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Establishment of the Urban Vehicle Fuel Consumption and Emission Inventory Platform: A Case Study in Shenzhen

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Abstract: Quantitative analysis of vehicle fuel consumption and emission (VFCE) is important for the establishment of the urban traffic emission inventory and the development of related environmental policies. The lack of uniform inventory methods and factors at the national level, and the shortage of basic data sharing and coordination at the local level are the two main obstacles of current research. This paper adopts the HBEFA approach to calculate vehicle fuel consumption and greenhouse gas emissions, determines localized VFCE factors, and establishes a refined bottom-up accounting model. It is proposed in this paper to establish the urban vehicle fuel consumption and emission inventory platform in Shenzhen by developing an inter-departmental and open collaboration mode, using the data-model-application functional framework, and making a breakthrough in the integration of traffic and environmental multivariate data. This platform serves as a technical tool for transportation environmental impact analysis to support governmental decision-making, plan business activities and provide resident travel guidance. **DOI:** 10.13813/j.cn11-5141/u.2018.0510-en

Keywords: intelligent transportation system (ITS); vehicle fuel consumption and emission (VFCE); inventory model; dynamic platform; multivariate data

0 Introduction

Motor vehicles are the major energy consumers, and the main sources of greenhouse gases and pollutants. With the rapid development of urban motorization, enhancing the management of mobile source emissions and improving air quality have become increasingly crucial for cities to implement transportation environment governance and demand management policies. In China, both state and local governments have promoted to establish an inventory, accounting and evaluation system for greenhouse gas emissions to support scientific decision-making [1–2]. A quantitative inventory of vehicle fuel consumption and emissions is a fundamental work in the field of transportation.

At present, a mature and uniform database of vehicle emission factors has not yet been established at the national level in China. The local authorities are also facing many problems, including the lack of technical capacities, inconsistencies in inventory methods, and obstacles in data sharing. Under this background, Shenzhen made a breakthrough in the integration of multivariate data, and built a localized Vehicle Fuel Consumption and Emission (VFCE) inventory platform to support the government on the decision-making of transportation and environment management [3]. Compared with the use of in-vehicle equipment such as Portable Emission Measurement System (PEMS), the VFCE platform can take into account both accuracy and economy, and has the advantages of low cost, high efficiency and easy application [4].

1 Methodology

Since the 1980s, European and American countries have gradually established databases of motor vehicle emission factors and multi-level emission models, such as MOBILE, Motor Vehicle Emission Simulator (MOVES), Computer Program to calculate Emissions from Road Transport (COPERT), and Handbook Emission Factors for Road Transport (HBEFA) [3,5], as summarized in Table 1. In recent years, China introduced European and American models and has begun to apply macroscopic models based on average speeds [6], whereas mesoscopic and microscopic models are still in the research stage. Considering the similarity of the automobile industry standards and emission standards

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between China and Europe, this paper adopts the European HBEFA approach [7], and uses localized parameters such as traffic situations, fleet composition and emission factors to develop a VFCE model that can be applied in Shenzhen.

Table 1 Typical transportation energy consumption and emission models

Model	MOBILE	MOVES	COPERT	HBEFA
Country/ Region	USA	USA	Europe	Europe
Key inputs	Average speed	Driving pattern	Average speed	Traffic situation
Analysis level	Street level and above	Street level and above	National & city level	Street level and above
Inventory items	Fuel consumption (FC), HC, CO, NO_x, CO_2, PM, Benzene, Formaldehyde, Acetaldehyde, etc.	FC, VOC, NO_x, CO, PM_{10}, $PM_{2.5}$, etc.	CO, NO_x, VOC, PM, NH_3, SO_2, CO_2, N_2O, CH_4, PM, etc.	FC, CO_2, CO, HC, CH_4, N_2O, O_3, NO_x, PM, FC, PN, etc.
Applications	Estimating vehicle source emissions; implementing the air quality improvement plan; replaced by MOVES in 2010	Evaluating management policies of traffic demand, smart-growth strategies, and transit priority policies	Emission Inventories in most European countries	Basic data for TREMOVE and COPERT models; macroscopic and mesoscopic emission inventories

Source: Reference [3].

1.1 Scope

1) Spatial scopes and temporal resolutions. Temporal resolutions are classified as high resolutions (e.g. 15 min or 1 hour), medium resolutions (e.g. 1 day or 1 month) and low resolutions (e.g. 1 year). Spatial scopes include street intersections or road segments, traffic zones, administrative districts and entire cities, as shown in Figure 1.

