

Article

# Fuel Consumption and Vehicle Emission Models for Evaluating Environmental Impacts of the ETC System

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Academic Editor: Marc A. Rosen

Received: 8 May 2015 / Accepted: 2 July 2015 / Published: 9 July 2015

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**Abstract:** The environmental outcome of the Electronic Toll Collection (ETC) system is an important aspect in evaluating the impacts of the ETC system, which is influenced by various factors including the vehicle type, travel speed, traffic volume, and average queue length of Manual Toll Collection (MTC) lanes. The primary objective of this paper is to develop a field data-based practical model for evaluating the effects of ETC system on the fuel efficiency and vehicle emission. First, laboratory experiments of seven types of vehicles under various scenarios for toll collection were conducted based on the Vehicle Emissions Testing System (VETS). The indicator calculation models were then established to estimate the comprehensive benefit of ETC system by comparing the test results of MTC lane and ETC lane. Finally, taking Beijing as a case study, the paper calibrated the model parameters, and estimated the monetization value of environmental benefit of the ETC system in terms of vehicle emissions reduction and fuel consumption decrease. The results shows that the applications of ETC system are expected to save fuel consumption of 4.1 million liters and reduce pollution emissions by 730.89 tons in 2013 in Beijing.

**Keywords:** Intelligent Transportation System (ITS); Electronic Toll Collection (ETC); benefit assessment; gasoline consumption; vehicle emission; environmental evaluation

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## 1. Introduction

As one of the most widely used sub-systems of the Intelligent Transportation System (ITS), the operation of the Electronic Toll Collection (ETC) system will greatly improve the capacity of freeway toll plazas, and it has obvious social and economic benefits including saving journey time of travelers, saving gasoline consumption, decreasing vehicle emissions and reducing labor cost [1].

The vehicles equipped with the ETC on-board unit (OBU) can pass the ETC tollbooths at an acceptable speed without any queue or stop. It has obvious advantages over the conventional Manual Toll Collection (MTC) both in improving traffic flow performance and lessening environmental impact. From the view of the environment, the outcomes include two aspects: vehicle emissions (hydrocarbon, carbon monoxide, and nitrogen oxide) reduction, and gasoline consumption decrease.

The environmental impacts of the ETC system are much more difficult to determine than the traffic performance improvement (congestion and delay, capacity, safety) and financial or fiscal outcomes, because it is influenced by various factors (the vehicle type, travel speed, traffic volume, and queue length).

However, scientifically evaluating the environmental impacts of ETC system is essential for post evaluation of ETC projects, and it also provides important instructions for determining future ETC development strategies. How to accurately measure the environmental influence differences between the ETC and MTC modes, as well as establish the quantitative environmental impact models of the ETC system, become a key point for ETC projects' post evaluation.

## 2. Literature Review

As part of the ITS evaluation and benefit analysis, the National ITS Architectures of various countries and regions usually propose the methodologies and analysis procedures of benefit analysis for ITS applications, and they also provide essential reference for the ETC system benefit analysis [2–4].

The other research on ETC benefit analysis mainly focused on the evaluation methodologies and indexes system; however, rare studies have been conducted on calculation models for evaluation indicators. Li *et al.* proposed a comprehensive framework to implement the benefit-cost evaluation, the case study showed that the ETC project would generate a benefit-cost ratio of 40 over the entire evaluation period [5]. The major benefits of ETC system include time saving, energy saving, emission reduction, and service improvement. Chaudhary established a monetized model for benefit estimation of ETC system, and revealed indicator values of benefits including travel time saving, gasoline saving and emissions reduction under different scenarios of lane configuration at different times [6]. Research also suggested estimating environmental impact by using the vehicle emission model proposed by Kirchstetter [7]. Cao reported the technical and economic evaluation methods for upgrading and modifying toll collection systems, and the Gray Correlation Degree (GCD) and Analytical Hierarchy process (AHP) methods were introduced to comprehensively measure the cost and benefit of ETC system construction [8]. Tseng considered three vehicle types: passenger cars, buses and trucks. Results show that the CO<sub>2</sub> emissions were reduced by 12.4% as the number of ETC lanes for all four toll plazas increased. The reduction of external costs fell by 60.1% in terms of value of transaction time [9].

In order to estimate the mobile emission reduction of ETC system, various simulation platforms and vehicle emission software are also widely used in evaluations of environment and energy. The rapid development of computer technology provides technical support for the modal vehicle emission model, and the Comprehensive Modal Emissions Model (CMEM) and MOtor Vehicle Emission Simulator (MOVES) that have been developed and are used as the main emission models [10–13]. Saka *et al.* selected Fort McHenry Tunnel toll facility as the study object, and the observed field data were used to adjust simulation model parameters and validate simulation results. By using the mobile emissions modeling software, Mobile 5b, the authors concluded that the mobile emissions rate ranged from an 11% (0.85 kg) decrease for NO<sub>x</sub> to a more than 40% (3.77 kg) decrease for HC and CO (36.04 kg), respectively, under a 28% market penetration of M-Tag [14]. Wang analyzed the influence factors of ETC System application and benefit, and suggested estimating the benefit of vehicle emission reduction under different operation conditions by using the Comprehensive Modal Emissions Model (CMEM) and simulation procedure, which was proposed by researcher groups from the University of California and University of Michigan [15]. Liu *et al.* developed an operational model of toll station using the microscopic simulation tool PARAMICS integrated with the Comprehensive Modal Emissions Model (CMEM). The study shows that the emission reduction is up to 51.78% when the passing speed rises from 0 to 30 km/h, and environmental benefit achieves the best value only when the ETC lane number is matched with the corresponding market penetration rate of ETC [16]. Based on the computational model, Lin and Yu demonstrated that open road tolling (ORT) can achieve significant air quality benefits over the conventional toll plaza design. The near roadside carbon monoxide (CO) concentration levels can be reduced by up to 37%, and diesel particulate matter (DPM) emissions can decrease by as much as 58% [17]. He *et al.* proposed a three dimensional Computational Fluid Dynamics (CFD) model to simulate pollutant dispersion at the toll plaza for different traffic volumes and toll collection procedures, and analysis showed that pollutant concentration around tollbooths decreases as the proportion of ETC-equipped vehicles increase. Every 10% increase ETC-equipped vehicles rate will lead to an about 4% reduction of pollutant concentration under the volume condition of 1500 vehicles/hour [18].

