highlands.

The rapid transition from MTC to ETC on Vietnam’s highways since 2015 can be observed through three main angles.

First, the number of ETC lanes increased by over 100-fold from 8 lanes in 2015 to 851 lanes in 2023. By May 2024, the count had reached 905 out of a total of 922 highway lanes[11], demonstrating a penetration rate of 98%. (Fig. 3)

Second, the number of vehicles equipped with eTags surged from 48,000 (1.5% of the total vehicle population on roads) in 2016 to over five million (94.5%) in 2023. By May 2024, this

[9] In this initial stage, Vietnam deployed DSRC passive technology following European standards on national highways and active DSRC technology following Japanese standards on the HCMC-Long Thanh-Dau Giay expressway.

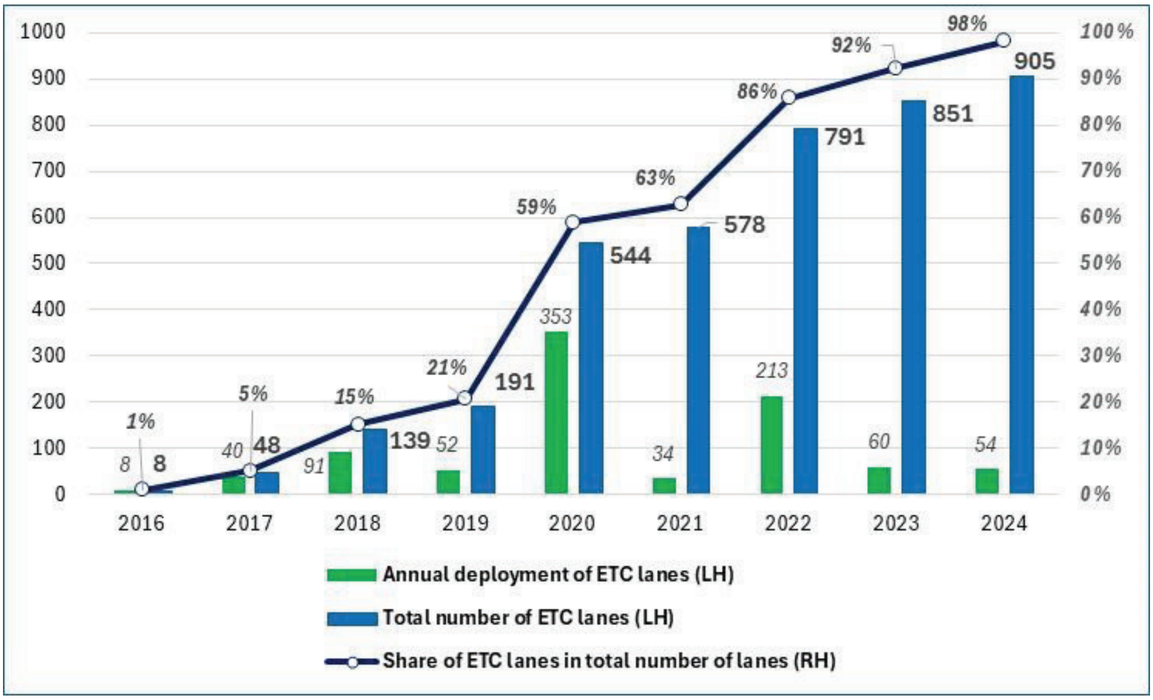
[10] From their study, the taskforce underscores RFID's clear advantage over DSRC in driving ETC adoption through the cases of Japan and Taiwan. In Japan, DSRC-based ETC adoption required 11.5 years to achieve 90%, while in Taiwan, it took 6.5 years to reach just 45% adoption. Yet, Taiwan's transition to RFID resulted in a remarkable turnaround, with adoption soaring from 45% to 90% in a mere 1.5 years, effectively overcoming DSRC saturation.

[11] The remaining 17 MTC lanes, belonging to highways constructed before 2016, have encountered some obstacles to ETC deployment, primarily related to financial arrangements associated with their BOT contracts. However, it is anticipated that these obstacles will be resolved by 2024-2025.

figure stood at 5.349 million out of 5.553 million vehicles on roads, indicating a penetration rate of 96.3% (Fig. 4)

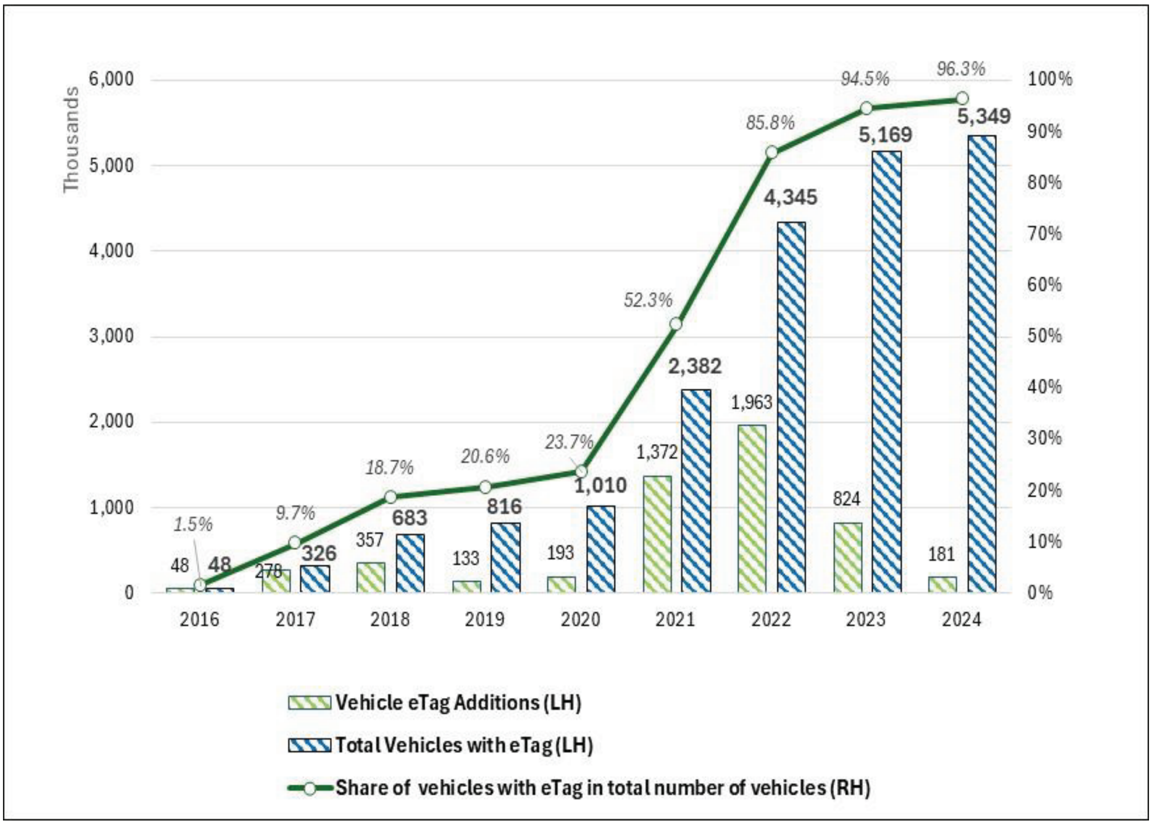
Third, the annual volume of ETC transactions surged from 29 million in 2019 to 414 million in 2023, recording a Compound Annual Growth Rate (CAGR) of 94%, nearly doubling each year over the four-year period from 2019 to 2023 (Fig. 5). This underscores Vietnam's remarkable strides in transitioning from MTC to ETC during this period. In the first quarter of 2024, the volume of ETC transactions was 113 million, suggesting a projected volume for 2024 of at least 450 million, representing a growth rate well about 8.9% compared to 2023. Cumulatively, the total volume of ETC transactions reached 878 million by the end of 2023 and 991 million by the first quarter of 2024 (Fig. 5).