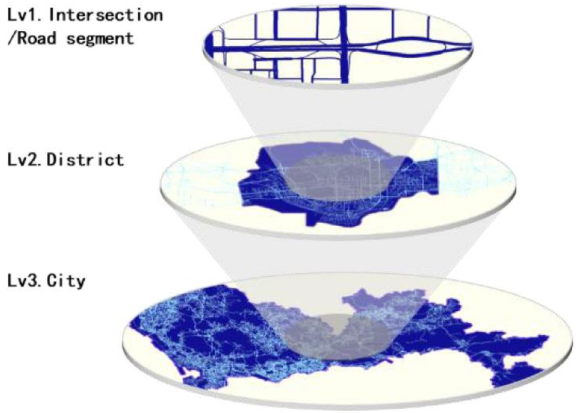


Figure 1 Spatial scopes of the inventory platform

Source: Reference [3].

2) Vehicle types. There are two main types of vehicles, passenger vehicles (e.g. private cars, normal buses, taxis, and coach buses) and trucks (heavy, medium and light duty trucks). Vehicles can also be classified according to energy type, engine capacity and emission standard, as shown in Figure 2.

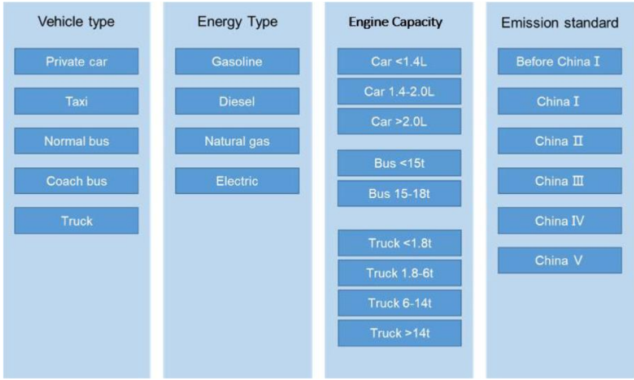


Figure 2 Types of motor vehicles

Source: Reference [3].

3) Accounting Process. According to the Life-Cycle Assessment (LCA) theory [8], the complete fuel pathway is Well-to-Wheel (WTW), divided into two parts: Well-to-Tank (WTT) and Tank-to-Wheel (TTW). Due to the difficulties in monitoring the fuel production and delivery, only the TTW part is included in this study.

4) Inventory Items. The TTW analysis quantifies the fuel consumption (FC) and emissions from motor vehicles. Fuels include gasoline, diesel and natural gas but do not include electricity which is considered as zero emission. Pollutants include greenhouse gases such as CO_2, CH_4, N_2O, and O_3 and air pollutants that are harmful to people's health such as NO_x, PM, HC, and CO.

1.2 Refined inventory model

To assess the emissions precisely at the street block level, a bottom-up model is established, which uses road segments as the basic unit. This model calculates the fuel consumption and emissions for all types of vehicles on road segments based on parameters such as traffic situations and emission factors, and then fuel consumption and emissions are summed up at the zone and city levels.

The vehicle emissions over a specific period on a specific road segment can be calculated by Equation (1).

$$E_{ij} = VKT_i \times \alpha_{ij} \times EF(\lambda_j, \rho_i), \qquad (1)$$

where E_{ij} is the emissions from type j vehicles on road segment i (unit: g); VKT_i is the vehicle kilometers of road segment i (unit: veh·km); α_{ij} is the proportion of type j vehicles among all vehicles on road segment i ; $EF(\lambda_j, \rho_i)$ is the emission factor of type j vehicles at the current level of service (LOS) on road segment i (unit: g·veh^{-1}·km^{-1}); λ_j is the vehicle factor, which accounts for vehicle type, fuel type, vehicle age, engine capacity, and emission standards, etc.; ρ_i is the road factor, which accounts for traffic conditions, LOS, and road gradient, etc.

The total emissions of all vehicles on road segment i can be calculated by Equation (2).

$$E_i = \sum_j E_{ij}. \qquad (2)$$

And the total vehicle emissions in the road network can be calculated by Equation (3).

$$E = \sum_i E_i \,. \tag{3}$$

1.3 Local input data

1.3.1 Traffic situation data

1) Travel demand: vehicle kilometer traveled. Travel surveys and Origin-Destination (OD) matrix estimation based on road traffic flow are used to build a four-step travel demand model [9], which models the travel demands of various vehicle types, such as cars, buses, and trucks. This model provides vehicle kilometers traveled (VKT) by each type of vehicles on a road segment. Dynamic data from floating cars, mobile phone GPS, the license plate recognition system, loop detectors, bus IC cards and VKT surveys etc., are used to calibrate traffic flow functions and parameters in trip distribution and mode choice. OD matrix estimation is then used to update the travel demand model.