Other researchers have introduced field tests on toll plaza to measure the vehicle emission reduction of ETC lanes in comparison with the MTC lanes. Song *et al.* selected the Volkswagen Jetta in Beijing to conduct the field experiment: The vehicle passed through tollbooths 48 times, and the vehicle emissions and travel speed were collected simultaneously for both MTC and ETC lanes using a portable emission measurement system (PEMS). The results showed that the mean emissions of NO<sub>x</sub>, HC, and CO of ETC lanes were 16.4%, 71.2%, and 71.3% less than those on MTC lanes, respectively, [19]. Coelho *et al.* quantified the emission impacts of toll facilities by conducting field experiments. Data shows that the service time and queuing length will directly affect the level of vehicle emissions, and the greatest percentage of emissions for a MTC vehicle is due to its final acceleration back to cruise speed after leaving the tollbooth [20]. Makino and Tsuji introduced ETC system operations, which have improved the air quality of Japan, and revealed carbon dioxide (CO<sub>2</sub>) reductions of 30% [21]. He *et al.* discussed the effects of wind speed, wind direction and topography on pollutant dispersion by using a three-dimensional computational fluid dynamics simulation [22]. Exhaust emissions and fuel consumption of Heavy Duty Vehicles (HDVs) in urban and port areas were evaluated by Zamboni *et al.* through a dedicated investigation. This paper used the on-board instrumentation to record HDV instantaneous speeds. They founded that the speed bumps produced the highest increases in NO<sub>2</sub> levels [23].

In conclusion, amount of research has been conducted on the evaluation methodologies, indexes system, and environmental impact of the ETC system; however, as for the mobile emission reduction estimation, most research is implemented based on the simulation software, field experiments on single vehicle or specified toll station, and even less research has comprehensive traffic data support. Therefore, few studies can respond to the questions of how to estimate the fuel consumption saving and vehicle emission reduction, how to evaluate the environmental impact of the whole ETC system, and how the factors influence the positive benefit. Additionally, the stop–start trait of vehicles in toll lanes makes it rather difficult to estimate the actual emission based on the conventional vehicle emission models if no on-board instrumentations were equipped.

Specifically, this study attempted to predict the environmental impact of the ETC system in Beijing by conducting field tests and establishing analysis models. Based on the proposed evaluation indexes, the laboratory emission test for different vehicle types and running scenarios (ETC and MTC) were implemented, and fuel consumption and vehicle emission data of seven typical vehicles were collected; then the research established calculation models to estimate fuel consumption saving and vehicle emission reduction for the whole ETC system. Finally, the total annual values of environmental benefit of the Beijing ETC system during 2009–2013 were calculated by using the proposed models.

### 3. Research Framework and Evaluation Indicators

The paper firstly established appropriate evaluation indicators in order to accurately reflect and evaluate the environmental impact of ETC system. Then, the representative vehicle types of the ETC system were determined by clustering method. The research designed and complemented a series vehicle emission test and experiments in laboratory based on the Vehicle Emissions Testing System (VETS), and the fuel consumption and emission data was obtained. Finally, the indicators calculation models based on multi-vehicle types and various queue lengths conditions were proposed, and it can be used to estimate the environmental benefits of fuel use and emissions, as shown in the case study of Beijing. Figure 1 lists the research framework and sections of the paper.

At the MTC lanes, the vehicle is in acceleration, deceleration or an idle state when stopping to pay or queuing, and the engine fuel consumption and exhaust emissions will correspondingly increase. The implementation of the ETC system changes the traffic flow operating status of the toll station, and the vehicle fuel consumption and pollutant emission will reduce when vehicles directly pass through the ETC toll lanes at a specified speed. Therefore, the fuel consumption reduction value and the emissions decrease value when vehicles passing through the ETC toll lane compared to the MTC lane can be selected as indicators for evaluating environmental impacts of ETC system.

