Exhaust emission analysis of expressway toll station based on PEMS data

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Abstract. The complex operation characteristics of vehicles at tollbooths on expressway lead to the increase of vehicle emission intensity. In order to reduce energy emissions at toll stations on highways, the toll stations on highways have been replaced with ETC charging mode. In order to effectively evaluate the environmental and energy efficiency after the abolition of toll stations, it is necessary to analyze the correlation between ETC charging mode and lane emission under manual charging mode. Using PEMS data, this paper analyzes in detail the correlation between vehicle operating characteristics and emissions in ETC lane and toll lane. The results show that ETC lane can increase the vehicle traffic efficiency and effectively reduce the exhaust emissions at the toll station. The results of this study will provide a basis for evaluating the energy efficiency of expressway tollbooths after their removal.

1. Introduction
With the steady development of China's society and economy, the number of motor vehicles in China is increasing year by year, and the air pollution caused by vehicle exhaust emissions is becoming increasingly serious, which restricts the green and healthy development of cities. Toll stations on expressways, as a frequent site of traffic congestion on expressways, operate under complicated conditions and burn fuel insufficiently, resulting in high concentrations of hydrocarbon and carbon monoxide and other exhaust pollutants discharged at toll stations. To reduce the toll of pollutant emissions, improve energy efficiency, environmental protection, in May 2019, the ministry of communications issued "eliminate highway boundary toll station working plan, the plan" since January 1, 2020, the national highway 487 provincial boundary 29 provinces networking toll all cancelled, adopt the no parking fee ETC (Electric toll collection) model to complete fee ". According to statistics, after the withdrawal from the station, under normal traffic conditions, the average time for passenger cars to pass through the provincial boundary was reduced from 15 seconds to 2 seconds, a decrease of about 86.7%, and the time for trucks to pass through the provincial boundary was reduced from 29 seconds to 3 seconds, a decrease of 89.7%. With the improvement of highway traffic capacity, the number of vehicle stops is reduced, and the exhaust emission is relatively reduced. However, the research on the exhaust emission reduction benefits after the withdrawal has not been carried out yet.

Based on this, this paper adopts the highway vehicle trajectory data to build the highway motor vehicle exhaust emission model. The results can indicate the exhaust emissions of the two different toll gates: the ETC (electronic toll collection), MTC (manual toll collection), and can evaluate the environment benefits after removing the MTC.
2. Literature review

Motor vehicle exhaust emissions are an important source of pollution at expressway tollbooths. Affected by the service mode and service capacity of expressway toll station, motor vehicles often idle, stop, start and other driving behaviors that are not conducive to atmospheric environment occur in the charging area. After the abolition of provincial tollbooths, the vehicle traffic efficiency in the tollbooths area has been significantly improved, which brings economic benefits such as fuel saving, exhaust emission reduction and labor operation cost reduction. At present, domestic scholars have seldom studied the energy and environmental benefits of vehicle emissions before and after the withdrawal of the station, leading to a lack of research on the quantitative assessment of environmental impact after the withdrawal. This section will summarize the research status of vehicle exhaust emission at home and abroad. Developed countries have done a lot of research on motor vehicle pollution control since the 1970s, among which the research on motor vehicle exhaust emission model is represented by the United States. This period has seen a shift from traditional emission models (MOBILE and EMFAC models) to integrated emission models more suited to modern traffic conditions (CMEM and NGM models). Similarly, Europe also experienced the development process from COPERT model to FOPEMOVE model [1]. Soylu used the COPERT model to evaluate the vehicle exhaust emissions from Turkey's road network in 2004, and found that passenger cars were the main contributors to CO and HC, while heavy vehicles were the main contributors to \(\text{NO}_x\), PM and \(\text{SO}_x\). Frey et al. used MOBILE model to calculate heavy vehicles and found that HC and CO emission rates were more sensitive to speed than acceleration. PM emission rates were not significantly sensitive to different average road speeds, but the emission rates showed an increasing trend with the increase of speed [3]. SajalS.Pokarel et al. used MOBILE model to simulate the vehicle exhaust emissions in Denver in recent years, and used remote sensing technology to measure the vehicle emissions in this area. The comparison between the simulation results and the measured results showed that the measured value was 40% lower than the simulated value for HC, 30-70% higher for CO, and 40-80% higher for \(\text{NO}_x\) [4]. Norman F.Robinson et al. used MOBILE4.1 and MOBILE5.0 to simulate motor vehicle emission factors in Pennsylvania and Maryland, and compared them with tunnel tests [5]. Zarate used COPERT model to establish the emission inventory of Bogota, Capital of Colombia [6]. And the United States environmental protection agency (epa) development of a new generation of motor vehicle exhaust quantitative model MOVES because in constantly develop and perfect, so the MOVES can be used to calculate both at home and abroad research of vehicle exhaust emissions is relatively mature model for relative to other less, but the U.S. environmental protection agency (epa) has decided to use the MOVES to take the place of MOBILE and NONROAD model, and MOVES the model can be used widely in the United States is being [7]. Foreign scholars mainly nested the MOVES model and other traffic models (such as VISSIM and Paramics) to achieve the effective output of simulation values. For example, Adel.W.Sadeka et al. [8] extracted the second-by-second vehicle characteristics using microscopic traffic simulation model Paramics and integrated it into the input data required by MOVES model to improve the simulation accuracy. Hatemabou-senna combined the micro-traffic simulation model and the MOVES emission model to analyze and compare the emissions of CO, \(\text{NO}_x\), PM2.5 and [CO] \(\_2\) when three different traffic parameters were input into the MOVES model for a single expressway [9]. It is found that due to their different processing processes, the average speed as the input parameter of traffic will be overestimated, while the driving cycle as the input parameter of traffic will be underestimated, and the simulation accuracy will reach the maximum when the operating condition distribution is used as the input parameter. He also analyzed the effects of traffic flow, speed, truck ratio, road slope and temperature on vehicle emissions. Compared with developed countries, due to the lack of sufficient and effective basic traffic data, domestic research on automobile exhaust emissions is mostly carried out in high schools, such as Southeast University, Tianjin University, Tsinghua University, etc. The relevant applied research is summarized as follows:

Hai-kun wang choice, also in Shanghai city business district and main road of the area of the income is relatively low, fast track and road three, a total of nine typical road, vehicle technology parameters, than the power distribution, starting condition, such as testing, using IVE model concluded in 2004,
Shanghai automotive CO, VOC, [NO]_x and PM emissions and high emissions vehicle emissions on the contribution rate of total emissions, etc [11].

On the basis of determining the basic parameters based on the measured data, Fu Lixin obtained the motor vehicle pollutant emission factor in Beijing by using the MOBILE model, obtained the total emission and emission sharing rate of motor vehicle exhaust pollutants in urban and municipal areas, and analyzed the contribution rate of different vehicle models and types in automobile exhaust pollution in urban areas [12].

By using CMEM model, Chunyu He calculated the emission factors of four types of typical light motor vehicles in Beijing (CO, CO, HC, NO)_x single cycle and the comprehensive emission factors of each model. By comparing with the measured emission factors of the same vehicle on the road, it was found that the emissions of CO, HC and [NO]_x calculated by CMEM model were in good agreement with the measured emission factors and emission characteristics [13].

Song Xiangyu used THE COPERT model to calculate the emission factors of motor vehicles in cities, suburbs and expressways in various provinces of China in 2002, and compiled China's motor vehicle emission inventory using geographic information system [14].

Huang Guantao in different sections and intersections in Beijing, on the basis of the GPS data, using MOVES model respectively based on the average velocity and based on the operation condition of motor vehicle exhaust emission into the simulation and comparison, analysis found that there are differences between simulated results and measured data, the precision of simulation, based on the operation condition of the calculation result is higher than the calculated results based on the average speed of [15].

In addition to the research application of vehicle exhaust emission, vehicle exhaust emission model has also been applied to environmental projects. Zhang Zesheng applied the MOBILE model in the environmental assessment of the transportation improvement project funded by the World Bank in Tianjin, analyzed the practical value of the model in the environmental impact assessment of the transportation improvement project, and believed that the promotion and use of the MOBILE model developed by the US EPA had important practical value in the evaluation of the transportation project [16].

As the research and development object of foreign exhaust emission models is motor vehicles, the amount of data required in simulation simulation is huge and the workload of data acquisition is large, so its practical application is poor. As mentioned above, in order to obtain more accurate exhaust emission simulation data, traffic operation data of motor vehicles is the key input data of emission model. Existing traffic detection and investigation while it is possible to obtain more accurate traffic data, however, emissions modeling data accuracy and range of demand is higher and higher, the investigation of the coverage is limited, so by the measured or on-the-spot investigation to study the road has a lot to the difficulty of the exhaust emission, now also is very difficult to achieve. Domestic scholars usually use MOBILE, IVE and other simulation models to calculate vehicle exhaust pollutant emissions, but lack of understanding and application of the newly developed ENVIRONMENTAL Protection Agency (EPA) emission software MOVES. China has not yet established a unified evaluation standard and control system for vehicle exhaust emission measurement, and there are too many qualitative results. Domestic and foreign researches on the relationship between road geometric design index and exhaust emission are rarely involved.