2) Fleet composition: average vehicle proportions. For a particular location and time period, vehicle fleet composition means percentages of different types of vehicles in the traffic, which can be calculated by matching the license plate recognition data and the annual vehicle inspection data. Specifically, Shenzhen's license plate recognition system covers 255 sites on arterial roads, dynamically collecting information such as time, site ID, encrypted license plate numbers and lane ID. The annual vehicle inspection data include the encrypted license plate number, date of inspection, year of registration, engine capacity, and vehicle type, etc. With the license plate number as the primary key, the fleet compositions on a road segment or in a district are calculated.

3) Traffic condition: road level of service. The average travel speed on each road segment is calculated based on the Shenzhen Traffic Index System. It is a floating car system, processing second-by-second real-time GPS data from 18 000 taxis and a portion of navigators equipped on local passenger cars. According to the approach by Chen et al.[10], the ratio of expected speed to average speed (SR) is used to define the Traffic Index (TI with possible values of 0 to 10) as well as the corresponding five levels of service (Table 2).

Table 2 Road level of service

Level of service (LOS)	LOS1 Free flow	LOS2 Relatively smooth	LOS3 Slow moving	LOS4 Slightly congested	LOS5 Congested
Traffic index (TI)	>0–2	>2–4	>4–6	>6–8	>8–10
Speed ratio (SR) = expected speed/average speed	>0–1	>1–4/3	>4/3–20/11	>20/11–2.5	>2.5

Source: Reference [10].

4) Typical driving cycles: time-speed curve. A typical driving cycle is a section of time-speed curve which can represent the typical driving condition for motor vehicles under a specific road type and LOS. The three steps to determine the typical driving cycles are [3,11]

Step 1: data collection and preprocessing. The 6 000 hours of one-second GPS data are collected by floating cars, which cover all four road types (highway and expressway, major arterial, minor arterial and collector street) and five LOSs in Shenzhen. The GPS data are pre-cleaned and matched to GIS maps and LOSs.

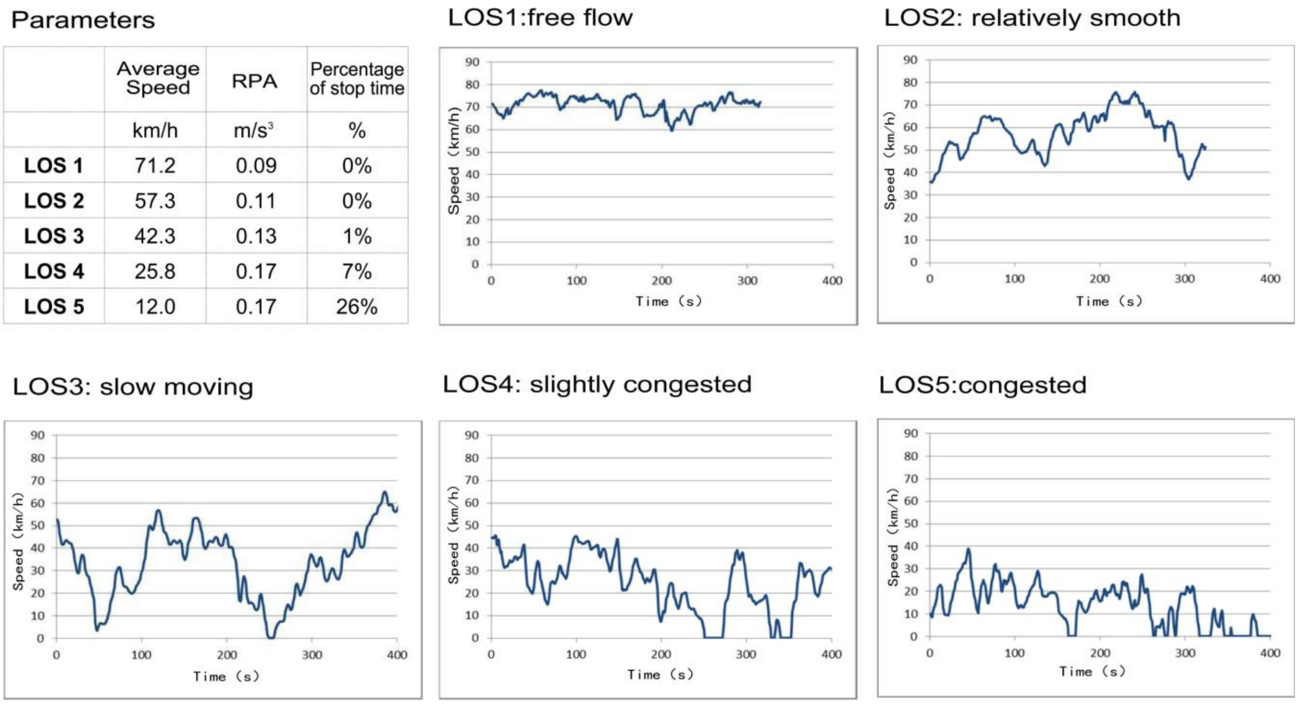
Step 2: separating driving cycles. The time-speed curve collected by a floating car is divided into several sections (driving cycle units) by road type and LOS based on the cross-classification method. For each section, parameters such as average speed, percentage of stop time, relative positive acceleration (RPA) are calculated and standardized by means of Z standardization.

