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基于隧道实验的机动车大气污染物实时排放因子研究

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摘 要: 机动车大气污染物动态排放因子是制约实时排放清单精度提升的一个关键参数.本研究选取某城市隧道,结合在线设备和监控摄像头开展7种大气污染物浓度和车流量的实时监测,采用YOLOv8l深度学习目标检测模型和SORT目标跟踪算法,获取车辆类型和速度;采用排放强度比值,推算车队整体和分车型的大气污染物排放因子.CO、NO、NO_2、NO_x、SO_2、BC和$PM_{2.5}$的平均排放因子分别为(1 064.9±479.8)、(496.5±209.3)、(55.5±30.4)、(578.6±267.6)、(6.3±2.2)、(3.3±1.5)和(37.7±19.2) mg/(km·辆);车队整体排放因子分别为(634.7±477.2)、(266.0±142.9)、(26.4±13.5)、(302.3±159.5)、(3.5±1.9)、(2.0±1.10)和(19.8±12.3) g/km.隧道内周末的日车流量为工作日的88.6%,工作日除$PM_{2.5}$外的污染物排放因子是周末的1.00~1.48倍.在逐小时排放因子情境下,凌晨的柴油车流量占比是其余时间的1.6倍,各污染物的凌晨高值分别是其余时间平均值的2.0~3.5倍;车队排放呈现出早晚(7:00~9:00;17:00~19:00)双峰特征,为全天平均值的1.8~3.3倍.本研究可为区域高精度动态机动车排放清单构建和机动车排放污染物的精准管控提供基础数据和科学依据.

关键词: 隧道实验;大气污染;动态排放因子;图像识别;单一车辆与车队.

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Real-Time Emission Factors of Motor Vehicle Air Pollutants Based on Tunnel Experiments

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Abstract: Dynamic emission factors of motor vehicle air pollutants are a key parameter limiting the improvement of real-time emission inventory accuracy. In this study, a tunnel in a metropolitan area was selected as an observation site. Real-time monitoring of the concentrations of seven air pollutants (CO, NO, NO_2, NO_x, SO_2, BC, and $PM_{2.5}$) and traffic flow was conducted using online monitoring instruments and surveillance cameras. Vehicle type and speed were obtained by applying the YOLOv8l deep learning object detection model in combination with the SORT tracking algorithm. Based on the emission intensity ratio method, the average emission factors for the entire fleet and for different vehicle categories were estimated to be (1 064.9±

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479.8), (496.5±209.3), (55.5±30.4), (578.6±267.6), (6.3±2.2), (3.3±1.5), and (37.7±19.2) mg/(km·veh) for CO, NO, NO_2, NO_x, SO_2, BC, and $PM_{2.5}$, respectively. The overall fleet emission factors were (634.7±477.2), (266.0±142.9), (26.4±13.5), (302.3±159.5), (3.5±1.9), (2.0±1.1), and (19.8±12.3) g/km for these pollutants, respectively. During the observation period, the average daily traffic volume on weekends was 88.6% of that on weekdays. Except for $PM_{2.5}$, weekday emission factors for all pollutants were 1.0－1.48 times higher than those on weekends. Hourly analysis showed that the proportion of diesel vehicles during the early morning was 1.6 times that of other periods, with pollutant emission peaks 2.0－3.5 times the daily average. Fleet emissions exhibited a bimodal diurnal pattern, peaking during morning (07:00－09:00) and evening (17:00－19:00) rush hours at 1.8－3.3 times the daily average. The findings provide essential data and scientific support for constructing high-resolution dynamic motor vehicle emission inventories and implementing refined control strategies for vehicular pollutant emissions.
Key words: tunnel test; air pollution; dynamic emission factor; image recognition; individual vehicle and vehicle fleet.