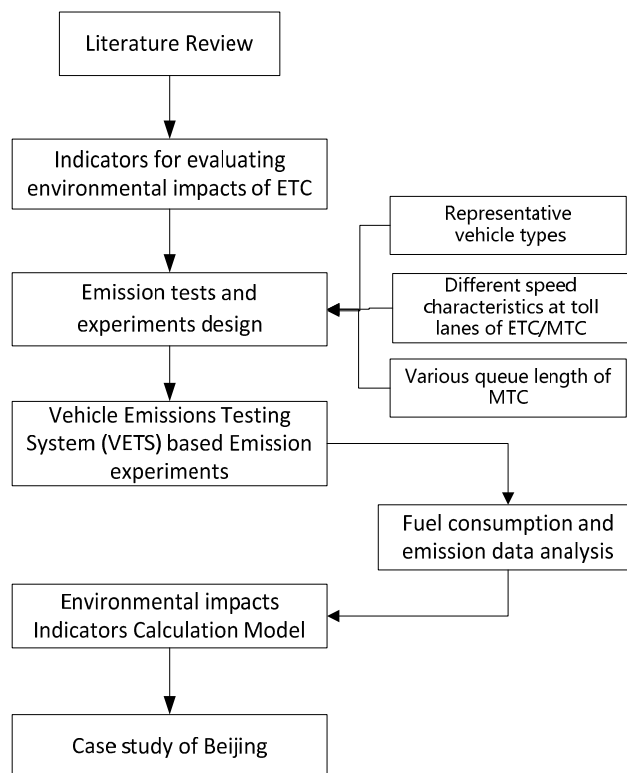
#### (1) The reduction value of fuel consumption:

The total fuel consumption difference when it passes through the ETC lane and MTC lane during the charging process can be defined as the reduction value of fuel consumption for a single ETC transaction.

#### (2) The emission reduction value:

At the toll station, the total emission difference when a vehicle passes through the ETC lane and MTC lane is the emission reduction value for a single ETC transaction. The emission reduction value can be

further divided into emission reduction values of hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxide (NO<sub>x</sub>).



**Figure 1.** Research framework of the paper.

Although the released congestion at the toll plazas may reduce vehicle emissions, the impact of ETC systems on emissions level is flexible. It is affected by various factors including the vehicle type, travel speed, traffic volume, queue length of MTC tollbooth, and even the congestion in downstream ramps. Thus, the experimental design and evaluation indicator analysis and should take these factors into account.

#### 4. Emission Test and Experiment Design

In order to accurately determine the vehicle fuel consumption and emissions of ETC lanes and MTC lanes, vehicle operating conditions of these two types of charging modes were tested by the real vehicles. There were three steps that should be made clear before determining the testing program: (1) typical vehicle types; (2) characteristics of the vehicle speed when passing through the toll lanes; and (3) experiment design and emission data collection.

##### 4.1. Test Vehicle Types Survey

There is a great difference of fuel consumption and exhaust emissions between various vehicle types. The study carried out a sample survey (sampling rate of 5%) at all ETC customer service centers in Beijing, and only the passenger cars involved in the ETC system samples, because the trucks are weight-based charge, and ETC module did not apply to the trucks up till now. The vehicle brand, types and displacement of sampled vehicles were collected. The recommended values of standard fuel

consumption for each type of registered vehicles can be retrieved from “light vehicle fuel consumption database”, released by Ministry of Industry and Information Technology of PRC [24].

All sample vehicles (about 30 thousand vehicles) were divided into seven categories by K-means clustering method in the SPSS software in accordance with the vehicle’s fuel consumption and emission data. The classification results are shown in Table 1. The clustering results showed that the optimum inter-classes distances occurred when there are seven classes. According to the class center emission and fuel consumption, seven representative kinds of experimental vehicles were selected to carry out the experiments: the Volkswagen Audi A6L, Ford FIESTA, Chevrolet EPICA, Refine Business, Citroen C5, Volkswagen PASSAT and Nissan TEANA. By the end of 2013, the total number of the ETC vehicles in Beijing was 1.15 million, and they can be divided into seven representative types.

**Table 1.** Clustering of typical vehicle type and ratios of ETC system users.

Vehicle Type	1	2	3	4	5	6	7
Displacement of class center (L)	2.79	1.51	1.91	2.36	2.15	1.74	2.54
Fuel consumption of class center (L/100 km)	16.61	5.96	9.5	13.82	10.83	7.76	12.07
Proportion (%)	3.85%	7.71%	23.80%	10.95%	10.73%	33.91%	9.05%
Representative vehicle	Volkswagen Audi A6L	Ford FIESTA	Chevrolet EPICA	Refine Business (Van)	Citroen C5	Volkswagen PASSAT	Nissan TEANA
Displacement of vehicle (L)	2.8	1.5	2	2.4	2.3	1.8	2.5
Manufacturing year	2010	2010	2010	2010	2010	2010	2010
Fuel consumption of vehicle (L/100 km)	(15.1, 7.9,	(8.9,	(12.9, 7.5,	(13.9, 9.1,	(12.8,	(11.6, 6.7,	(12.1,
(Urban conditions, suburban conditions, integrated condition)	10.5)	5.6, 6.7)	9.5)	10.9)	7.6, 9.5)	9.2)	8.0, 9.5)