Step 3: determining typical driving cycles. Based on the least squares method, 20 typical driving cycles by four road types and five LOSs are determined for Shenzhen. For example, Figure 3 shows the typical driving cycles for major arterials in Shenzhen.

1.3.2 Localized fuel consumption and emission factors

Passenger Car and Heavy-Duty Emission Model (PHEM) is a microscopic model [12], based on a large amount of measured data such as driving situations, road gradients and gear shift patterns in Europe. This model depicts transient "engine maps" for different types of vehicles, and simulates the relationship among engine speed, engine power, and emissions. Due to the similarity between the vehicle standards in China and Europe, PHEM is adopted to calculate engine speed and power based on the typical driving cycles and vehicle characteristics in Shenzhen. Then, fuel consumption and emissions are obtained based on transient engine maps, and finally the emission factors in the unit of $g \cdot km^{-1}$ are developed (see Figure 4).

Shenzhen developed 4 500 fuel consumption and emission factors, classified by vehicle type, pollutant, road type, LOS and other factors. Taking passenger cars as an example, there are in total 2 700 emission factors for three engine capacities (< 1.4 L, 1.4 L–2.0 L, and > 2.0 L), five emission standards (China I–V), four types of roads (highway and expressway, major arterial, minor arterial and collector street), five LOSs as shown in Table 2, and nine inventory items including fuel consumption, CO_2, CO, HC, NO_x, etc. The CO_2 emission factors of two typical passenger cars are shown in Figure 5. Results show that the difference between emissions calculated by PHEM and measured by PEMS is about 5%, indicating that the model is accurate enough for city-level emission inventory and policy evaluation.



	Average Speed	RPA	Percentage of stop time
	km/h	m/s^3	%
LOS 1	71.2	0.09	0%
LOS 2	57.3	0.11	0%
LOS 3	42.3	0.13	1%
LOS 4	25.8	0.17	7%
LOS 5	12.0	0.17	26%

Figure 3 Typical driving conditions of major roads in Shenzhen

Source: Reference [3].

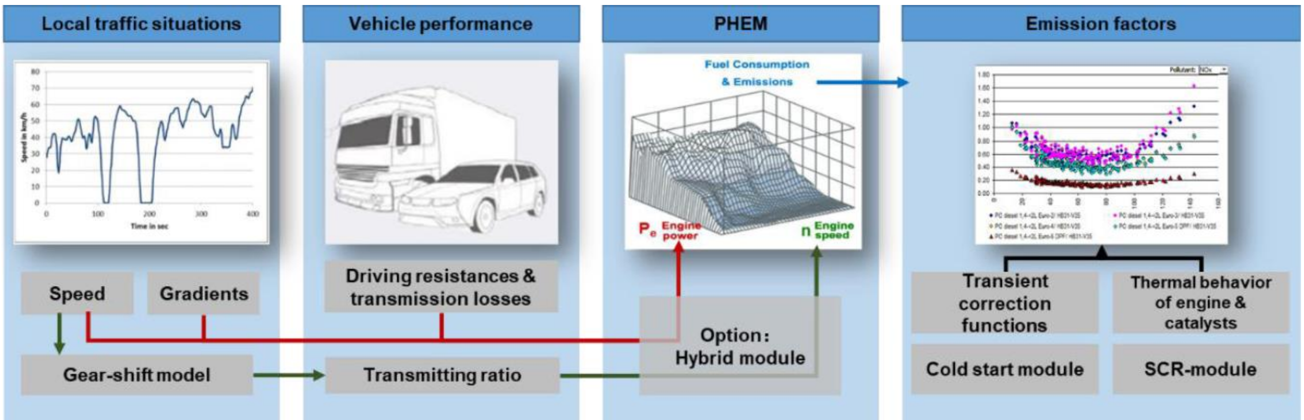
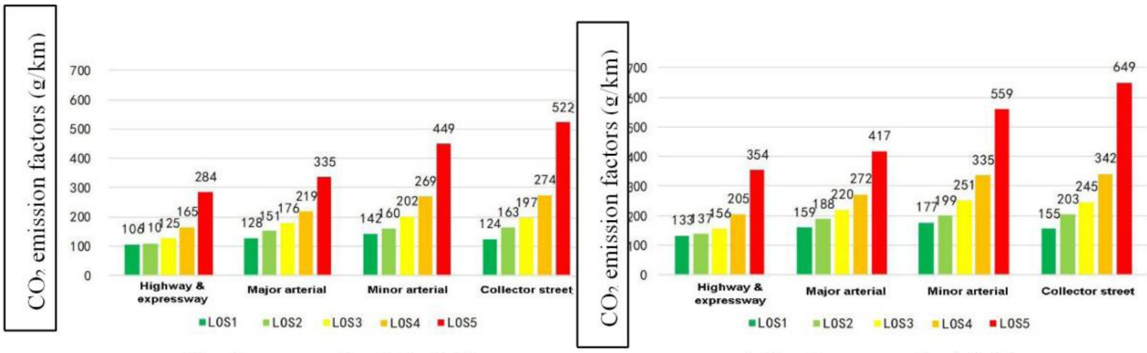