3. Analysis of vehicle emission characteristics at expressway toll station

3.1 Datasets
Portable Emission Measurement System (PEMS) is a new exhaust emission measurement method emerging after 2000. The vehicle-mounted detection equipment is light in weight and small in size, which can be conveniently and quickly placed on the test vehicle. In the actual driving process of the vehicle, the tail gas is directly sampling and analyzed to obtain the vehicle emission concentration and emission quality every second. Meanwhile, the vehicle's driving speed and longitude and latitude
information can also be recorded in real time. This paper takes Beijing as an example to analyze the characteristics of vehicle exhaust emission at expressway tollbooths. This paper takes August 17, 2015 as an example to analyze hourly PEMS data between 6:00 and 22:00 on working days, and selects two toll stations of Jingcheng Expressway and Beijing-Tibet Expressway for analysis. Choose peace at peak period of the passenger car and bus 100 groups of samples under different lanes of PEMS distribution data, GIS will be the vehicle of PEMS contains latitude and longitude information by second test results map matching, using the all of the sections of PEMS sample statistics the vehicle-timeses test vehicles through this section of the average of all kinds of pollutants emission intensity, average speed, average acceleration.

3.2. Analysis of vehicle running characteristics at toll station

The operation process of the vehicle passing through the expressway toll station can be simplified into the process of entering the station, paying the fee and leaving the station. Vehicles passing through ETC and manual toll lanes vary in speed, acceleration and idle state. The process of a vehicle passing through ETC toll lane can be divided into the process of decelerating into the station, paying fees at a uniform speed and accelerating out. The process of a vehicle passing through a toll lane can be divided into the process of slowing down to enter the station, idling to pay the toll and accelerating to leave the toll station. Vehicle emissions intensity and road dynamic and static characteristics of the correlation analysis is the basis of the emission model building, therefore, this article to distinguish the two kinds of charging mode, the dynamic characteristics of the running train sections including the average velocity and average acceleration and toll roads static factors such as length, analysis the influence of different factors on vehicle emissions. By analyzing the track data of PEMS vehicles, the change behavior of the running characteristics of the road section passing through the toll station can be detected respectively. The length of the road section that the vehicle passes through the change process of the toll station is defined as the length of the road acting by the toll station, and the time of the vehicle passing through the toll station is defined as the length of the road acting by the toll station. Table 1 and Table 2 show the characteristic distribution of average running time and influence length of vehicles passing through different toll lanes based on PEMS data analysis. It can be found from Table 1 that for the same toll lane, the driving time of each vehicle type in different running states during peak hours is higher than that during normal peak hours. This is because when the vehicle is in the state of acceleration, the vehicle has completed the payment and left the station successively, and there is a certain time interval between adjacent vehicles, so that the front vehicle can accelerate freely even in the rush hour without being affected by the traffic flow. For different toll lanes in the same period, the average running time of bus models in each stage of toll lanes is greater than that of ETC lanes, except that the truck model only has manual payment. It shows that ETC system can significantly reduce vehicle running time and improve vehicle traffic efficiency.

| periods     | Lanes type | Car type | Average vehicle running time |
|-------------|------------|----------|----------------------------|
|             |            |          | Deceleration time | Constant speed/idle time | acceleration time |
| Pick hours  | ETC        | car      | 12.36          | 5.66                     | 8.12              |
|             | Manual     | coach    | 15.61          | 6.18                     | 9.63              |
|             | TC         | car      | 28.17          | 32.11                    | 9.81              |
|             | ETC        | coach    | 56.76          | 43.98                    | 10.71             |
|             | Manual     | coach    | 11.88          | 5.01                     | 7.97              |
| Everage hours | ETC      | car      | 14.32          | 5.98                     | 8.98              |
|             | Manual     | coach    | 26.55          | 30.19                    | 10.12             |
|             | TC         | coach    | 52.31          | 40.26                    | 11.36             |