Figure 3. Number of lanes with ETC deployment on Vietnam's highways, 2016-2024



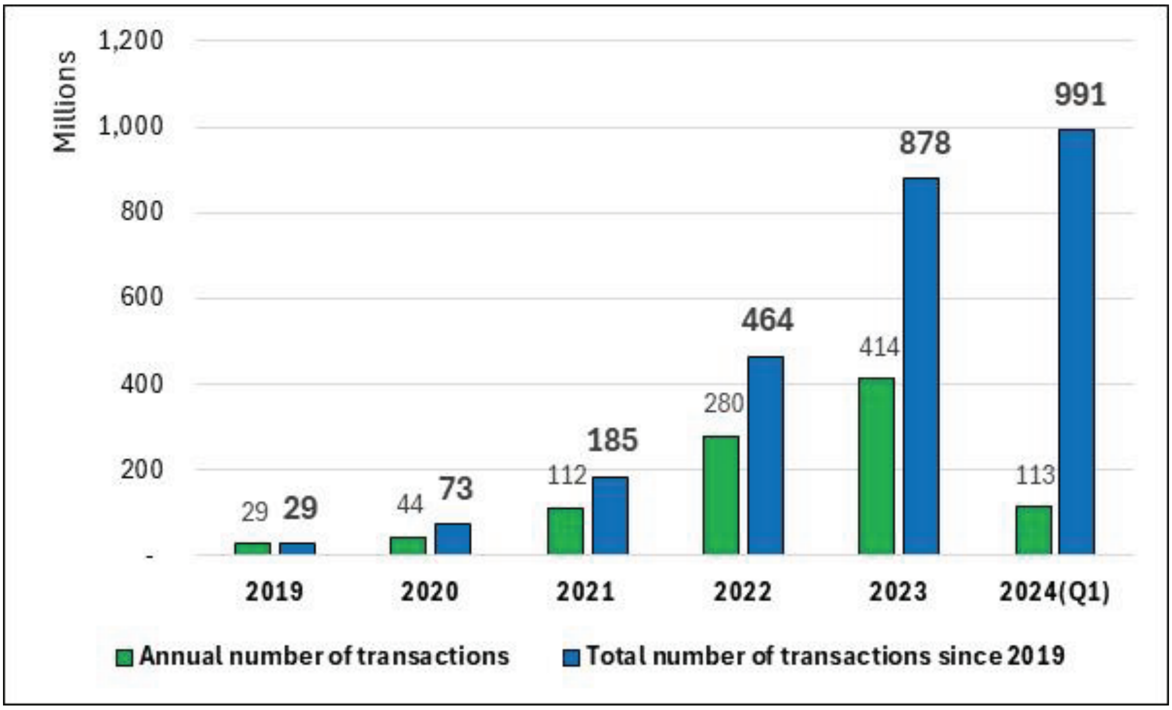
Source: Authors, with data from MOT.

Figure 4. Penetration of Vehicles with eTags, 2016-2023



Source: Authors, with data from MOT and GSO.

Figure 5. ETC transactions on Vietnam's highways, 2019-2023



Source: Authors, with data from MOT.

5. Estimating gains from ETC deployment on Vietnam's highways

The estimation exercise using the data from the case of Vietnam aim to provide fresh insights into the realized gains from deploying ETC systems on highways in a developing country with highway networks being rapidly developed from scratch over the recent decades. The estimation is focused on quantifying these gains through the following five measures: (i) time savings for ETC user; (ii) CO2-equivalent emissions reduction; (iii) cost saving for tolling management; (iv) energy saving; and (v) monetary equivalent value savings.

5.1. Estimation objectives and the core data

5.1.1. Estimation objectives

As discussed in Section 3, the deployment of ETC systems on highways is expected to yield substantial benefits across crucial metrics. Among these, time savings, energy efficiency, emission reduction, cost-effectiveness, safety enhancements, and user satis- faction stand out as the most significant direct gains.

With the data collected from our research on this project, our goal is to quantify the benefits of ETC development on Vietnam's highways across five key metrics: (i) time savings for ETC users and their vehicles; (ii) Fuel savings; (iii) reduction in CO2-equivalent emissions; (iv) savings in toll collection costs; and (v) total cost savings.

Our estimation will focus on the years from 2019 to 2023, for which data on the annual volume of ETC transactions are available. Additionally, we will extend this analysis to provide projections for the period from 2025 to 2030. These projections will be based on the anticipated growth of ETC transaction volume, considering the expected expansion of toll highway length and the increase in the number of vehicles on the roads.

5.1.2. The core data

The total amount of time saved by highway users due to the transition from MTC to ETC is the cornerstone of our estimation. This core data requires reliable raw data from the Ministry of Transport and the ETC operator, as well as rigorous estimation techniques. This core data is the average time saved by a vehicle from transition from MTC to ETC systems.

This average time saving comprises two components: time saved from payment transactions and waiting time that vehicles must spend in line awaiting their turn to make manual payments at the toll gate.

To estimate the time saved from payment transactions, we examine archived real-time data extracted from surveillance camera systems several highways before and after their ETC implementation. Thanks to our research collaborators from Ministry of Transport and ETC operators, we were able to draw two random samples: one comprising 333 ETC transactions and the other 204 MTC transactions. For illustration, Appendix 1 provides 45 observations from each of these two samples.

Table 6 provides the summary statistics of the ETC and MTC samples. As shown, it takes a vehicle only 8.3 s to complete an ETC transaction, compared to 41.6 s for MTC, indicating a time reduction of 33.3 s. This time saving is observed for all vehicle types, including cars (30.8 s), buses (38.0 s), trucks (31.8 s), and trailers/heavy trucks (47.8 s).

Table 6. Estimation of ETC and MTC transaction times (in seconds) based on surveillance data sample

Vehicle Type	Transaction time required by mode of payment						Difference	
	ETC			MTC			MTC-ETC	
	N	Mean (1)	SD (2)	N	Mean (3)	SD (4)	Mean (3)-(1)	SD (4)-(2)
Cars	226	8.3	7.5	134	39.1	11.6	30.8	4.1
Buses	49	7.4	1.9	24	45.4	16.7	38.0	14.8
Trucks	33	7.5	2.0	27	39.3	11.7	31.8	18.0
Container Trailers	25	10.6	2.6	19	58.4	20.6	47.8	18.0
Total	**333**	**8.3**	**6.3**	**204**	**41.6**	**14.4**	**33.3**	**8.1**

Data source: MOT; Note: The mean of the total sample is the average of total 333 observations.

It is also important to note that while ETC allows vehicles to pass through the toll gate at full speed, MTC requires them to stop for manual payment. Therefore, the overall time saved by adopting ETC, compared to MTC, includes not only the time saved from the payment transaction but also the time a vehicle spends waiting in line before making the manual payment.

To estimate the average waiting time for a vehicle before passing through an MTC toll gate, we conduct two complementary ex- ercises. The first approach involves a simple perception survey of drivers with experience using both highway MTC and ETC for a rough estimation. The second approach entails running a simulation based on a typical Vietnamese highway with six lanes and a daily traffic volume of 25,000 vehicles to refine this estimation.

5.1.2.1. Average waiting time from the driver survey. For the survey of drivers, we collected a sample of 125 observations. Despite using a convenience sampling approach, we made every effort to minimize sample bias. As such, we reached out to two groups of drivers: the 'North' group, which includes those mainly using highways in the vicinity of Hanoi, and the 'South' group, which includes those mainly using highways in the vicinity of Ho Chi Minh City (see the questionnaire and respondent profile in Appendix 2).

As shown in Table 7, which summarizes the survey's results, the average waiting time for the overall sample is 3.5 min under normal conditions. However, this time notably increases to 7 min when it is raining, 15.8 min during rush hours, and 22.8 min on major holidays. Additionally, the table indicates that the standard deviation for each measure is notably large, implying significant unpredictability in the waiting times drivers encounter on MTC highways.

Furthermore, the average waiting time for the 'South' group is significantly higher than that for the 'North' group. This can be explained by two main reasons. First, respondents from the 'South' group primarily drew their experiences from using highways near Ho Chi Minh City (Ho Chi Minh-Long Thanh-Dau Giay and Trung Luong-My Thuan), which are relatively busier than those near Hanoi (Ha Noi-Hai Phong and Phap Van-Cau Gie), as reported by the 'North' group (see Appendix 2 for more information on these highways). Second, as highways in Vietnam have experienced rapid growth in traffic volume over time [12], the earlier deployment of ETC systems on the highways experienced by the 'North' group (2018 for Ha Noi-Hai Phong and 2020 for Phap Van-Cau Gie) compared to those referred to by the 'South' group (2022 for both Ho Chi Minh-Long Thanh-Dau Giay and Trung Luong-My Thuan) resulted in notably lower traffic volumes during the last MTC periods for the 'North' highways compared to the 'South' highways.

Besides, the bottom panel of the table shows that drivers almost unanimously recognize the very significant improvement after MTC was replaced by ETC.

Table 7. Results of the driver survey

	North	**South**	**Total**
	(n=68)	**(n=57)**	**(N=125)**
	Average waiting time in normal conditions (minutes)		
Mean	2.9	4.2	**3.5**
Std. dev.	1.5	2.8	**2.3**
	Average waiting time when it is raining (minutes)		
Mean	6.0	8.1	**7.0**
Std. dev.	6.2	5.8	**6.1**
	Average waiting time during heaving traffic hours (minutes)		
Mean	12.1	20.3	**15.8**
Std. dev.	11.5	11.4	**12.2**
	Average waiting time on major holidays (minutes)		
Mean	15.2	31.8	**22.8**
Std. dev.	12.0	14.9	**15.7**
	Level of satisfaction with transition from MTC to ETC		
Mean	2.9	3.0	**2.9**
Std. dev.	0.3	0.1	**0.3**

Notes: The satisfaction level reported by a surveyed driver could take one of three possible values representing their perception of the improvement by replacing MTC with ETC: 1 indicates insignificant; 2 indicates significant; and 3 indicates very significant.

5.1.2.2. Average waiting time from the simulation exercise. While the survey of drivers provides an estimate of the average waiting time based on real user experiences on highway

[12] For example, the four highways examined in this paper recorded a compound annual growth rate of over 10% in traffic volume from 2019 to 2024.

MTC, the simulation exercise offers a rigorous approach to estimate the hypothetical average waiting time on Vietnamese highways if ETC were not implemented. As detailed in Appendix 3, the simulation exercise examines a typical highway based on its daily traffic volume. During the 24-h span of an ordinary day, traffic on a highway follows three typical patterns, depending on the time of travel: (i) 'low-traffic hours' (5 h, from 12am to 5am); (ii) 'medium-traffic hours' (7 h, from 5am to 7am and from 7pm to 12am); and (iii) 'high-traffic hours' (12 h, from 7am to 7pm). These three patterns, respectively, account for approximately 10%, 20%, and 70% of the highway's total daily traffic volume.