Figure 4 Determining localized fuel consumption and emission factors using PHEM

Source: References [3, 12].



a Engine capacity 1.4–2.0L b Engine capacity >2.0L

Figure 5 CO_2 emission factors of typical passenger vehicles

Source: Reference [3].

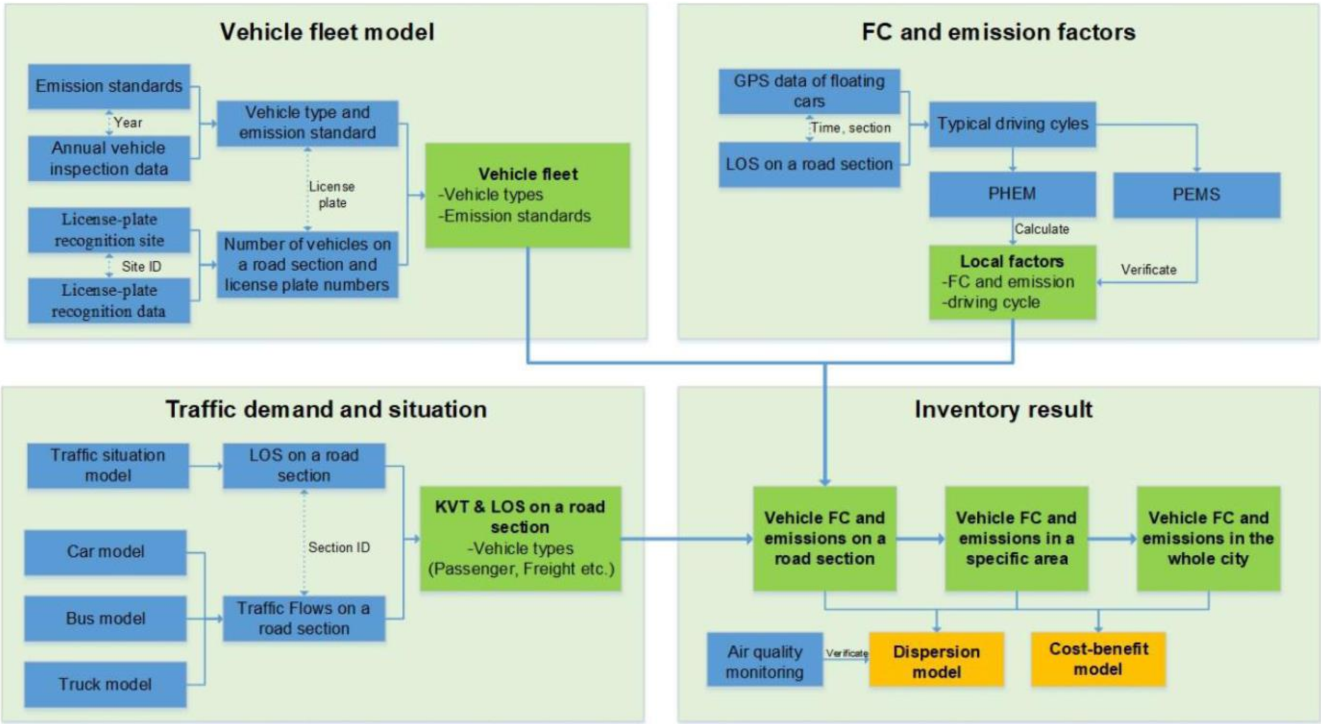


Figure 6 Theory and data flow of the inventory model

In conclusion, the theory and data flow of the inventory model are shown in Figure 6.

2 Platform establishment

The application of emission models currently focuses on the development of off-line software tools to calculate emissions. For example, an affiliated software package of HBEFA was developed using Microsoft-Access/Visual Basic[12]. Nevertheless, its data management is decentralized and the operation process is complicated, which is unable to meet the requirement of dynamic assessment and quick response. Therefore, a technical and automated platform, the Vehicle Fuel Consumption and Emissions (VFCE) inventory platform[9], has been established in Shenzhen, as a part of the urban comprehensive evaluation system for transportation decision-making.