0　引言

机动车排放是影响城市空气质量的一类重要污染源(Llaguno-Munitxa and Bou-Zeid, 2023).源解析研究表明,交通源对我国北京、上海、广州、武汉、西安、兰州、郑州和成都等重点城市大气细颗粒物($PM_{2.5}$)的贡献率在8.8%～37.4%(Zíková *et al.*, 2016; Gong *et al.*, 2017; Li *et al.*, 2017, 2020; Tan *et al.*, 2017; 邵龙义等, 2018; Wang *et al.*, 2020),对京津冀、长三角、四川盆地和珠三角等区域的大气 $PM_{2.5}$ 贡献率为4.2%～48.7%(Huang *et al.*, 2017b, 2018; Feng *et al.*, 2021; Hong *et al.*, 2021).机动车排放也是氮氧化物(NO_x)(Lu *et al.*, 2016; Zong *et al.*, 2020)、一氧化碳(CO)(Lang *et al.*, 2012; Liu *et al.*, 2017)、二氧化硫(SO_2)(Che *et al.*, 2011)和黑碳(BC)(Uherek *et al.*, 2010; Klimont *et al.*, 2017)的重要贡献源.Wu *et al.*(2024)指出,2017年交通运输源排放对于我国 $PM_{2.5}$、CO、NO_x、SO_2 和BC的贡献率,分别为5.9%、16.0%、31.6%、2.8%和20.5%.因而,对于机动车排放大气污染物的管控,是我国空气质量持续改善的关键.

排放清单作为空气质量模型的关键输入数据(Jing *et al.*, 2016; Farren *et al.*, 2020; Davison *et al.*, 2021),在空气质量预报预测和大气污染的科学管控中起到了重要作用.前人针对机动车排放清单开展了大量研究,清单的时间分辨率逐步从年(McDonald *et al.*, 2012; Yu *et al.*, 2021; Yan *et al.*, 2024)提升到月(Jiang *et al.*, 2020),再到日(Crippa *et al.*, 2020; Huo *et al.*, 2022).近年来,随着交通流量、遥感数据的累积和大数据分析技术方法的应用,小时尺度的机动车排放清单研究开始被报道.Deng *et al.*(2020)根据道路实测数据修正了《道路机动车排放清单编制技术指南(试行)》(下称《指南》)的参考排放因子,结合货车的北斗卫星轨迹数据,构建了TrackATruck货车排放模型和京津冀地区的高分辨率货车排放清单;但该研究与柏洋洋等(2023)、Wang *et al.*(2023a)的研究都只关注了货车这一车型排放情况,而未涉及其他车型,无法全面反映道路交通的排放情况.此外,排放因子的准确性和代表性也制约了高时空分辨率机动车排放清单的研究发展.Liu *et al.*(2018)、Zhu *et al.*(2023)利用COPERT模型估计了机动车排放因子,构建了佛山市和京津冀地区高时空分辨率的机动车排放清单,清单的不确定性区间为6.0%～18.6%和－39.0%～58.1%.除模型估算外,潘玉瑾等(2020)、Feng *et al.*(2023)、孙世达等(2023)和Wang *et al.*(2025)在修正《指南》的标准排放因子后进行了清单计算,并指出基于《指南》的排放因子估算已成为清单构建的最大不确定性来源.Shah and Zeeshan(2016)采用IVE模型编制清单时指出,车队数据和位置数据是模型的重要输入文件,而这些数据的获取渠道较少.因此,模型估算除了会引入较大不确定性外,难以获取输入数据也是将其应用至构建区域排放清单所面临的挑战(郝艳召等, 2017).