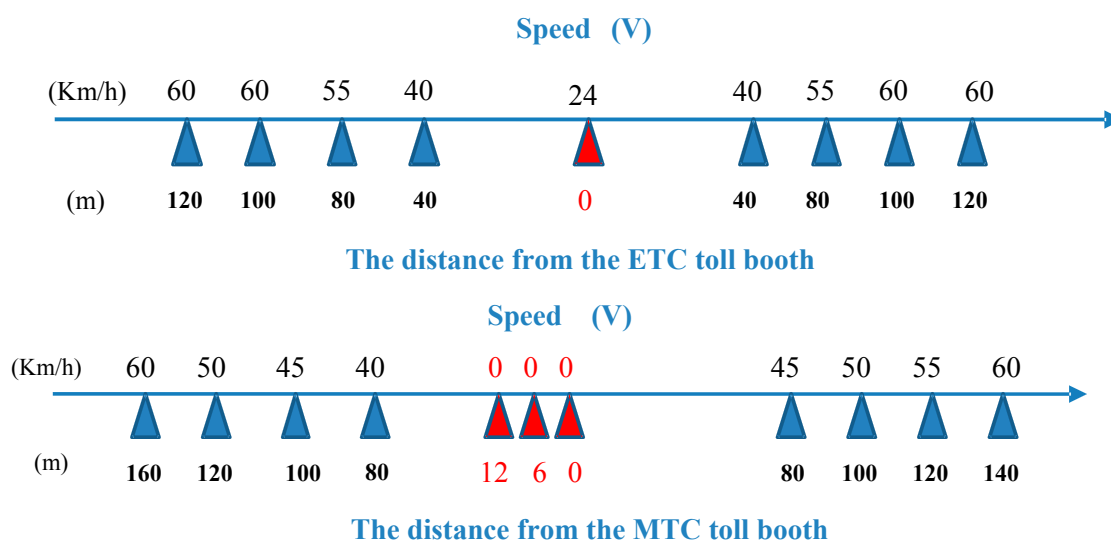
#### 4.2. Speed Characteristics Survey of Vehicles at Toll Plazas

The speed features of vehicle passing through the ETC lanes and MTC lanes are the foundation of driving simulation. A field investigation was conducted at different types of toll plazas, including the Bailu toll station (mainline toll station), Taihu toll station (ramp toll station) of Beijing–Shenyang freeway and Beijing–Chengde freeway toll station (mainline toll station). Spot speeds were collected within the range of 200 m from the tollgate, respectively, to upstream and downstream, and the radar detectors were used to detect the instantaneous velocity at 20 m interval. There are over 2000 cars were observed during three hours in every toll stations. The average speeds of vehicle at ten investigation points were collected. In order to exclude the effect of queuing length on speed, only the data was selected when the queue length is two vehicles. Additionally, the service time per vehicle for MTC lane, queuing time and the vehicle speed passing through ETC lane also were investigated.

According to the speed data analysis, the vehicles speed of ETC and MTC lanes are different only in the toll-affected zone. The toll-affected zone can be defined as the distance between vehicles approaches the toll station area from 60 km/h slow down to complete the charges and then accelerate to 60 km/h leaving the toll station. The toll-affected zone lengths of the two modes are different.

The survey results indicated that the average transaction time of the MTC lane is  $14.2 \text{ s} \pm 1.4$ , 14 s for the convenience of calculation. The affected zone of ETC lane is within the range of 240 m from

upstream 120 m where vehicle starts to decelerate from 60 km/h, to downstream 120 m where the vehicle has accelerated to 60 km/h. The average speed when the vehicle approaches the toll lane is 24 km/h, and after payment it will accelerate to 60 km/h at around 120 m distance from the toll point. The affected area of MTC lane is within 300 m from upstream to downstream of the tollbooths. Vehicles start to decelerate at about 160 m upstream from the toll booth, then stop at the toll or the end of the queue, and move forward a parking space every 12–14 s or so. After payment, vehicles will accelerate to 60 km/h at about 140 m downstream from the toll point. The relations of vehicles' speed and distance are shown as in Figure 2.



**Figure 2.** Vehicle speed change model of ETC lane and MTC lane. Note: The payment cycle time is 14 s when the speed is 0. Here, taking two waiting vehicles in queue as example, additional payment cycles should be added with more than two vehicles in queue.

#### 4.3. Experiment Design and Implementation of Vehicle Emissions

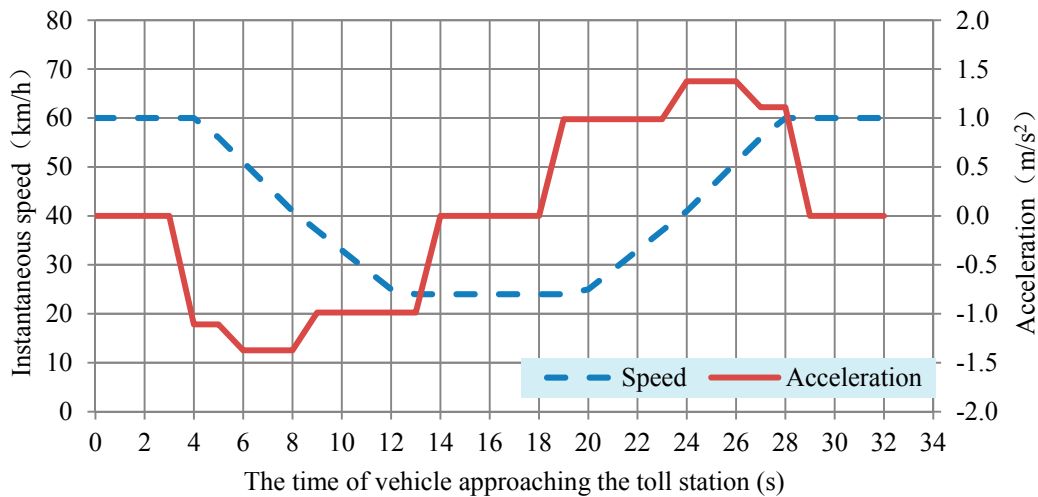
The experiments were conducted at “Energy Testing Center of Motor Transport Industry of Ministry of Transportation”, after being approved and authorized by the Ministry of Environmental Protection of China as an automotive emission pollution monitoring and test laboratory. The fuel consumption and emissions of different vehicle types were tested on the Vehicle Emissions Testing System (VETS). The test system consists of a 48-inch rolling drum produced by German company Schenck and an AMA-2000D emissions analyzer produced by the German company Pierburg. Because of the exhaust gas analyzer, the emission values of CH, CO and NO<sub>x</sub> were recorded at intervals of one second during the vehicle's drive, and the instantaneous fuel consumption would be calculated using of carbon conservation model (13). VETS is shown in Figure 3.