2.1 Requirement analysis

The goal of the VFCE platform is to assess the impact of traffic on the environment and to support the government's decision making. The Shenzhen Department of Transportation takes the lead and takes into account the demands and responsibilities of various other departments. In detail, the transportation department manages the construction of transportation facilities, and quantitatively evaluates the environmental impact of transportation construction and motor vehicle management policies. The development and reform commission coordinates the energy conservation and emission reduction efforts, develops the emission inventories and forecasts the emission reduction potential. The environment department monitors the spatial and temporal distribution of emissions and their impacts on the atmospheric environment, in order to control the motor vehicle emission pollutants.

2.2 Working mode

Reference [4] indicates that the lack of collaboration and data-sharing is the biggest obstacle to similar research. To overcome this obstacle and to ensure the reliability and authority, a working mode of cross-departmental collaboration has been established since the project initiation stage, and the sharing of various basic data is realized (see Table 3).

Table 3 Basic data of associated administration departments in Shenzhen

Administration departments		Basic data
Development	Development and Reform Commission	Fuel consumption (FC)
Transportation	Transportation Department	GIS map/Operating vehicles and FC/GPS data of taxis, buses and trucks/ IC card data/Road traffic situations
	Traffic Division of the Police Department	License plate recognition system/Annual vehicle inspection data/Loop detector data
Environment	Habitat Environment Committee	Vehicle emission standards/Greenhouse gas (GHG) and air pollutant monitoring data/Air quality monitoring data
Technical institution		Urban transportation model/Traffic index system

Source: Relevant departments of Shenzhen Municipal Government

(1) The platform is integrated into the city's Intelligent Transportation System (ITS) framework. As a sub-module

of the comprehensive evaluation system of transportation decision-making, it shares data and results with other modules in the system. (2) The working mode is for the transportation department to lead the development of the platform, with the collaboration of the environment department, the traffic division of the police department, the development and reform commission, etc. Technical resources are integrated across departments, and basic data are shared. Results are published, and policies are developed cooperatively. (3) The platform is developed in an open architecture and interfaces have been reserved for other data such as the rail/subway system and external transportation.

2.3 Platform architecture

The platform consists of three logical layers (see Figure 7):

Layer 1: Data. Based on the uniform basic GIS maps, standardized databases and interfaces are established to realize automatic access and centralized management of cross-department and multivariate data, as well as data pre-processing such as data cleaning and fusion.

Layer 2: Model. Based on the data from the data layer and the inventory model, data processing and calculation modules are developed. Using fast calculation techniques such as partition table, spatial index and parallel computing, the platform can perform online calculation with a minimum interval of 15 min based on dynamic data and can also perform monthly or annual calculation offline.

Layer 3: Application. Application modules to support decision-making and provide public information services are developed, including functions such as visual display, inquiry and statistics, warning, and association analysis. A website (see Figure 8) is established based on this platform, which shows three indicators (fuel consumption, greenhouse gases, and air pollutants) and four thematic maps (heat map, grid map, district map, and road network map).

In terms of hardware, the platform is composed of field detectors, data processing servers and a communication network. The computing resource is provided by the National Supercomputing Center in Shenzhen (Shenzhen Cloud Computing Center).