前人通过实测实验和模型估算获取机动车大气污染物排放因子.实测实验主要包括台架实验(Nakashima and Kondo, 2022; Li *et al.*, 2025)、遥感检测(Smit *et al.*, 2022; Ghaffarpasand *et al.*, 2023)、车载实验(Luján *et al.*, 2018; 谢岩等, 2020; 黄志雄等, 2025)和隧道实验(Blanco-Alegre *et al.*, 2020; Huang *et al.*, 2022a; Yao *et al.*, 2023).台架试验所采用的底盘测功机是通过控制车轮负载在实验室环境中精确测量单车尾气排放和能耗特性,实现对车辆排放性能和能效标准符合程度的评估(Nakashima and Kondo *et al.*, 2022).台架

试验可以作为评估实际排放情况的重要补充,但是不能完全反映真实情景下的道路排放(Wu *et al.*, 2012; Anenberg *et al.*, 2017).车载实验是一种将气体分析仪器等设备集成到车载平台,在实际驾驶过程中动态反映真实排放情况的测试方法(Khan *et al.*, 2020),但其购置、校准、维护及试验人力成本较高(Yang *et al.*, 2018).遥感检测方法能在短时间内获取较大的样本量(Carslaw and Rhys-Tyler, 2013),进而对高排放车辆进行识别(Yang *et al.*, 2022; Ghaffarpasand *et al.*, 2023),但其仅能在车辆经过测量点时捕获排放瞬间,存在较大的不稳定性(Zavala *et al.*, 2017; Huang *et al.*, 2020),需要大量的样本测验才能得出稳定的排放值(Huang *et al.*, 2022b).隧道实验最早由 Pierson and Brachaczek (1983)提出,是基于质量平衡原理,在相对独立的隧道环境内对真实道路情况下的大量车辆样本进行污染物浓度的数据采集. Song *et al.*(2018b)在天津五经路隧道开展观测实验,得到$PM_{2.5}$、NO、NO_2、NO_x和CO的实测排放因子及其昼夜变化,并指出仅通过《指南》计算会低估重型柴油车对总排放的贡献,达39.1%~54.2%.隧道实验可以对真实道路情况下的大量车辆样本进行连续的污染物在线数据采集,在较低成本下能够实现对机动车排放变化稳定而充分的捕捉,进而获取机动车的动态排放因子.

机动车排放因子模型,如MOVES(motor vehicle emission simulator, https://www.epa.gov/moves)、COPERT(computer programme to calculate emissions from road transport, https://www.emisia.com/utilities/copert/)、EMFAC(emission factors model for California, https://arb.ca.gov/emfac/)、IVE(international vehicle emissions, https://www.issrc.org/ive/),可通过输入机动车参数和运行工况信息对排放因子进行估算. Liu and Frey (2015)采用MOVES模型对CO_2、NO_x、CO和HC的排放因子进行估算,与车载尾气检测设备(portable emission measurement system, PEMS)的实测数据进行对比发现,除CO_2的实测与模型排放因子没有偏差(斜率k=0.91)外,MOVES的估值均为实测值的3~4倍.香港环保署曾将EMFAC模型修正为EMFAC-HK来估算当地污染状况, Wang *et al.* (2021b)采用EMFAC-HK对香港Shing Mun隧道的CO_2、CO、非甲烷总烃(NMHCs)、NO、NO_2、NO_x和$PM_{2.5}$在2003和2015年的排放因子进行估算,研究与实测结果相比较,2015年模型计算值与测量值之间的一致性(偏差<50%)优于2003年的0.6~2.3倍. Zhu *et al.*(2023)的研究表明,COPERT模型所需要的车辆行驶公里数(VKT)极少有官方数据,故该研究所采用的VKT数据来源于文献调研,并加以线性插值补充缺失数据;吴雨涟等(2024)、宋晓伟等(2020)在基于COPERT模型构建机动车大气污染物排放清单时,由于缺乏年均行驶里程的相关统计数据,故参考现有研究和《指南》数据进行估计,清单的不确定性区间分别为−55%~69%和−44%~80%;瞿美丽等(2024)基于IVE模型编制重型柴油车(HDV)的排放清单时,缺乏HDV的注册和报废日期的统计数据,选择基于HDV的注册量和保有量数据构建生存曲线,进而确定模型所需的技术分布数据.因此,模型估算因难以完备获取本地化数据,而使清单编制存在较大不确定性.