It can be seen from Table 2 that, during peak hours, the length of variable speed influence interval of ETC lane is smaller than that of manual toll lane, and the shortened distance is about 50~60m.
Table 2. Distance effects of the toll gates base on PEMS dataset (m)

| periods   | Lanes type | Average | stdet |
|-----------|------------|---------|-------|
| Pick hours| ETC        | 98.62   | 25.32 |
|           | Manual TC  | 152.11  | 28.01 |
| Everage   | ETC        | 70.09   | 24.18 |
| hours     | Manual TC  | 128.72  | 27.63 |

Based on PEMS data, the velocity and acceleration distributions of vehicles passing through different toll lanes can be analyzed, as shown in Table 3. From the table, we can get the difference of running characteristics of each vehicle in different lanes (taking speed and acceleration as characteristic values). In general, the average speed in the ETC lane is higher than that in the artificial lane in both time periods, which proves that the ETC lane has a higher passing efficiency. Compared with the bus, the average speed of the bus in the artificial lane is greater than that of the bus. For acceleration, the acceleration of passenger cars in ETC is greater than that in other cases, indicating the higher efficiency of peers in ETC.

Table 3. Summary on various cars velocity and acceleration distribution.

| periods   | Lanes type | type | Average speed | Acceleration speed |
|-----------|------------|------|---------------|--------------------|
| Pick hours| ETC        | car  | 42.11         | -1.2               |
|           | Manual TC  | car  | 20.76         | -1.0               |
| Pull out of the toll booth | ETC        | car  | 62.16         | 4.2                |
|           | Manual TC  | car  | 40.28         | 2.1                |
| Everage hours | ETC        | car  | 50.89         | -1.1               |
|           | Manual TC  | car  | 22.12         | -0.9               |
| Pull out of the toll booth | ETC        | car  | 39.12         | -0.9               |
|           | Manual TC  | car  | 12.96         | -0.4               |

The emission standards of vehicles studied in this paper are national IV standards and National V standards, which are also the most commonly used vehicle emission standards at present. The main pollutants emitted by cars are HC (hydrocarbons), NOx (nitrogen oxides) and CO (carbon monoxide). PEMS data can obtain the tail gas emission efficiency of different vehicle types when passing through different lanes, and the correlation analysis between emissions and various circumstances can be used to obtain the correlation between emissions under different circumstances. Figure 1~2 shows the influence of peak hour average speed and average acceleration on emissions.

It can be seen from the figure that although the distribution of scatter points at different average speeds is relatively dispersed, the overall trend of emission intensity of CO, HC and NOx of vehicles decreases with the increasing average speed of the road section. On the whole, within the average speed range of 10 ~ 80 km/h, the average emission intensity of CO is mainly distributed in the range of 0.3 ~ 1.4 g/km, the average emission intensity of HC is mainly distributed in the range of 0.03 ~ 0.15 g/km, and the average emission intensity of NOx is mainly distributed in the range of 0.03 ~ 0.08 g/km. Further comparison of the correlation between different emissions and the average speed of a road segment shows that the correlation between HC and NOx emission intensity and the average speed of a road segment is slightly stronger than that of CO. However, the squared Pearson correlation coefficient between the emission intensity and the average speed of the three pollutants is all lower than 0.5, and the correlation is all low.
Figure 1. The relationship between emissions and average velocity.

The variation of the average emission intensity of vehicles along a road segment with the average acceleration of a road segment is shown in Figure 2. It can be seen from the figure that the average acceleration of the road segment of the vehicle is generally distributed between -0.2 ~ 0.2 m/s². The correlation between the average emission intensity of the three types of pollutants in a section and the average acceleration of a section is very weak, with R² all lower than 0.25. However, it can still be observed that the average emission intensity of each pollutant in a section is positively correlated with the average acceleration of a section.
4. Conclusion
The study on the emission characteristics of vehicles in different lanes of toll stations (manual toll lanes and ETC lanes) is important for evaluating the environmental benefits after removing the manual toll stations. This paper analyzes the relationship between the vehicle running characteristic and emission at different toll station by using PEMS data. The results are summarized as follows: the ETC lanes of traffic efficiency is higher than that of artificial charge lane, lane and ETC of vehicle emissions is less than human toll lane; with the acceleration of vehicle running speed, the vehicle emission intensity of CO, HC and NOx decreases gradually. In this paper, there are still the following deficiencies: the research model is relatively single, and the data collection method is relatively single. In future studies, multiple models should be considered and video data should be used to study the vehicle operation characteristics at the toll station, so as to lay a foundation for evaluating the environmental benefits after the toll station is removed.

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