The average waiting times estimated from the simulation exercise for Vietnam's highways, based on five scenarios of daily traffic ranging from 30,000 to 100,000 vehicles, are reported in Table 8 below. The results reveal a notable correlation between average waiting time and traffic volume. On an average day, the waiting times vary from 3.5 min for a highway with a daily traffic volume of 30,000 vehicles, to 4.9 min for 40,000 vehicles, 7.7 min for 60,000 vehicles, 10.0 min for 80,000 vehicles, and 12.7 min for 100,000 vehicles. These estimates, consistent with the driver survey's results, suggest that it is plausible to use the average waiting time of 4.9 min for an MTC transaction (the estimate for a 40,000-vehicle highway) to analyze the time saving of ETC implementation on Viet- nam's highways. It should be emphasized that this estimate is conservative for two reasons: (i) it is based on scenarios under normal conditions, without accounting for days of adverse weather conditions or holidays; and (ii) with traffic volumes on Vietnam's highways rapidly increasing, it's highly probable that most highways in Vietnam will experience traffic surge and the daily traffic volume will surpass 40,000 vehicles in the coming years, including the period from 2024 to 2030.

By combining the time saved from payment transactions (approximately 0.5 min (33.3 s)) and the waiting time associated with manual toll collection (4.9 min) as presented above, we assume that the total time saving enabled by ETC implementation is 5.4 min in estimating the gains of ETC deployment on Vietnam's highways.

Table 8. Results of the simulation exercise

Unit: minutes (for average waiting time)

Indicator	Highway by daily traffic volume (two directions)*				
	30,000	**40,000**	**60,000**	**80,000**	**100,000**
	During low-traffic hours (0am-5am, 5 hours)				
Share in traffic volume	10%	10%	10%	10%	10%
Average waiting time	**1.0**	**1.0**	**2.8**	**3.9**	**5.1**
	During medium-traffic hours (5-7 am & 7pm-0am, 7 hours)				
Share in traffic volume	20%	20%	20%	20%	20%
Average waiting time	**1.6**	**2.6**	**4.3**	**3.2**	**6.1**
	During high-traffic hours (7am-7pm, 12 hours)				
Share in traffic volume	70%	70%	70%	70%	70%
Average waiting time	**4.4**	**6.1**	**9.4**	**12.8**	**15.7**
	Overall results for a typical day				
Share in traffic volume	100%	100%	100%	100%	100%
Average waiting time	**3.5**	**4.9**	**7.7**	**10.0**	**12.7**
Std. Deviation	***1.4***	***2.0***	***2.9***	***4.4***	**11.3**

*Notes: * These highways are assumed to have three lanes and six MTC lanes at the toll plaza in one direction.*

5.2. Basic assumptions, estimation equations, and input data

This subsection estimates the benefits of ETC deployment on Vietnam's highways, focusing on five key measures: Manpower time savings, Fuel savings, CO2-equivalent emissions reduction, vehicle time savings, and toll collection efficiency improvement. For each measure, the estimation considers both the volume in relevant units and its equivalent monetary value.

5.2.1. Basic assumptions

For our estimation exercise, we follow a common approach adopted by previous studies such as Gillen et al. (1999a, 1999b) and Holguin-Veras et al. (2006) in making some basic assumptions. These assumptions help plausibly determine the value of various variables in the models used. They include:

1. The distribution of vehicles using highways follows the distribution of the country's overall vehicle population observed
2. The energy consumption by idling vehicles and CO2-equivalent emissions per unit of energy consumed are consistent with in- ternational benchmarks.
3. The monetary value per hour of labor is two-thirds of the country's average labor productivity, which was approximately $3/hour in 2023.
4. The monetary value per hour of a vehicle is proportional to its hourly rental price.
5. The average number of occupants per type of vehicle, as well as the key statistics above, are stable throughout the examined period.

   Our estimation is based on the conservative assumption. According to Gillen et al. (1999b:65), the average occupancy observed in the US was 1.84 for passenger cars, 1.1 for trucks, and 21.2 for buses.

5.2.2. Estimation equations and input data

The estimation equations below are for estimating the gains realized during a given year. They employ the following common notations:

- t_{ETC} for the overall time saved from the MTC-ETC transition, which is 5.4 mins as estimated in Subsection 5.1.2.
- C is the annual volume of ETC transactions.
- s_k is the share of type k in the total population of vehicles on roads as introduced in Subsection 5.2.1.

(i) <u>Manpower time savings (in hours) and monetary equivalent value</u>

Total manpower time savings measured in hours, T_{man}, and its monetary equivalent value, M_{man}, are estimated as follows:

$$T_{man} = (t_{ETC}/60) * C * \sum_{k=1}^{5}(s_k * n_k) \quad (1a)$$

$$M_{man} = T_{man} * w_h \quad (1b)$$

where

- n_k is the average number of occupants in vehicle type k.
- w_h is the time value of manpower per hour, estimated as a proportion of the average hourly labor productivity.

(ii) <u>Fuel savings and monetary equivalent value</u>

Fuel used by vehicles on highways consists of gasoline (vehicles of types 1 and 2) and diesel (vehicles of types 3-5). The total fuel savings in gasoline (F_{gas}) and in diesel (F_{diesel}), as well as their overall monetary equivalent value, are estimated in the equations below:

$$F_{gas} = (t_{ETC}/60) * \sum_{k=1}^{2}(s_k * C * f_k) \quad (2a.1)$$

$$F_{diesel} = (t_{ETC}/60) * \sum_{k=3}^{5}(s_k * C * f_k) \quad (2a.2)$$

$$M_{fuel} = F_{gas} * P_{gas} + F_{diesel} * P_{diesel} \quad (2b)$$

where

- F_{gas} is the total amount of gasoline saved by passenger cars (k=1), and minibuses (k=2) and F_{diesel} is the total amount of diesel saved by buses (k=3), trucks (k=4), and heavy trucks/trailers (k=5).
- f_k is the fuel consumption by type-k vehicle at idling (averaged between no load and load).
- M_{fuel} is the total monetary equivalent value of the fuel savings.
- P_{gas} and P_{diesel} are the price per ton of gasoline and that of diesel, respectively.[13]

[13] In this estimation exercise, we use gasoline and diesel prices from the US market to estimate the monetary value of fuel savings for two main reasons.
First, US fuel prices are in the mid-range compared to global prices and are comparable to those in Vietnam. For instance, on September 24, 2024, the gasoline price in the US was $0.85 per litter, while in Vietnam, it was about VND 20,000 (~$0.80 per litter). Although this price is higher than in oil-rich countries like Saudi Arabia ($0.62 per litter), it is lower than in most other countries, such as China ($0.90 per litter), India ($1.12 per litter),

(iii) CO2-equivalent emissions reduction

The total CO2-equivalent emissions reduction, E, is the sum of the contributions from fuel savings in gasoline and diesel:

$$E = F_{gas} * e_{gas} + F_{diesel} * e_{diesel} \quad (3)$$

where

- e_{gas} and e_{diesel} are the CO2-equivalent emissions per unit of consumed gasoline and diesel, respectively.

(iv) Vehicle time savings and monetary equivalent value

Total vehicle time savings (measured in hours), $T_{vehicle}$, and its monetary equivalent value, $M_{vehicle}$, are estimated as follows:

$$T_{vehicle} = (t_{ETC}/60) * C \quad (4a)$$

$$M_{vehicle} = T_{vehicle} * \sum_{k=1}^{5}(s_k * r_k) \quad (4b)$$

where

- r_k is the average hourly value of vehicle type k.

(v) Toll collection efficiency improvement and cost savings

Toll collection efficiency improvements resulting from ETC implementation manifest through two main aspects, installment and operation. First, it eliminates the need for constructing additional lanes at toll plazas and their associated MTC toll booths. Observations from Taiwan (Lin et al., 2020) and Vietnam indicate that prior to ETC system deployment, highways often had to at least double their lanes at toll plazas to accommodate additional MTC toll booths, aimed at reducing vehicle wait times. Second, the operational cost of a booth is notably lower for ETC compared to MTC, on average. Our survey of selected cases in Vietnam revealed that operating an MTC booth accounted for 6-8% of collection revenue, whereas for ETC, it was only 2-3%.[14] This suggests that the total operational cost reduces savings, $S_{operating}$, from the MTC-ETC transition can be estimated as:

South Korea ($1.22 per litter), and Germany ($1.90 per litter). Source: https://tradingeconomics.com/country-list/gasoline-prices. Second, time series data for US fuel prices is publicly accessible through the U.S. Energy Information Administration (EIA) website, providing a reliable and widely used benchmark for international studies. https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm

[14] More specifically, the number of personnel required for a booth during a 24-hour period reduces significantly from 8-10 for MTC to just 3 for ETC, representing a reduction of 60-70%. Furthermore, ETC eliminates the need for paper receipts, enhancing sustainability and cutting off the receipt expense, which is approximately VND200 (US$0.0009) per transaction. The percentage range of these savings is based on our survey of toll collection operators.

$S_{operating} = C * p * q$ (5)

Where p is the average toll fee per toll transaction and q is the reduction in operational cost as a share of revenue, which can be assumed to fall within the range from 3% to 5%, as specified above.