综上,现有研究在高时空分辨率清单构建和实测方法方面虽有进展,但仍受车型覆盖有限、排放因子不确定性高、模型偏差及数据获取难等问题的制约.基于此,本研究选择一条市区内隧道,通过对$PM_{2.5}$、CO、NO、NO_2、NO_x、SO_2和BC这7类大气污染物浓度与交通流量的实时监测,结合视觉识别算法、目标追踪算法和排放强度比值方法,获取不同工作时段、不同类型车辆的单车和车队整体的大气污染物动态排放因子,以期为高时间分辨率排放源清单构建提供基础数据支撑.

1 观测实验与数据处理方法

1.1 隧道与实验介绍

本研究选择的隧道位于湖北省宜昌市西陵区中心城区,呈东西走向,连接夷陵区和西陵区.隧道全长1 500 m,为单向通行的双车道,限速60 km/h,规定大型货车只能在夜间22:00至次日06:00通行,隧道出口外约20 m处设有交通信号灯.隧道截面为半圆形,宽10.5 m、高6.35 m(图1),两侧各留有1.5 m宽的人行道.在隧道内距离出入口20 m处的南侧人行道上分别设置监测点,监测时间为2020年11月28日至12月5日,共计8天,包括5个工作日、2个周六和1个周日.采样周期为23.5 h,涵盖了交通的高峰与平峰期.