In order to measure fuel consumption and emissions of different vehicle types passing through the ETC and MTC lanes, experiments using seven vehicle types were, respectively, conducted by setting time-speed trajectories and time-acceleration evolvment curves, as shown in Figures 4 and 5. As for the queue length affecting the MTC lane case, preliminary experiments showed that the fuel consumption and emissions increment was basically steady for each additional queuing car. Therefore, the experiments selected the case of two waiting vehicles in queue, and the values can be

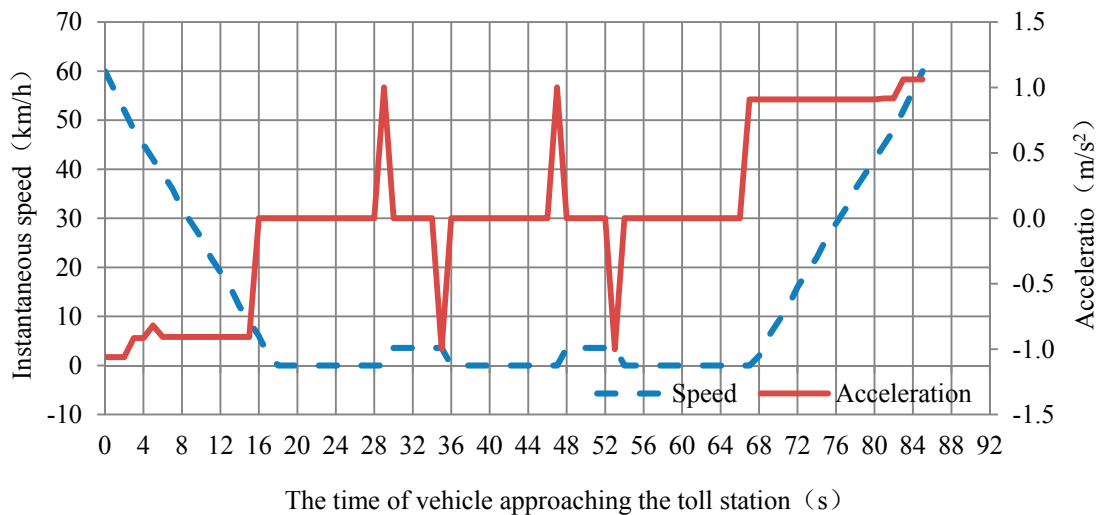
calculated by the equal increment for more queuing vehicles conditions. By intercepting experimental data at regular time periods, the values of fuel consumption and emissions with no car, one car or two cars in the queue can be obtained, as well as the incremental values for each additional queue vehicle.



**Figure 3.** The vehicle runs on the vehicle emissions testing system (VETS).

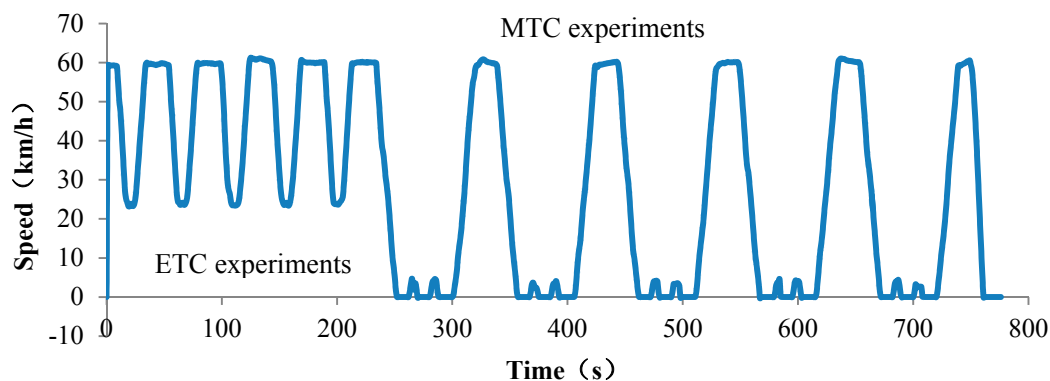


**Figure 4.** Time-speed trajectory when a vehicle passes through ETC lane.



**Figure 5.** Time-speed trajectory when a vehicle passes through MTC lane.

There were five repeated experiments for each scenario, and the simulated travel process of each vehicle type is shown in Figure 6, including five ETC and five MTC driving tests. From the view of data quality, the tested vehicles will run 20 min unloaded after it was warmed up when, emissions come to a steady state according the pre-tests.