(vi) Projections of the ETC gains for 2024-2030

To project the ETC gains for the next seven years, from 2024 to 2030, we assume that the ETC gains per unit of ETC transactions remain constant throughout the years for each of the five measures presented above. Let g denote the projected compound annual growth rate (CAGR) over the period 2024-2030. To establish this projected growth rate, we examine its three influencing factors. First, Vietnam is making robust efforts to expand its toll highway networks, aiming to increase their total length from less than 1,200 km in 2020 to 5,000 km by 2030, implying a CAGR of 15%. Second, the vehicle population is expected to increase by 6-8% annually. Third, Vietnam's GDP growth, which represents economic activity, is projected to grow at 6-7% annually towards 2030. Combining these three factors, it is conservatively plausible to project that the CAGR of the ETC transaction volume over 2024-2030 will fall between 6.0% (low-Case) and 11% (high-Case), with its midpoint at 8.5%. As supportive evidence, the observation of 112 million ETC transactions in the first quarter of 2024 suggests that the annual volume for 2024 would be around 8.9% higher compared to 2023.

Projections of the five measures of ETC gains for 2030 and for the seven-year period from 2024 to 2030 can be derived from the equations below.

$Q^G_{2030} = Q^G_{2023} * (1 + g)^7$ (6a)

$Q^G_{2024\_2030} = Q^G_{2023} * \sum_{m=1}^{7}(1 + g)^m$ (6b)

Where

- Q^G_y is the amount of gain G in year y (2023 or 2030) where G is one of the five measures of ETC gains presented above and Q is measured in relevant units or in monetary equivalent value.
- $Q^G_{2024\_2030}$ is the total gain G for the seven-year period from 2024 to 2030, measured in relevant units or in monetary equivalent value.

The input data for the equations presented above are summarized in Table 9. These data come from various sources, including our own estimations, Vietnam's official statistics, and international benchmarks based on data provided by US government agencies.

Table 9. Data for input variables in estimation equations

Variable	Description and source	Value
t_{ETC}	Average time saved per toll transaction from the MTC-ECT transition. Estimated in Subsection 5.2.1	5.4 minutes
C	Volume of ETC transactions per year. Derived from Figure 5, Section 4.	414 million (2023) 280 (2022);

		112 (2021) 44 (2020); 29 (2019)
s_k	Share of vehicle type k in Vietnam's vehicle population (k=1 for passenger cars; 2 for minibuses; 3 for buses; 4 for trucks; 5 for container trailers and special purpose vehicles). Data for 2022 from GSO (2023)	s_1=58.6%; s_2=3.5%; s_3=3.2%; s_4=32.1%; s_5=2.6%
n_k	Average number of occupants per vehicle type k (based on the authors' survey, with reference to Gillen et al. (1999), and adopting a conservative approach)	n_1=2.0; n_2=5.0; n_3=20; n_4=1.5; n_5=1.5;
w_h	Average hourly value of manpower; assumed to be 2/3 of Vietnam's average labor productivity in 2021, which is US$3.0 (APO, 2023).	$2.0
f_k	Average fuel consumed (gallons/hour) at the idling of vehicle type k, using the midpoint between the no-load and load values.	f_1=0.236 f_2=0.49; f_3=0.975 f_4=0.97; f_5=1.025
e_{gas} and e_{diesel}	CO2-equivalent emission by a unit of energy consumption (kg/gallon). Source: US Environmental Protection Agency; https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references	Gasoline: 8.887 Diesel: 10.180
P_{gas} and P_{diesel}	Prices of gasoline and diesel ($/gallon), averaged for 2023. Source: US Energy Information Administration; https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm	Gasoline: $3.64 Diesel: $4.21
r_k	Hourly value of vehicle type k: estimated as 50% of the rental price for passenger cars, which is averaged at $5/hour from various quotations; for other types of vehicles, author's estimation is based on their sales prices and lifespans.	r_1=$2.50 r_2=$4.00; r_3=$7.50 r_4=$5.00; r_5=$10.00
p	Average toll fee per transaction: calculated from data for 2023 as total toll revenue divided by total volume of transactions, which is approximately VND57,000 or $2.35. Data from MOT (2024)	$2.35
q	The operational cost saving as a share of total toll revenue (%). Midpoint of the 3%-5% range of the cost saving. Discussed in Subsection 5.2.2.	4%
g	Projected annual growth of the volume of ETC transactions from 2024 to 2030. Discussed in Subsection 5.2.2.	11% (Base-Case) 7% (Low-Case) 15% (High-Case)

5.3. Estimation results

The estimation results on the gains for Vietnam from highway ETC implementation during the years 2019 to 2023, and projected for the period 2024 to 2030, are reported in Table 10. Four main findings are notable from these results.

First, the gains for 2023, the first year of the country's full ETC implementation on highways, are substantial. The total CO2 emissions reduction amounted to 191,860 tons, resulting from a reduction in fuel consumption at toll gates by 60,816 tons of gasoline and diesel fuel. For the same year, the time savings were 93.3 million hours for manpower and 37.3 million hours of vehicle lifespan savings. In terms of monetary equivalent value, the total cost savings for 2023 across four measures—energy, manpower, vehicle lifespan, and operational costs—amounted to $442.7 million.

Second, The ETC gains in terms of CO2-equivalent emissions reduction and total monetary equivalent savings increased 14 times in 2023 compared to 2019, when the country began making a significant push for the transition from MTC. This growth indicates a near doubling rate annually over the four-year period from 2019 to 2023.

Third, compared to 2023, the ETC gains projected for 2030 are expected to be 1.77 times higher in the base-case scenario and 2.21 times higher in the high-case scenario. Even in the low-case scenario, this expansion is projected to be 1.41 times higher.

Fourth, in cumulative terms, the total gains Vietnam has realized for the 2019-2023 period include 407,036 tons in CO2 emissions reduction, 129,023 tons of gasoline and diesel consumption savings, time savings of 197.9 million hours for manpower and 79.1 million hours for vehicle lifespan, and $82.6 million in operational cost savings for toll collection. In monetary equivalent value, the total gains Vietnam achieved from the ETC implementation during this period reached nearly $1 billion.

Considering the projected gains for the years leading up to 2030 in the base-case scenario, the total ETC gains for the period from 2019, when Vietnam made its major push for highway ETC implementation, to 2030, when the country completes its strategic plan for highway development for 2020-2030, are substantial. These gains include 2.3 million tons in CO2 emissions reduction, 727 thousand tons of gasoline and diesel consumption savings, more than 1 billion hours of manpower time savings, 445 million hours of vehicle lifespan savings, and $465 million in operational cost savings for toll collection. In monetary equivalent value, the total gains over the 2019-2030 period are projected to stand at approximately $5.3 billion.

Table 10. Estimation results on the gains of ETC implementation on Vietnam's highways, 2019-2023 and 2024-2030 (projected)

Year/ Period	ETC transactions (million)	CO2 emission reduction (Tons)	Fuel consumption savings		Manpower time savings		Vehicle lifespan savings		Operational cost savings ($ million)	Total cost savings ($ million)
			Amount (Tons)	Value ($ million)	Hours (million)	Value ($ million)	Hours (million)	Value ($ million)		
Actual realization										
2019	29.4	13,602	4,312	5.6	6.6	13.2	2.6	9.8	2.8	31.4
2020	43.5	20,172	6,394	8.3	9.8	19.6	3.9	14.5	4.1	46.6
2021	111.8	51,818	16,425	21.4	25.2	50.4	10.1	37.3	10.5	119.6
2022	279.6	129,584	41,076	53.5	63.0	126.0	25.2	93.3	26.3	299.0
2023	414.0	191,860	60,816	79.2	93.3	186.6	37.3	138.1	38.9	442.7
2019-2023	***878.4***	***407,036***	***129,023***	***168.0***	***197.9***	***395.8***	***79.1***	***293.0***	***82.6***	***939.3***
Projections, 2030										
Base-Case	732.9	339,619	107,653	140.1	165.1	330.3	66.0	244.4	68.9	783.7
Low-Case	582.6	269,966	85,575	111.4	131.3	262.5	52.4	194.3	54.8	623.0
High-Case	915.3	424,141	134,445	175.0	206.2	412.5	82.4	305.3	86.0	978.8
Projections for seven-year period, 2024-2030										
Base-Case	***4,070.1***	***1,886,106***	***597,862***	***778.3***	***917.1***	***1,834.2***	***366.3***	***1,357.5***	***382.6***	***4,352.5***
Low-Case	3,539.6	1,640,232	519,925	676.8	797.5	1,595.1	318.6	1,180.5	332.7	3,785.1
High-Case	4,678.4	2,167,959	687,205	894.6	1,054.1	2,108.3	421.1	1,560.3	439.8	5,002.9
Cumulative gains realized for 2019-2023 and base-case projections for 2024-2030										
2019-2030	**4,949**	**2,293,142**	**726,886**	**946**	**1,115**	**2,230**	**445**	**1,650**	**465**	**5,292**
2030/2023 expansion multiplier										
Base-Case	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77
Low-Case	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41
High-Case	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21

Source: Authors.

6. Policy discussion

The global dynamics of ETC deployment on toll facilities, especially on highways, have been accelerating over the past three decades since it became a feasible option. Examined facts and findings from this study reveal a number of important policy reflections and issues.