1.2 监测仪器与数据采集

采用黑碳监测仪(AE-33,美国Magee Scientific)对黑碳浓度进行观测(Drinovec *et al.*, 2015).采

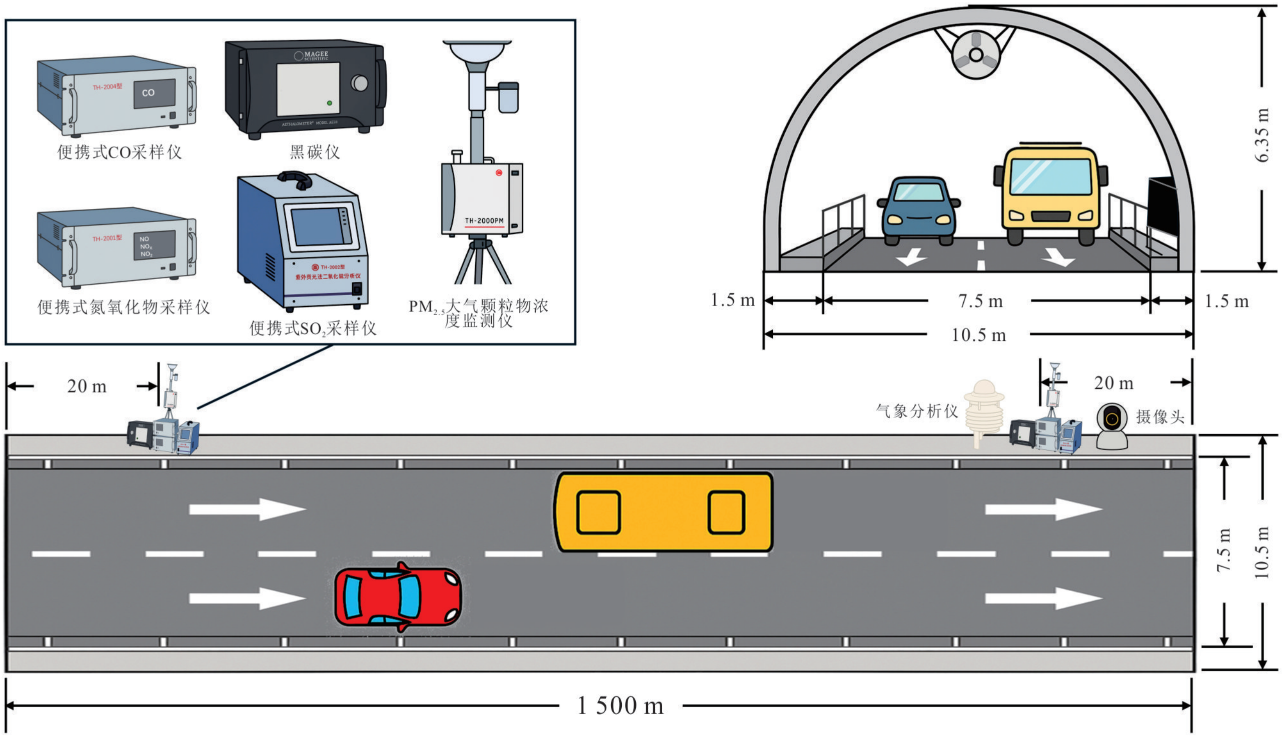

图 1　隧道实验采样示意

Fig.1　Layout of sampling configuration and detail of the tunnel

用以连续β射线法和DHS动态加热法(岳玎利等, 2014)为原理的$PM_{2.5}$大气颗粒物分析仪(TH-2000PM,武汉天虹)观测$PM_{2.5}$浓度.对于气态污染物的检测,采用化学发光法(李泫等, 2023)氮氧化物分析仪(TH-2001H,武汉天虹)、紫外荧光法(刘辉翔等, 2024)二氧化硫分析仪(TH-2002H,武汉天虹)、红外吸收法一氧化碳分析仪(TH-2004H,武汉天虹)在隧道内每5 min采集一个浓度数据,对隧道内污染物进行连续在线监测.

利用时间分辨率为1 min的气象分析仪(WS600,德国Lufft)对隧道内的气象数据进行检测.本实验在隧道出口处采样点设置监控摄像头(MJSXJ02CM,上海创米科技有限公司)对隧道内机动车同时进行录制,为后续车辆识别和分析提供车流量的视频素材.

1.3　隧道内机动车类型识别与移动速度计算

为获取隧道内机动车的类型分布与速度特征,本研究采用YOLOv8l(You Only Look Once v8l)深度学习目标检测模型,结合SORT目标跟踪算法,对隧道监控视频进行分析(图2).将隧道试验期间录制的视频合并剪辑后输入训练优化的YOLOv8l模型,算法对车辆边界框(x, y, w, h)进行划定,并依靠算法内置的图像识别区分车辆类型,实现车辆类型识别与初步定位.本研究所用YOLOv8l模型是在Ultralytics官方发布的COCO预训练权重的基础上进行训练和微调后,对机动车目标进行检测.为避免远距离小目标引起的误检与误跟踪,检测框的最小尺寸被设置为50像素×50像素,且每隔5帧(约0.17 s)进行一次目标检测以降低计算成本.

划定实际尺寸为7.50 m×2.35 m矩形区域作为与像素距离参照的锚点,将视频中的车辆像素位移转化为实际位移;利用SORT算法完成车辆连续帧间的稳定跟踪,计算车辆的瞬时速度,并按5 min间隔输出车辆平均速度及分类计数结果.考虑到目标跟踪的实时性与稳定性,SORT算法参数设置:最大丢失帧数(max_age)为30帧,即若目标连续30帧未检测到则视为消失;最小有效命中帧数(min_hits)为3帧,仅当目标连续被检测至少3次才被确认;匹配IOU阈值(iou_threshold)为0.3,即检测框与跟踪框之间的交并比需大于0.3才视为同一目标.在车流高峰时段,由于隧道内车辆密集,出现大量车辆重叠,算法识别车辆可能存在误差或出现遗漏.在算法识别后再对高峰时段(7:00~9:00、17:00~19:00)的车辆数量和对应车型进行人工计数,对算法进行校验和补充,以保证车辆计数和分类的准确性.