**Figure 6.** The whole time-speed trajectories for a single experimental vehicle.

According to the vehicle fuel consumption and emissions results for each second, the fuel consumption and emissions for different types of vehicles passing through the ETC lane or different queuing lengths in the MTC lane were calculated by the experimental data results. The experimental results include: (1) Fuel consumption and emissions of seven vehicle types passing the ETC lane. (2) Fuel consumption and emissions of seven vehicle types when the queue length is 0, 1 and 2 vehicles through the MTC lane.

## 5. Data Analysis and Estimation Model

### 5.1. Experiment Data Analysis

According to the same experiment, the fuel consumption values and emission values of the seven vehicle types were obtained in both ETC procedure and MTC procedure. Due to being the largest proportion of current vehicles, we take the sixth vehicle type (Volkswagen PASSAT) as an example; the following tables list the fuel consumption and emissions results of vehicle No. 6 in each test through the ETC or MTC lane. Table 2 lists the experiment result of the ETC lane test, and Table 3 shows the test values of the MTC lane when the queue length is 0, 1 and 2 vehicles, respectively.

**Table 2.** ETC test results of fuel consumption and emissions for the sixth vehicle type.

Experimental Parameter	Fuel Consumption (L)	HC Emission (g)	CO Emission (g)	NO <sub>x</sub> Emission (g)
Mean	0.0271	0.1921	1.0191	0.3869
Standard Deviation	0.0012	0.0243	0.1270	0.1166
Coefficient of Variation	0.0443	0.1265	0.1246	0.3014
Test Times	5	5	5	5

**Table 3.** MTC test results of fuel consumption and emissions for the sixth vehicle type.

Queue Vehicles		0				1				2			
Parameters	Fuel	HC	CO	NO <sub>x</sub>	Fuel	HC	CO	NO <sub>x</sub>	Fuel	HC	CO	NO <sub>x</sub>	
	(L)	(g)	(g)	(g)	(L)	(g)	(g)	(g)	(L)	(g)	(g)	(g)	
Mean	0.0325	0.3446	5.8728	0.4670	0.0377	0.3916	6.0982	0.4848	0.0410	0.4494	6.4310	0.5208	
Standard Deviation	0.0006	0.0543	0.9168	0.0723	0.0007	0.0589	1.1348	0.0819	0.0006	0.0642	1.6181	0.1035	
Coefficient of Variation	0.0185	0.1576	0.1561	0.1548	0.0186	0.1504	0.1861	0.1689	0.0146	0.1429	0.2516	0.1987	
Test Times	5	5	5	5	5	5	5	5	5	5	5	5	

The experimental results show that the fuel consumption and emissions data will obviously be different for various displacement vehicle types, and in the five repeated experiments of the same vehicle, the fuel consumption values remain very stable, but some fluctuations exist in the emission values as shown in Table 3. This indicates that the test results of emissions are sensitive to the driver's operation and the engine work status, which can easily cause large fluctuations in emission values for the same driving process.

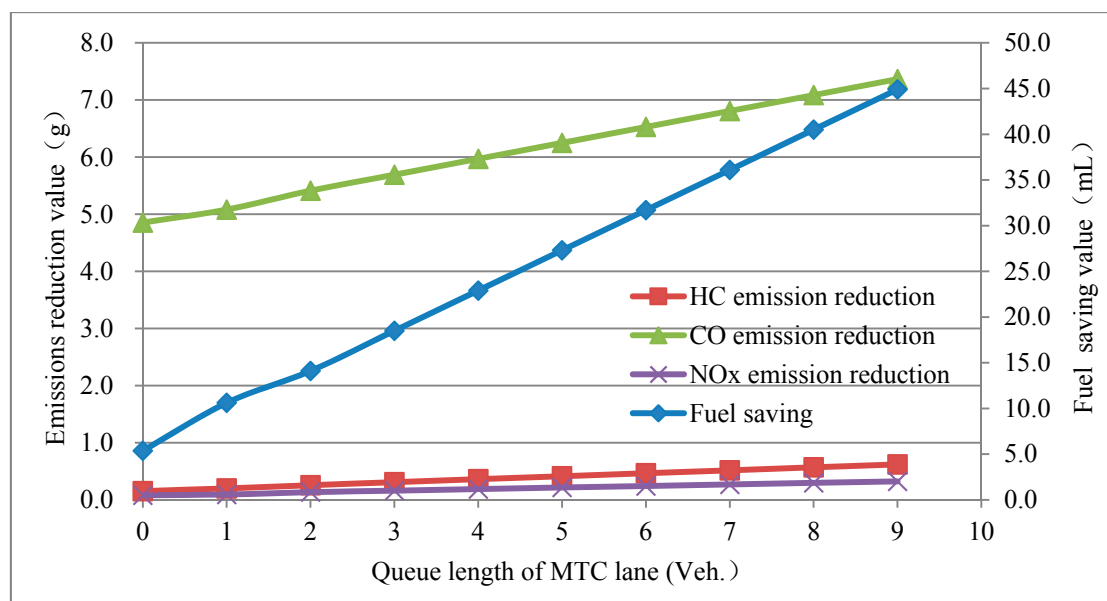
There are usually no queues at the ETC lanes, however the queue length at MTC lanes will influence the model result. The difference between the two groups of experimental results is the fuel and emissions savings under same traffic volume condition:

$$\Delta_{ij}^S = S_{ij}^{MTC} - S_j^{ETC} \quad (1)$$

where  $\Delta_{ij}^S$  represents the saving value of fuel consumption and emission that vehicle  $j$ , respectively, through the ETC lane and the MTC lane with  $i$  cars in queue;  $S_j^{ETC}$  represents the test value of fuel consumption or emission when vehicle  $j$  pass through the ETC lane;  $S_{ij}^{MTC}$  represents the test value of fuel consumption or emission when vehicle  $j$  passes through the MTC lane with  $i$  cars in queue.