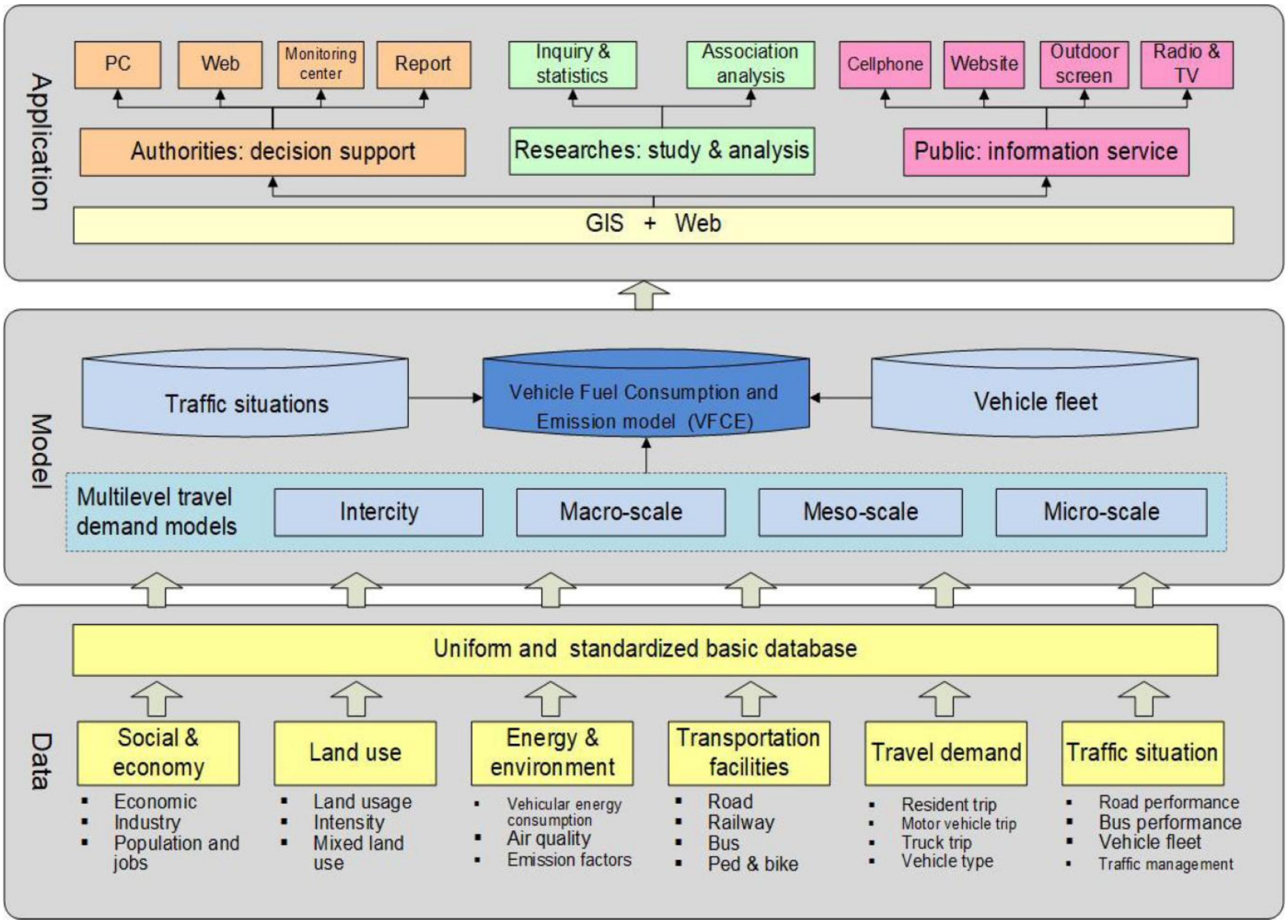


Figure 7 Overall functional architecture of the platform

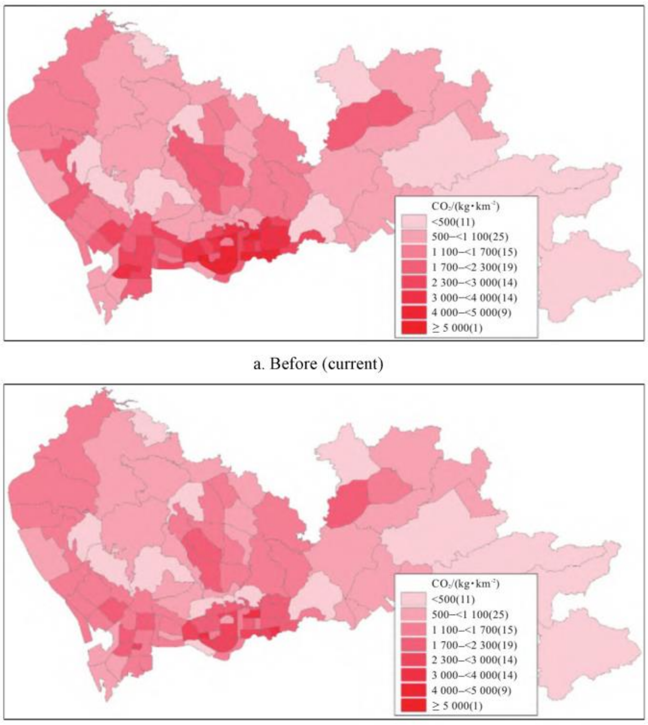
Source: Reference [3].

Figure 8 Website interface of the platform

Source: Reference [3].

3 Applications

Since the trial operation in 2014, the inventory platform has played an important decision-supporting role in Shenzhen in building a green transportation system, implementing travel demand management and prompting green travel, etc. Some applications are listed below: (1) Establish an official inventory of urban traffic emissions. The result showed that motor vehicles in the urban area of Shenzhen consumed about 7 000 tons of fuel daily and produced about 23 000 tons of CO_2, which provides a quantitative basis for the development of energy conservation and emission reduction targets. (2) Evaluate the environmental impact of major transportation infrastructure projects. For example, before and after the building of the Xincai tunnel, the peak-hour average speed at Meilin checkpoint increased by 7%, and the total carbon emissions of motor vehicles decreased by 12%. (3) Assess the environmental benefits of transportation management policies. Taking the parking rate adjustment program as an example, the platform forecasted that due to the increase in the parking rate, carbon emissions of motor vehicles in Shenzhen would be reduced by nearly 20% [13] (see Figure 9). (4) Improve planning techniques and methods. With the use of the platform, environmental capacity can be considered as a new constrained objective in both transportation and land use planning.



a. Before (current)

b. After (prediction)

Figure 9 CO_2 emissions before & after parking rate adjustments

Source: Reference [13].