First, ETC provides a new and extremely valuable solution, offering substantial benefits to all stakeholders, ranging from highway users to toll agencies and from communities to the economy. These gains extend beyond efficiency improvements, encompassing cost savings and reduced pollution emissions, to include enhanced effectiveness in travel experiences, data generation for improved traffic and economic forecasting and management, and increased transparency and fairness. Furthermore, ETC enables developing countries to leverage their latecomer disadvantage into advantage by fostering the development of new highways with early deployment of ETC systems, thus potentially avoiding any installation of MTC on newly built highways.

Second, the transition from MTC to ETC systems on highways is a complex process that requires effective coordination by the government and robust learning efforts and collaboration among stakeholders in the related ecosystem. The case of Vietnam offers illustrative insights. In June 2014, a task force formed by the Ministry of Transport, comprising representatives from government agencies, private companies, and banks, embarked on a diligent process to research and deliberate the suitable ETC technology for application in Vietnam. This process, spanning from June 2014 to November 2015, involved various steps including surveys, pilot implementations, and meticulous evaluations by specialized agencies and stakeholders. Ultimately, passive RFID technology was selected as the most appropriate ETC solution for a developing country like Vietnam, given its advantages in low user adoption costs and potential for rapid penetration .[15]

The effective role of the government was also evident in decisive decisions that promoted universal adoption of ETC across highways once the feasibility and benefits of deployment became clear. This role is particularly critical in transitioning from MTC to ETC, as toll agencies may hesitate to proceed due to the sizable sunk costs invested in MTC booths and lanes. In the case of Vietnam, the government's decision to mandate full ETC implementation on all highways starting August 1, 2022, significantly increased the share of vehicles with Etags in the total vehicle population. This share jumped from 52.3% in 2021 to 85.8% in 2022 and further to 94.5% in 2023.

Third, engaging the private sector strengthens the country's absorptive capacity and capability (Cohen and Levinthal (1990); Rogers Everett, M. (1995)). in its endeavors to adopt new technologies like ETC. This is evident in the case of Vietnam. Emerging private companies such as Tasco actively engaged with the government's task force to identify and select the suitable ETC technology, and subsequently assimilated and applied it for commercial purposes.

[15] The task force focused on two ETC options: passive RFID technology and DSRC. After careful consideration, the team opted for the former based on three main selection criteria: (i) Expected rapid penetration with tangible results; (ii) Lower user adoption cost per vehicle: Passive RFID tags, such as Etags, offer a cost-effective solution with an estimated price range of $1-2 per vehicle, in contrast to the higher cost of $30-40 for the required on-board unit (OBU) of DSRC, as observed in Japan, Singapore, and France; and (iii) Convenient maintenance and management: RFID tags affixed to vehicles serve as unique identifiers and require no internal energy, enhancing convenience for maintenance and management tasks. In addition, experiences of Taiwan and Japan show the super advantage of the RFID over DERC technology.

Consequently, Tasco has emerged as a key driver of ETC deployment and is currently accountable for facilitating over 75% of ETC transactions.

Fourth, ETC implementation is only an initial step in embracing digital technologies for efficiency improvement and green transformation. Related applications, such as payments for parking and gasoline/charging stations, should also be adopted as soon as possible.

Fifth, the rich data generated from ETC systems has enormous potential value for enhancing traffic management, economic analysis, and business decision-making. This calls for major initiatives to make this data available to the public while introducing regulatory measures to safeguard user data and transactions, including encryption methods and data protection policies.

Finally, The sizable gains from ETC implementation on Vietnam's highways, amounting to millions of tons of CO2-equivalent emissions reduced and billions of dollars saved from 2019 to 2030, suggest extremely high returns on investing in strategic infra- structure projects alongside digital support deployment to maximize their benefits. In particular, investments in metro systems and toll facilities such as tunnels and skyways to reduce daily traffic congestion by hours for millions of people in megacities could result in enormous environmental and economic gains, including hundreds of billions of dollars saved and the reduction of dozens of millions of tons of CO2-equivalent emissions over time.

7. Conclusion

The transition to Electronic Toll Collection (ETC) systems represents a transformative shift in highway management and opera- tions, as well as in strategic approaches aimed at boosting productivity, sustainability, and digital transformation. This paper examines the global landscape of ETC deployment on highways, offering practical policy insights and implications for policymakers in devel- oping countries. One of the paper's key contributions is its detailed examination of Vietnam's transition from manual toll collection (MTC) to ETC, along with a comprehensive estimation of the benefits from this transformation.

Globally, the ETC market has experienced substantial growth, reaching USD 9.2 billion in 2023, with a compound annual growth rate (CAGR) of 9.4% since 2020. It is projected to continue growing at a CAGR of 8.10%, reaching USD 14.7 billion by 2029. This growth is primarily driven by the highway segment, which constitutes about 90% of the ETC market. RFID and DSRC are the pre- dominant technologies used in ETC systems, with RFID leading in market share and growth, while emerging technologies are expe- riencing rapid growth from a smaller base.

In addition to providing empirical evidence and policy insights, this paper makes a modest theoretical contribution by utilizing the Poisson distribution to estimate vehicle waiting times at toll gates. Our analysis shows that even a 30–40 s delay per vehicle in transaction time can result in significant wait times when multiple vehicles arrive simultaneously.

Based on Vietnam's experience with ETC adoption, this study draws several key findings and policy implications for driving the transition from MTC to ETC on highways.

First, ETC systems significantly reduce travel time, lower fuel consumption, and decrease CO_2-equivalent emissions, contributing to transportation efficiency, environmental sustainability, and public health by reducing air pollution. In Vietnam, the shift to ETC has eliminated traffic congestion at toll gates and provided substantial cost savings for users and toll agencies.

Second, a proactive government approach, including the creation of a dedicated task force and a mandate for universal ETC adoption, has been critical in overcoming resistance and ensuring rapid implementation. This emphasizes the need for governmental leadership and policy support in fostering the adoption of new technologies and infrastructure development.

Third, the involvement of private companies through public-private partnerships has improved the deployment and operational efficiency of ETC systems. Vietnam's use of PPPs has leveraged the private sector's expertise, entrepreneurship, and resources to accelerate adoption and enhance system efficiency and effectiveness.[16]

The deployment of ETC systems marks the beginning of a broader digital transformation in transportation. ETC generates valuable data that can be used for advanced traffic management, economic analysis, and business decision-making. To fully realize these benefits, robust data management and protection policies are essential, ensuring that ETC data is secure and accessible for analysis. This data has applications beyond toll collection, offering insights for urban planning, infrastructure development, and policy formulation.

In conclusion, ETC systems are integral to modernizing road transportation infrastructure. By reducing congestion, lowering emissions, and improving operational efficiency, ETC systems offer sustainable solutions to urban mobility challenges. Continued innovation, supportive policies, and collaboration among stakeholders are necessary to fully harness the potential of ETC technology in creating smarter, more efficient transportation networks.

7.1. Directions for Future Research

Future research on ETC deployment should address several key areas. First, this study's focus on highway systems leaves a gap in understanding ETC's potential in urban environments. Given the challenges posed by increasing urbanization and congestion, further research is needed to investigate ETC deployment in cities, its integration with smart city technologies, and its impact on urban mobility patterns.

Additionally, future research should explore how socioeconomic factors, such as income levels and vehicle ownership rates, affect ETC adoption and success in both highway and urban settings. Comparative studies between countries with different levels of infrastructure development would provide valuable insights into best practices and scalable solutions.

Another promising area for research is the integration of ETC with emerging technologies, such as autonomous vehicles, the Internet of Things (IoT), and artificial intelligence. These

[16] In Vietnam, the PPP model has accelerated the adoption of advanced ETC technology, with private companies leading the deployment and management of toll collection systems. For example, VETC, a leading ETC provider, was established through a PPP collaboration and operates under the Build-Own-Operate (BOO) model. This approach has enabled Vietnam to rapidly implement ETC across its highway networks, delivering substantial benefits to both the government and PPP partners (see Appendix 4 for further details).

technologies could significantly enhance the efficiency and effectiveness of toll systems across different contexts.

Finally, addressing technical and financial barriers, exploring new technologies, and developing frameworks for global interop- erability will be essential to maximize the impact of ETC systems and expand their application to diverse environments. These areas of research are critical for driving future advancements in ETC deployment and infrastructure development.

References

Al-Deek, H.M., Mohamed A.A. and Radwan, A.E. (1997). Operational Benefits of Electronic toll collection: Case Study. Journal of Transportation Research, Volume123 No 6, Pages 467-477.

Anas, R., Tamin, O.Z., Tamin, R.Z., Wibowo, S.S., 2017. Measuring regional economic impact of Cipularang toll road investments: using an input-output model (Case study: Bandung District). Int. J. Civ. Eng. Technol. 8.

Andani, I Gusti Ayu, La Paix Puello, Lissy, Geurs, Karst, 2019. Effects of toll road construction on local road projects in Indonesia. J. Transp. Land Use 12 (1), 179–199. https://doi.org/10.5198/jtlu.2019.1258.

Andani, I. G. A., Puello, L. L. P., & Geurs, K. (2021). Modelling effects of changes in travel time and costs of toll road usage on choices for residential location, route and travel mode across population segments in the Jakarta-Bandung region, Indonesia. Transportation Research Part A: Policy and Practice, 145, 81-102.