Based on the experiment values, the reduction values of fuel consumption and emissions in ETC lanes can be directly calculated for each type of vehicle when the queue vehicle is 0, 1, or 2. Furthermore, the difference of the reduction values of fuel consumption and emissions also can be calculated according the results, the average difference can be regarded as the increment of saving for every one additional queue vehicle. Then, the reduction values when the vehicle queue has more than three vehicles can be indirectly calculated by sequent equations.

Figure 7 shows the estimated fuel consumption reduction and emissions reduction for experiment vehicle No. 6 under different queue length of MTC lanes. Similarly, the reduction values of fuel consumption and emissions for all seven typical vehicle types also can be calculated.



**Figure 7.** The calculated reduction value of the sixth vehicle type under different queue lengths.

### 5.2. Indicators Calculation Model

For the environmental benefits evaluation of the ETC system, the fuel consumption and emissions should be comprehensively calculated according to various typical vehicles and different vehicle types and queue length. The indicators calculation model of total fuel consumption reduction and pollutant emission reduction brought by ETC systems can be estimated as follows:

$$\Delta^S = \sum_{i=0}^i \sum_{j=1}^j V_{ETC} \cdot r_i \cdot r_j \Delta_{ij}^S \quad (2)$$

where,  $V_{ETC}$  is the total transaction volume of ETC during the analysis period;  $r_j$  is the proportion of vehicle  $j$  in all vehicle types, for the case study of Beijing, the values of  $j$  is 1–7;  $r_i$  is the probability of  $i$  vehicles in queue when the vehicle arriving at MTC lane, and for the case study of Beijing,  $i$  range from 0 to 9;  $\Delta_{ij}^S$  is the saving value of fuel consumption or emission that vehicle  $j$ , respectively, through the ETC lane and the MTC lane with  $i$  cars in queue.

For this study, the reduction values of fuel consumption and emission can be, respectively, defined as  $\Delta^{SO}$  and  $\Delta^{Sg}$ . According to the calculation model, the environmental benefits generated by the ETC system can be estimated based on data including the proportion of different vehicles, ETC transaction times and probable distribution of different queue length of MTC lane.

### 5.3. Environmental Impacts Evaluation of ETC System—A Case Study of Beijing

The freeway ETC system test has been running in Beijing since 1 May 2009. Up until December 2013, there have been over 412 ETC lanes, and 1.154 million ETC users, the annual ETC transactions exceeded 130 million when a connected ETC system was actualized among five provinces in eastern of China. This section takes Beijing as a case study to estimate the environmental benefits of the ETC System by using the proposed calculation models.

Due to various fuels consumption and emission characteristics of the different vehicle models, the type of vehicle equipped with ETC modules have obvious influence on the comprehensive environmental benefits. As in Section 5.1, there are seven typical vehicle types, which were clustered and determined according to the user data registered in the Beijing ETC customer service center. The composition ratios are shown in Table 1.

According the freeway toll station management regulation, the queue length at ETC lanes will keep unchanged with the continually increasing of numbers of ETC lanes, correspondingly as in the ITS plan of Beijing Freeway. The existing MTC lanes will be reconstructed into ETC lanes to preferentially ensure the vehicle can smoothly pass ETC lane with the increase of ETC users. So, the queues at ETC lanes are expected to be kept at zero.

The queue length at MTC lanes probability distribution will influence the model result. The M/M/C model under the queuing theory can be used to describe the queue procedure at toll plazas, and the probability of different queue lengths at MTC lanes can be estimated [25]. Suppose the vehicle arriving follows the Poisson distribution, and the charge services time follows the Negative Exponential distribution, the queue length of MTC lanes can be estimated in accordance with the following Equation. The average number of waiting vehicles  $L_q$  is:

$$L_q = \frac{(\lambda / \mu)^{c+1}}{c \times c! (1 - \lambda / c\mu)^2} P_0 \quad (3)$$

where,

$P_0$ —The probability of no vehicle at MTC Lanes;

$\lambda$ —Average vehicle arriving rate, vehicles/hour;

$\mu$ —Average service rate of MTC lane, vehicles/hour;

$c$ —The number of MTC lanes; and

$L_q$ —The average number of waiting vehicles.

Based on the queuing theory model, the average queue lengths of toll stations under distinct time periods, different vehicle arriving rates, and various numbers of opened lanes can be estimated. According to the actual collected data of hourly traffic volume in different time of day and lane numbers of toll stations in Beijing, which including 1165 MTC Lanes covered about totally 920 km freeways, the MTC lanes operation scenarios can be classified into the 80 most frequently occurring scenarios, which represent specified traffic volume, number of opened toll lanes, and ETC penetration. Numbers of occurrences of every queue length are summarized in Table 4, and the proportion of various vehicle queue length,  $r_i$ , can be calculated according to  $n$  divided by the total scenarios number of 80.