In addition, for enterprises, the platform can provide reference to environmentally sensitive businesses on site selection, and provide reference to enterprises that participate in traffic emission trading and enterprises that promote energy saving and emission reduction of vehicles. For the public, the platform releases information on traffic energy consumption and emissions (such as personal carbon footprint) through various channels such as TV and mobile APP, and guides the public to pay attention to traffic environment and choose healthy and green travel modes.

4 Conclusion

The construction of Shenzhen's VFCE inventory platform fully reflects the importance of resource integration and technological innovation in a multivariate data environment. The interdisciplinary knowledge integration of transportation and environment ensures the scientificity of the technical method. The multi-departmental data sharing and open collaboration provide the primary protection to ensure that the platform is moving forward. The well-maintained travel demand model, strong information foundation and the integration of multivariate data improve the utilization efficiency of information resources. The building of local technical capacity ensures the continuous operation of the platform.

The future work includes at least the followings: 1) optimize the inventory model and factor database, e.g. refine complex factors such as climatic conditions and road conditions (e.g. gradient and evenness), add other transportation modes (such as air, ocean and rail) into the model, and study the emission dispersion model; 2) build localized emission models and inventory platforms in other cities according to local data and technical conditions, and gradually build a nationwide emission factor database and inventory; 3) strengthen the integration of environment evaluation and other information systems such as operation and monitoring, land development, safety management and economic analysis, to build a comprehensive urban transportation assessment system.

References

[1] General Office of the State Council of the People's Republic of China. 国务院关于印发"十二五"控制温室气体排放工作方案的通知 (国发[2011]41 号) [EB/OL]. 2011 [2016-11-30]. http://www.gov.cn/zwgk/2012-01/13/content_2043645.htm (in Chinese).

[2] Development and Reform Commission of Shenzhen Municipality. 深圳市国民经济和社会发展第十二个五年规划纲要 [EB/OL]. 2011 [2016-11-30]. http://www.szpb.gov.cn/xxgk/ghjh/fzgh/201202/t20120202_1801427.htm (in Chinese).

[3] Chen W, Duan ZY, Song JH, et al. Shenzhen Transport Emission Monitoring Platform and Application [R]. Shenzhen: Shenzhen Urban Transport Planning Center, 2014 (in Chinese).

[4] Dror MB, Wang WW, Kang LP. Experience in Development, Design and Applications of Traffic Emission Calculation Tools at Home and Abroad [R]. Beijing: Innovation Center for Energy and Transportation (iCET), 2015 (in Chinese).

[5] Dünnebeil F, Knörr W. How Do the Urban Transportation Departments Monitor the Greenhouse Gas Emissions [R]. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2012 (in Chinese).

[6] HJ/T180—2005 Method for Estimation of Air Pollution from Vehicular Emission in Urban Area [S] (in Chinese).

[7] Keller M, Wüthrich P. Handbook Emission Factors for Road Transport 3.1/3.2 [R/OL]. 2014[2016-12-01]. http://www.hbefa.net/e/index.html.

[8] Curran S J, Wagner R M, et al. Well-to-Wheel Analysis of Direct and Indirect Use of Natural Gas in Passenger Vehicles [J]. Energy, 2014, 75: 194–203.

[9] Zhang XC, Zhao ZX, Song JY, et al. 城市交通综合评估及决策支持系统 [R]. Shenzhen: Shenzhen Urban Transpor Planning Center, 2014 (in Chinese).

[10] Chen W, Duan ZY, Zhou ZY, et al. 基于出行时间的道路交通运行指数算法与应用研究 [C]//中国城市规划学会城市交通规划学术委员会. 中国城市交通规划 2012 年年会暨第 26 次学术研讨会论文集, 2012: 1703–1711 (in Chinese).

[11] de Haan P, Keller M. Modelling Fuel Consumption and Pollutant Emissions Based on Real-World Driving Patterns:the HBEFA Approach [J]. International Journal of Environment and Pollution, 2004, 22 (3): 240–258.

[12] Hausberger S, Rexeis M, et al. Emission Factors from the Model PHEM for the HBEFA Version 3 [R]. Graz University of Technology, 2009.

[13] Lv GL, Lu Y, Sun ZA, et al. Study on the Parking Toll Adjustment Policy in Shenzhen [R]. Shenzhen: Shenzhen Urban Transport Planning Center, 2014 (in Chinese).