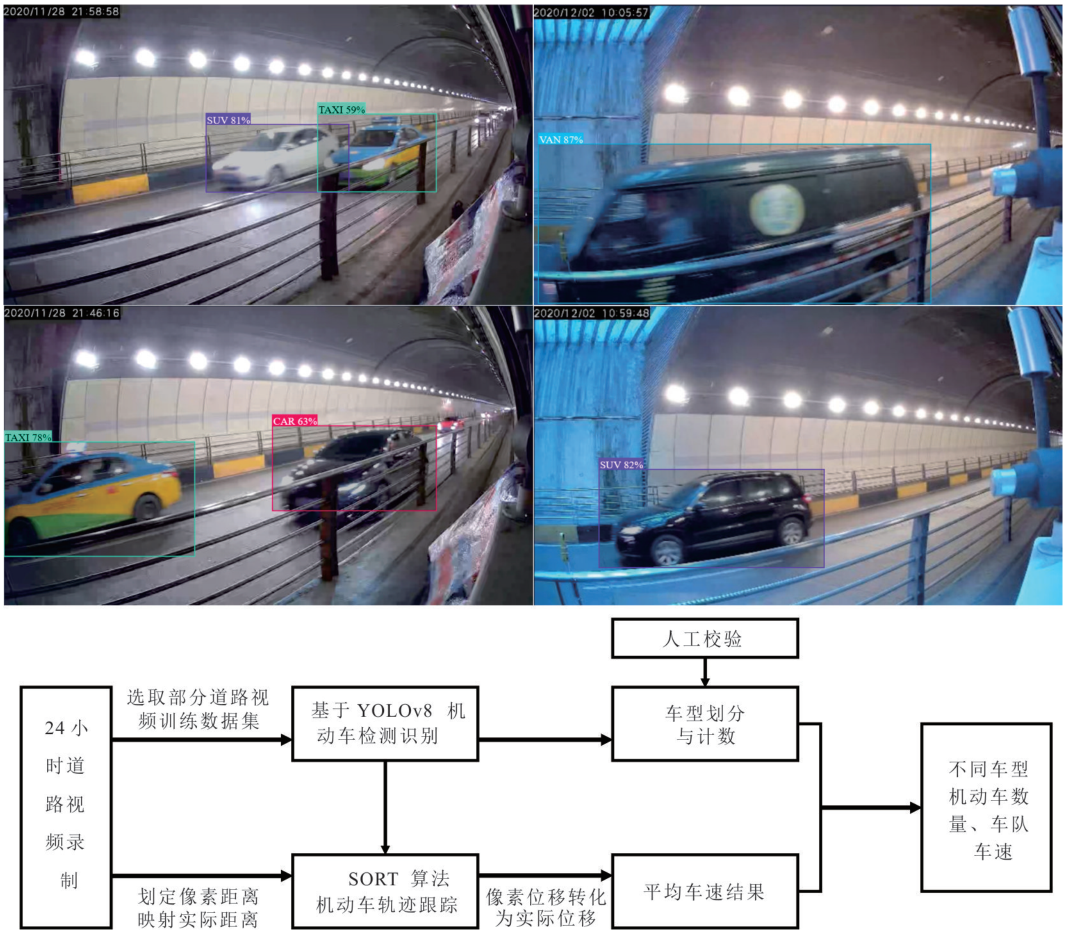

图 2 车辆识别界面和流程

Fig.2 Interface and flowchart for vehicle detection and classification

1.4 排放因子计算

1.4.1 车队整体和单一车辆的平均排放因子 在单位时间内隧道出口和入口的污染物质量浓度差（$C_{out}-C_{in}$）即为车队穿过隧道排放出的污染物质量浓度，将其乘以通风量后得到车队排放的污染物总质量；除以采样点间距 L（km）即可以得到机动车的车队平均排放因子（公式（1）），再除以通过的车辆数 N（辆），便可以得到单车的排放因子（公式（2））（Pierson *et al.*, 1996）.

$$EF_{fleet}=\frac{C_{out}-C_{in}}{L}\cdot A\cdot T\cdot v\ , \tag{1}$$

$$EF_{individual}=\frac{C_{out}-C_{in}}{NL}\cdot A\cdot T\cdot v\ , \tag{2}$$

其中，EF_{fleet} 为机动车车队整体排放因子，单位为 g/km；$EF_{individual}$ 为机动车单车平均排放因子，单位为 mg/(km·辆)；A 为隧道横截面积，单位为 m^2；T 为采样时长，单位为 s；v 为风速，单位为 m/s.