Asian Productivity Organization. (2023). *APO Productivity Databook 2023*. https://www.apo-tokyo.org/wp-content/uploads/2023/12/APO-Productivity-Databook-2023.pdf

Baidu (2024). *ETC* Retrieved May 10, 2024, from. https://baike.baidu.com/item/ETC/563188?fr=ge_ala#reference-3

Central Government Portal. (2015, September 28). What benefits will the ETC National Network bring to the public? https://www.gov.cn/xinwen/2015-09/28/content_2939813.htm

Chen, Y., Lu, Y., & Jin, C. (2024). Spatiotemporal differentiation calendar for car and truck flow on expressways: A case study of Jiangsu, China. Journal of Transport Geography, 116, 103847.

Chinanews.com. (2015). What benefits will ETC's nationwide network bring to the public? Save travel time. https://www.chinanews.com.cn/m/cj/2015/09-28/7548497.shtml.

Chinahighway.com. (2021). 2020 National Toll Highway Statistical Bulletin released. https://www.chinahighway.com/spec/?id=65391769

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. Administrative science quarterly, 35(1), 128-152.

Gillen, D., Li, J., Dahlgren, J., & Chang, E. (1999a). Assessing the benefits and costs of ITS projects: volume 1 methodology.

Gillen, D., Li, J., Dahlgren, J., & Chang, E. (1999b). Assessing the benefits and costs of ITS projects: volume 2 an application to electronic toll collection.

Holguin-Veras, J., Cetin, M., & Xia, S. (2006). A comparative analysis of US toll policy. Transportation Research Part A: Policy and Practice, 40(10), 852-871.

Huang, C. V., Teaño, M. C., & Wee, H. M. (2020). A Comparative Study of Toll Collection Systems between Philippines and Taiwan. In IOP Conference Series: Materials Science and Engineering (Vol. 730, No. 1, p. 012034). IOP Publishing.

IHMCL (2024). ETC Transaction Reports, FY2015-16 to FY2023-24; available at https://ihmcl.co.in/etc-transaction-reports/

Indian Infrastructure. (2017, February 6). ETC Focus: FASTag deployment gains momentum. https://indianinfrastructure.com/2017/02/06/etc-focus/

Kamiliah, D. R., & Wijaya, C. (2023). Policy Issues and Challenges in the Introduction of Electronic Toll Collection in Indonesia: A Qualitative System Dynamics Approach. Migration Letters, 20(8), 784-798.

Karsaman, R. H., Nugraha, Y. A., Hendarto, S., & Zukhruf, F. (2015, November). A comparative study on three Electronics Toll Collection systems in Surabaya. In *2015 International Conference on Information Technology Systems and Innovation (ICITSI)* (pp. 1-6). IEEE.

Kim, J., Kurauchi, F., Uno, N., Hagihara, T., & Daito, T. (2014). Using electronic toll collection data to understand traffic demand. *J. Intell. Transp. Syst. Technol. Plan. Oper., 18*(2), 190–203. https://doi.org/10.1080/15472450.2013.806858

Lin, M. Y., Chen, Y. C., Lin, D. Y., Hwang, B. F., Hsu, H. T., Cheng, Y. H., ... & Tsai, P. J. (2020). Effect of implementing electronic toll collection in reducing highway particulate matter pollution. Environmental Science & Technology, 54(15), 9210-9216.

Ministry of Information & Broadcasting, P. I. B. (2023, July 10). India's Infrastructure Revolution. https://pib.gov.in/FeaturesDeatils.aspx?NoteId=151518&ModuleId%20=%202

Ministry of Public Works and Housing, I. T. R. A. (2017, March 3). Implementing Electronic Toll Collection in Indonesia Toll Road. https://www.unescap.org/sites/default/files/7.2%20Use%20of%20electronic%20toll%20collection%20system%20at%20toll%20network%20in%20Indonesia.pdf

Ministry of Transport, Vietnam, J. I. C. A. (JICA). (2010). The Comprehensive Study on the Sustainable Development of Transport System in Vietnam (VITRANSS 2). https://openjicareport.jica.go.jp/pdf/11999935_01.pdf

Mint. (2023). India's road network grows 59% in last 9 years: Gadkari. https://www.livemint.com/industry/infrastructure/indias-road-network-grows-59-in-last-9-years-gadkari-11687870574906.html

OECD (2010) The OECD Innovation Strategy: Getting a Head Start on Tomorrow; https://doi.org/10.1787/9789264083479-en

OECD (2019) Enhancing the contribution of digitalisation to the smart cities of the future, OECD Regional Development Papers, 28 June 2019; https://doi.org/10.1787/f6970913-en

Parmar, N., Vatukiya, A., Zala, M., & Chauhan, S. (2018). A Comparative Study of Toll Collection Systems in India. International Journal of Research in Engineering, Science and Management, 1(4).

Pham, C. (2022, September 9). Why Vietnam's Infrastructure is Crucial for Economic Growth. Vietnam Briefing. https://www.vietnam-briefing.com/news/why-vietnams-infrastructure-crucial-for-economic-growth.html/

PWC. (2022, June). *Evolving toll payments landscape in India*. https://www.pwc.in/assets/pdfs/consulting/financial-services/fintech/payments-transformation/evolving-toll-payments-landscape-in-india.pdf

Reja, B., Amos, P., & Hongye, F. (2013, June 14). China Road Tolls Policy: Past Achievements and Future Directions. https://www.worldbank.org/en/news/opinion/2013/06/14/china-road-tolls-policy-past-achievements-and-future-directions

Rogers Everett, M. (1995). Diffusion of innovations. New York, 12.

Shahrier, M., Hasnat, A., Al-Mahmud, J., Huq, A. S., Ahmed, S., & Haque, M. K. (2024). Towards intelligent transportation system: A comprehensive review of electronic toll collection systems. *IET Intelligent Transport Systems*. Volume18, Issue 6, June 2024, pp: 965-983, https://doi.org/10.1049/itr2.12500.

Shangpu Consulting. (2023). *Shangpu Consulting: Overall development and trend analysis of the ETC industry market in 2023*. Baidu.com. https://baijiahao.baidu.com/s?id=1779619110546160364&wfr=spider&for=pc

Statista (2024a). Fixed asset investment in China's highway 2016-2022; https://www.statista.com/statistics/1331265/china-fixed-asset-investment-in-highway/

Statista (2024b). Value of tolls collected on national highways across India from financial year 2017 to 2023(in billion Indian rupees); https://www.statista.com/statistics/1225139/toll-collected-on-national-highways-india/

Tseng, P.H., Lin, D.Y., Chien, S. (2014) Investigating the impact of highway electronic toll collection to the external cost: A case study in China. Technol. Forecast. Soc. Change 86, 265–272. https://doi.org/10.1016/j.techfore.2013.10.019

Tseng P.H and Pilcher N. (2022). Political and technical complexities of electronic toll collection: Lessons from Taiwan, *Case Studies on Transport Policy*, Volume 10, Issue 1, March 2022, pp: 444-453, https://doi.org/10.1016/j.cstp.2022.01.005

Vu K. and Asongu S. (2020) Backwardness advantage and economic growth in the information age: A cross-country empirical study, *Technological Forecasting and Social Change,* Volume 159, October 2020. https://doi.org/10.1016/j.techfore.2020.120197

Vu, K. and Austin R. (2015)."Vietnam's Embrace of ICT for Economic Development: Success and Future Challenges" Case Study, *Ivey Publishing*, 2015.

WEF (2021) Infrastructure 4.0: Achieving Better Outcomes with Technology and Systems Thinking, World Economic Forum; available at https://www3.weforum.org/docs/WEF_Infrastructure_Technology_Adoption_2021.pdf

World Bank. 2024. Digital Progress and Trends Report 2023. Washington, DC: World Bank.

Appendix 1. Example observations from camera surveillance data

To estimate the transaction time required by the Manual Toll Collection (MTC) and Electronic Toll Collection (ETC) modes, we rely on a sample of data extracted from surveillance camera systems on various highways. The table below provides 45 example observations for each mode of payment from this sample, including 25 passenger cars, five buses, 10 trucks, and five container trailers. Note that the vehicle population distribution in Vietnam, as specified in Section 5, is approximately 59% cars, 6.5% buses, 32% trucks, and 2.5% container trailers/special purpose vehicles.