**Table 4.** The proportion of various MTC queue length under designed scenarios.

Queue Length (Veh.)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	>9
Times of occurrences	8	7	8	11	12	11	5	5	5	8
Proportion $r_i = N/80$ (%)	10.00%	8.75%	10.00%	13.75%	15.00%	13.75%	6.25%	6.25%	6.25%	10.00%

By using the vehicle classify models, probabilities of different queue lengths, and the vehicle emission experiment results, the comprehensive environmental benefits of every ETC transaction in Beijing can be calculated according Equation (2). Assuming the  $V_{ETC} = 1$ , and the reduction values of

fuel consumption,  $\Delta^{SO}$  and the reduction values of HC, CO, and NO<sub>x</sub> emission of each times of ETC transaction can be determined as listed in Table 5.

**Table 5.** Calculated environmental benefits indicators of per ETC transaction in Beijing.

ETC Environmental Indicators	Fuel Consumption $\Delta^{SO}$ (L/Times)	HC Emission $\Delta^{SHC}$ (g/Times)	CO Emission $\Delta^{SCO}$ (g/Times)	NO <sub>x</sub> Emission $\Delta^{SNO}$ (g/Times)
Reduction Value $\Delta^S$	0.0314	0.6749	4.6533	0.2674

Based on the statistics data of annual transaction times of ETC system in Beijing (2009–2013), the annual vehicle emissions (HC, CO, and NO<sub>x</sub>) reduction and gasoline consumption decrease, and the comprehensive value of environmental benefits since the ETC system began trial operation in Beijing can be calculated, and the results are listed in Table 6.

**Table 6.** Calculated environmental benefits indicators of ETC system in Beijing (2009–2013).

Year	Transaction Times Rate of ETC (Millions/Year) $V_{ETC}$	Fuel Saving (L)	HC Emission Reduction (kg)	CO Emission Reduction (kg)	NO <sub>x</sub> Emission Reduction (kg)
2009	23.14	726,500	15,615.30	107,664.33	6186.89
2010	52.68	1,654,000	35,550.42	245,113.04	14,085.32
2011	86.49	2,715,900	58,374.40	402,479.74	23,128.34
2012	105.64	3,317,000	71,294.14	491,558.79	28,247.23
2013	130.62	4,101,500	88,155.44	607,814.05	34,927.79
Total	398.57	12,514,900	268,989.70	1,854,629.95	106,575.57
Total reduction of emissions			2,230,195.22 (2230.20 tons)		

Additionally, we can estimate the monetization value of environmental impact assessment indicators based on average fuel costs and wasted gas treatment costs. The unit fuel cost can be calculated based on the weighted average retail price in various regions, and the unit mass emission benefit can also be estimated in accordance with the recovery costs of the air pollutants control, for the local or national environmental protection departments.

As results show in Table 6, taking Beijing as an example, the ETC system is expected to save fuel consumption by 4,101,500 L, reduce pollution gas emissions by 730.89 tons in 2013. Supposing the average fuel cost is 7.5 RMB Yuan/L, and the average air pollutant treatment cost is 8.98 RMB Yuan/kg according to the data in Environment Statistical Yearbook 2008 published by Ministry of Environmental Protection of the People's Republic of China [26]. It is expected that the estimated monetization value of the environmental benefits arising from the ETC system is about 38.55 million RMB Yuan in 2013.

## 6. Discussion and Conclusions

The Energy consumption saving and vehicle emissions (hydrocarbons, carbon monoxide, and nitrogen oxide) reduction are two main aspects of the environmental benefits of ETC in comparison with the conventional MTC lane. Two evaluation indicators were proposed to measure the quantitative benefit and the emission test and field experiments based on seven different vehicle types were conducted on the Vehicle Emissions Testing System (VETS). Then, the indicator calculation model was put forward

to estimate the comprehensive benefit of ETC system. Finally, taking Beijing as a case study, the paper validated the model parameters by using the collected data and queuing theory model, and estimated the monetization value of environmental benefit of the ETC system from the view of vehicle emissions reduction and gasoline consumption decrease.

The main conclusions derived from the study are summarized as following:

- (1) The environmental benefit of the ETC system was influenced by various factors including the vehicle types, travel speed, traffic volume, and average queue length of MTC lanes.
- (2) The gasoline consumption saving in the repeated experiments are rather steady; however, the vehicle emissions reductions are easily affected by the driver's behaviors, control procedures and vehicle performances.
- (3) The proposed indicator calculation models can be used to calculate the comprehensive environmental benefit of the whole ETC system, according to parameters including vehicles types proportion, various queue lengths probabilities, transaction rates of ETC and vehicle emission experiment results based on the VETS.
- (4) The operation of the ETC system in Beijing is expected to save fuel consumption of 12.5 million liters, reduce vehicle emissions by 2230.20 tons and monetization value of the environmental benefits is up to 113.89 million RMB Yuan (about 18.52 million US Dollar) during 2009–2013.

In future studies, the experimental database will be enlarged. The experimental emission factors of different vehicle brands, types and mileage should be comprehensive in order to develop fuel consumption and vehicle emission models more accurately. In addition, the queue length distributions also need to be considered for the ETC when evaluating its environmental impacts in future research.

## Acknowledgments

The authors would like to show great appreciation for the support from the Ministry of Industry and Information Technology of P.R. China under the Major Program of national science and technology with No. 2013ZX01045-003-002.

## Author Contributions

The authors contributed equally to this work. All authors have read and approved the final manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

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