MTC[17]				ETC			
DATE	TIME_IN	TIME_OUT	T_DURATION	DATE	TIME_IN	TIME_OUT	T_DURATION
Passenger cars (25 observations/mode of payment)							
1/3/2022	8:20:46	8:21:18	32	12/2/2024	0:09:54	0:10:00	6
2/3/2022	9:28:44	9:29:36	52	10/1/2024	18:06:16	18:06:21	5
2/3/2022	11:32:05	11:33:00	55	3/1/2024	20:23:50	20:23:55	5
2/3/2022	11:34:31	11:35:11	40	3/1/2024	6:40:10	6:40:14	4
2/3/2022	11:35:01	11:35:41	40	3/1/2024	11:41:00	11:41:00	4
2/3/2022	11:35:28	11:36:02	34	10/1/2024	12:06:26	12:06:31	5
2/3/2022	15:39:24	15:40:00	36	10/1/2024	18:03:56	18:04:01	5
2/3/2022	15:41:40	15:42:07	27	31/1/2024	15:10:51	15:10:56	5
2/3/2022	15:52:54	15:53:16	22	23/2/2024	6:32:30	6:32:35	5
2/3/2022	15:57:42	15:58:22	40	23/2/2024	15:51:06	15:51:11	5
2/3/2022	22:01:56	22:02:29	35	23/2/2024	15:51:25	15:51:31	6
2/28/2022	6:00:00	6:32:38	32	31/1/2024	15:11:17	15:11:21	4
2/28/2022	6:03:00	6:33:11	30	27/2/2024	11:35:49	11:35:54	5
2/28/2022	5:54:00	6:34:22	40	27/2/2024	11:57:32	11:57:36	4
2/28/2022	6:08:00	6:43:18	35	5/2/2024	9:56:55	9:57:06	11
2/28/2022	6:18:00	6:44:09	26	11/2/2024	1:24:19	1:24:27	6

[17] It should be noted that the MTC observations were made before August 1, 2022, when full ETC implementation became mandatory on all highways.

2/28/2022	6:05:00	6:45:31	40	21/02/2024	7:38:59	7:39:05	6
2/28/2022	6:12:00	6:47:27	35	21/02/2024	9:48:05	9:48:14	9
2/28/2022	6:17:00	6:48:32	31	22/02/2024	4:56:34	4:56:38	4
2/28/2022	6:04:00	6:49:10	45	28/2/2024	06:30:31	06:30:40	9
2/28/2022	6:23:00	6:58:06	35	28/2/2024	11:30:07	11:30:15	8
2/28/2022	6:25:00	6:58:25	33	28/2/2024	17:01:09	17:01;16	7
8/3/2022	6:29:35	6:30:31	56	9/2/2024	6:50:17	6:50:21	4
10/3/2022	7:29:34	7:30:04	30	29/2/2024	6:30:31	6:30:36	5
10/3/2022	10:32:14	10:33:02	48	9/2/2024	8:59:06	8:59:12	6
Buses (5)							
2/5/2022	17:32:05	17:33:17	72	3/1/2024	6:11:37	6:11:42	5
11/2/2022	9:02:57	9:04:30	93	11/2/2024	7:30:37	7:30:44	7
28/2/2022	18:28:55	18:29:42	47	26/2/2023	7:20:30	7:20:40	10
28/2/2022	17:33:24	17:34:09	45	29/2/2024	6:38:05	6:38:12	7
28/2/2022	17:49:08	17:49:43	35	14/2/2024	21:01:03	21:01:10	7
Trucks (10)							
1/3/2022	16:17:55	16:18:42	47	24/02/2024	7:26:04	7:26:11	5
2/28/2022	6:06:00	6:46:02	40	1/11/2023	11:29:52	11:29:58	6
2/28/2022	6:18:00	6:52:22	34	24/11/2023	18:02:43	18:02:52	9
2/28/2022	6:18:00	6:56:40	38	6/2/2024	20:01:30	20:01:37	7
9/3/2022	9:52:16	9:52:51	35	14/2/2024	20:13:45	20:13:52	7
1/3/2022	16:21:35	16:22:10	35	3/1/2024	21:34:23	21:34:33	10
10/3/2022	7:28:15	7:29:13	58	10/1/2024	14:16:16	14:16:23	7
2/28/2022	6:00:00	6:46:41	46	31/1/2024	15:11:03	15:11:09	6
9/3/2022	7:51:30	7:52:16	46	31/1/2024	16:23:21	16:23:26	5

9/3/2022	18:02:26	18:03:25	59	31/1/2024	22:55:23	22:55:31	8
Container Trailers (5)							
9/3/2022	11:52:00	11:53:21	81	29/2/2024	14:44:25	14:44:33	8
10/3/2022	7:29:44	7:30:42	58	13/2/2024	0:39:52	0:40:05	13
15/3/2022	22:37:23	22:38:44	81	20/02/2024	15:47:45	15:47:55	10
16/3/2022	0:27:15	0:28:45	90	28/2/2024	07:29:36	07:29:42	6
2/5/2022	17:30:07	17:31:09	62	28/2/2024	17:03:21	17:03:30	9

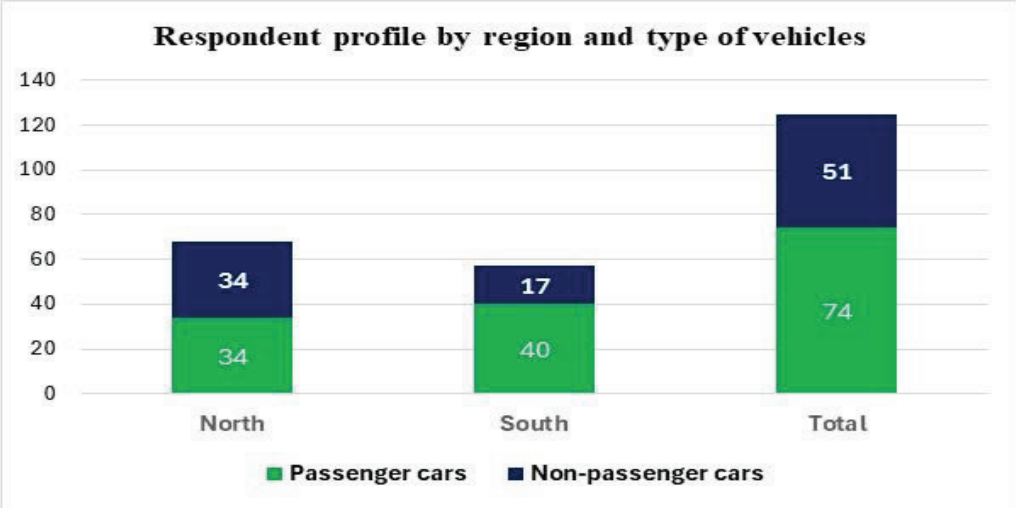
Appendix 2. The Driver Perception Survey

Our survey employs a convenience sampling method to gather initial insights into drivers' perceptions of their experiences with Manual Toll Collection (MTC) and Electronic Toll Collection (ETC) in Vietnam. We specifically targeted the management of 10 companies that operate large vehicle fleets, ensuring that their drivers have experience with both MTC and ETC systems. This approach allowed us to tap into a pool of drivers familiar with both toll collection methods, providing a rough but valuable understanding of their preferences, challenges, and benefits associated with each system.

By focusing on companies with extensive fleet operations, we aimed to capture practical insights from drivers who regularly engage with toll systems, giving us a broader view of user experiences across both traditional and electronic toll methods. While the con- venience sampling approach has limitations in terms of representativeness, it serves as an effective starting point to gauge perceptions and identify areas for deeper and more focused research.

Survey sample

The sample comprises 125 observations, with 68 drivers reporting their experiences on highways in the North (around Hanoi) and 57 drivers reporting their experiences on highways in the South (around Ho Chi Minh City). The figure below describes the respondent profile of the sample.



Questionnaire

Question 1. Compared to your previous MTC experience, how would you best describe your current experience with ETC??

1. Almost the same
2. Significantly better
3. Very significantly better

Question 2: In your experience with MTC systems, what is the estimated average waiting time at the toll gate for a passthrough?

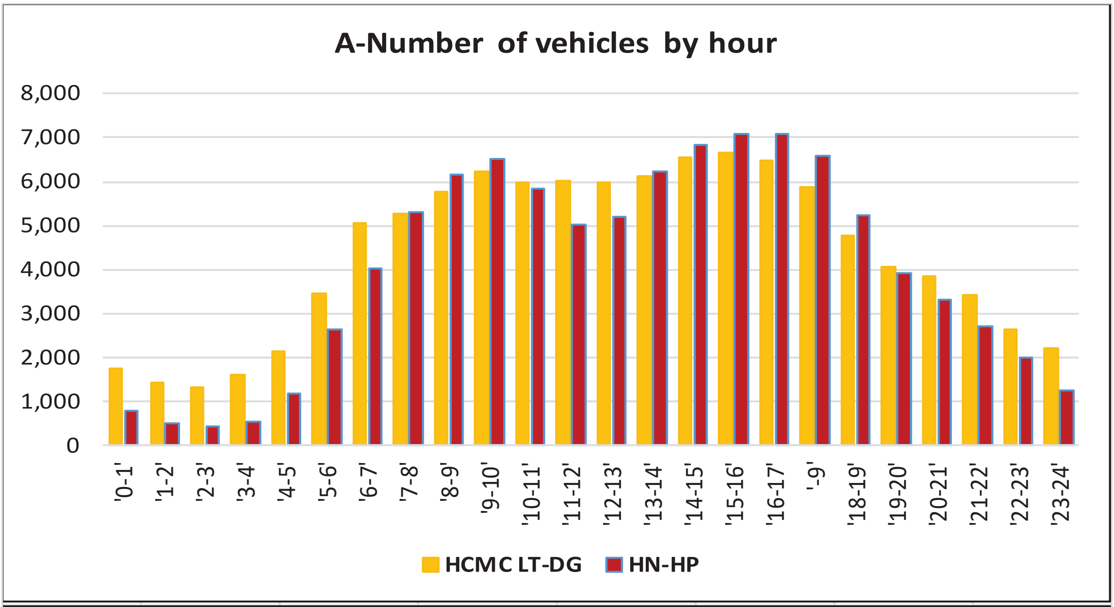
4. a) During normal times and conditions: ____________ minutes
5. b) During peak times: ____________ minutes
6. c) When it is raining: ____________ minutes
7. d) During holiday periods: ____________ minutes

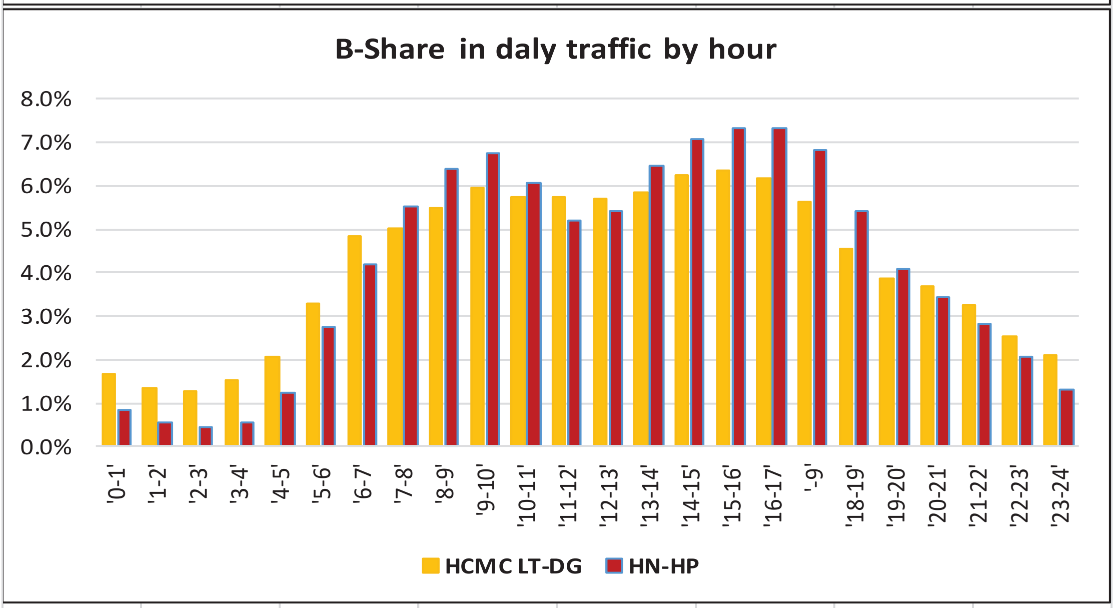
Question 3. Please specify the main highways where you had the above experiences.

Appendix 3. Simulation exercise to estimate average waiting time at the toll gate under MTC regimes

One can conduct a simulation to estimate the average waiting time for a vehicle at the toll gate on a highway that relies entirely on MTC systems, utilizing the Poisson distribution model. To prepare for this exercise, we examine the traffic patterns of two major highways, Hanoi-Haiphong (HN-HP) in the North and Ho Chi Minh-Long Thanh-Dau Giay (HCM-LT-DG) in the South, with daily traffic volumes of 96,521 and 104,633 vehicles, respectively (based on the data for 2023).

The traffic distribution observed for the two highways, as illustrated in the figure below, shows that traffic on a highway during an average 24-hour day follows three typical patterns based on the time of travel: (i) 'low-traffic hours' (five hours, from 12am to 5am); (ii) 'medium-traffic hours' (seven hours, from 5am to 7am and from 7pm to 12am); and (iii) 'high-traffic hours' (12 hours, from 7am to 7pm).





Observations from the HN-HP and HCM-LT-DG highways provide illustrative examples that generally support the two assumptions necessary for using the Poisson model to estimate the average waiting time a vehicle must spend at the toll gate on a typical highway in Vietnam. First, traffic is relatively stable during each of the three patterns. Second, the shares of the three traffic patterns in the total daily traffic volume are approximately 10% for 'low traffic', 20% for 'medium traffic', and 70% for 'high traffic'.

Let's examine a typical highway with three lanes each way and a daily traffic volume of N vehicles, which entirely rely on MTC for toll collection. Furthermore, we assume that this highway has twice more MTC lanes on each way at the toll plaza gate to reduce the queueing in waiting for payment transaction as observed in practice (see Section 3 for a discussion).

The average waiting time for a vehicle travelling during a given traffic pattern (low-traffic, medium-traffic, or high-traffic), denoted as t, can be estimated as follows.

$$t = \sum_{k=0}^{N} P(X = k) * [(k/6 - 1)] * t_{MTC}) \quad \text{(A1)}$$

Where $P(X = k)$ represents the probability of k vehicles arriving at the toll gate at nearly simultaneously within a three-minute duration; t_{MTC} denotes the average time required for a single MTC transaction, approximately 41.6 seconds as detailed in Subsection 5.1.2.

Given k vehicles arriving nearly simultaneously at the toll gate, a vehicle must wait in a queue for $(k/6 - 1)$ vehicles before its turn to make the toll payment. This calculation assumes the availability of six MTC lanes at the toll gate of a three-lane highway in one direction, as previously specified.

According to the Poisson distribution model, the probability that k vehicles show up at the same time within q minutes during a given traffic pattern before its payment transaction at an MTC booth can be calculated as:

$$P(X = k) = e^{-\lambda}\lambda^{k}/k! \quad \text{(A2)}$$

Where λ is the average number of vehicles arriving at the toll gate in within q minutes during the traffic pattern, which is calculated as

$$\lambda = (\frac{N}{2} * S)/(H * 60/q) \quad \text{(A3)}$$

with $S = 10\%\ and\ H = 5\ hours$ for 'low-traffic', $S = 20\%\ and\ H = 7\ hours$ for 'medium-traffic', and $S = 70\%\ and\ H = 12\ hours$ for 'high-traffic' patterns. We set q=3, as three minutes is a typical duration a driver expects spend in queuing under favorable conditions, which is supported by our survey of drivers.

Note that $(\frac{N}{2} * S)$ represents the traffic flow during the traffic pattern in question, where $\frac{N}{2}$ is the volume of traffic in one direction of the highway and S is the share of the traffic pattern in this volume. $H * 60/q$ is the number of 3-minute durations within this traffic pattern.

For illustration, the probability that a vehicle travelling on a highway three lanes in one direction and a daily traffic 60,000 during the 'median-pattern' period will have to wait for seven vehicles in queueing (which means $k = 48$) is calculated as follows:

$$\lambda = \frac{\frac{60,000}{2} * 20\%}{7 * \frac{60}{3}} = 42.857$$

$$P(X = 48) = e^{-42.857} * \frac{42.857^{48}}{48!} = 0.0427$$

That is the probability that a vehicle travelling during the median-traffic hours (5-7am or 7pm-0am) has to wait in queue of exact seven vehicles before its turn to make the toll payment is 4.27%. In this case, the waiting time is 7*(41.6/6)=4.85 (minutes).

Appendix 4. PPP Models in Vietnam ETC Deployment

Context

From 2010 to 2014, toll collection in Vietnam was predominantly manual and cash-based, managed by private investors operating the toll stations. These systems had minimal technology and limited data collection, which affected fee transparency.

The government identified several key challenges:

- Significant capital investment was required to implement a nationwide electronic toll collection (ETC) system.
- Public entities lacked technical expertise in tolling technology.
- Manual toll station operators had no experience in managing automated systems.

To mitigate inefficiencies and avoid budget waste, partnering with experienced private firms became crucial.

PPP Models

A Build-Own-Operate (BOO) model was recommended and approved, where the government maintains control over revenue (via fee regulation and centralized deposits) while partnering with private operators who invest in infrastructure, supply technology, and manage the tolling system.

Private operators participate in public tenders, with the winning bid selected based on the competitive proposed government fee as well as criteria such as system quality, operational experience, and financial stability. Vietnam's highway ETC systems are currently managed by two BOO operators responsible for implementing and overseeing the tolling system under specified conditions. This approach effectively addresses financial, technical, and operational challenges, promoting efficiency, transparency, and improved service quality. The benefits to both the government and BOO operators are summarized in the table below.

Appendix 4: Table of Benefits to the Government and Private Partners under the BOO Mode

Government	BOO Operator
• *Revenue Control:* Ensures all toll revenue supports road maintenance and investment recovery. • *Private Sector Collaboration:* Provides access to advanced technology and management expertise without requiring large government investments. • *Cost Savings:* Reduces initial financial burden and minimizes budget risks. • *Enhanced Service Quality:* Experienced private companies improve toll system efficiency and reduce congestion. • *Environmental Benefits:* ETC systems lower emissions by reducing stop-and-go traffic. • *Digital economy:* ETC systems provide real time on traffic flows and types of vehicles, which are valuable for economic analysis and policy decisions.	• *Long-Term Stability:* Secure, multi-year contracts (15-20 years) generate consistent revenue. • *Technology Leverage:* BOO operators optimize operations through their technological capabilities, expertise, and ongoing innovation efforts. • *Revenue Sharing:* While toll revenue goes to the government, operators receive compensation through fixed fees or revenue-sharing, per contract terms. • *Investment and Expansion*: Opportunities to invest in related infrastructure, potentially expanding into smart parking and maintenance tolling. • *Reputation Building:* Public partnerships enhance credibility and visibility. • *Operational Efficiency*: Expertise in ETC allows BOO operators to streamline costs and maximize efficiency.