1.4.2 分车型排放因子 本研究采用排放强度比值方法，对公式(1)或公式(2)求得的机动车排放因子进行分车型的划分. 由于图像识别无法区分出燃油类型信息，因此参考 Grieshop *et al.*(2006)、Deng *et al.*(2015)的研究，将车辆类型划分为柴油车(diesel vehicle, DV)、汽油车(gasoline vehicle, GV)和电动汽车，并假设货车、公交巴士为 DV，小轿车、SUV、面包车和出租车为 GV，电动汽车则视为无尾气排放. 如表 1 所示，以 COPERT 模型(Gkatzoflias *et al.*, 2007)和 MOVES 模型(Koupal *et al.*, 2003)的基准排放因子数据库提供的相应车型的 CO、NO_x、PM 和 SO_2 排放因子及 $BC/PM_{2.5}$ 比值(DV：$BC/PM_{2.5}$=0.75；GV：$BC/PM_{2.5}$=0.20)作为参考.

基于以上数据，通过以下公式对 DV 和 GV 的各类大气污染物排放因子进行推算.

$$EF_{GV}=\frac{EF}{\frac{N_{DV}\cdot R+N_{GV}}{N_{DV}+N_{GV}}}\ , \tag{3}$$

$$EF_{DV}=R\cdot EF_{GV}\ , \tag{4}$$

其中，柴油车和汽油车的排放因子分别为 EF_{DV} 与 EF_{GV}，单位为 mg/(km·辆)(单车)或 g/km(车队)；

表 1　污染物排放因子比值参考

Table 1　Reference for pollutant emission factors

车型	CO [a]	NO [a]	NO_2 [a]	NO_x [a]	SO_2 [a]	BC [b]	$PM_{2.5}$ [a]
GV	0.85	0.05	0.05	0.05	0.02	0.006	0.001 5
DV	0.45	0.3	0.3	0.3	0.03	0.022 5	0.03
R	0.53	6	6	6	1.5	3.75	20

注:其中,a. COPERT 模型据 Gkatzoflias *et al.* (2007);b. MOVES 模型据 Koupal *et al.* (2003).

柴油车和汽油车的通行量分别为 N_{DV} 与 N_{GV},单位为辆;排放因子比值为 R.

1.5　异常数据处理

在进行数据处理前,对于原始数据中的异常高值或低值进行剔除.本研究设置的采样点较接近隧道的入口和出口,可能会受到隧道外环境因素的影响,导致夜晚车流量较少或无车通过时出现污染物浓度出口小于入口的现象.因此针对出现此类现象时间段的排放因子数据整组移除,避免其他因素对机动车排放计算产生干扰.

本研究共获取 2 128 组 CO、NO、NO_2、NO_x、SO_2、$PM_{2.5}$ 和 BC 有效采样数据,排除仪器异常、电力不足等问题造成的数据异常 5 组(0.2%),排除无机动车通过时段的数据 13 组(0.6%),排除出口小于入口的数据 258 组(12.1%).异常数据剔除后,有效数据 1 852 组,占原始数据的 87.0%.

2　结果与讨论

2.1　隧道内分车型机动车流量实时变化

观测期间交通特征变化情况如图 3a、图 3b 所示,日平均车流量为(16 664±2 878)辆,小时平均车流量为(694±448)辆.在整个观测期间 GV 占总车流量的比例最高,占比约为 94.9%,DV 和电动汽车的占比分别为 4.0% 和 1.0%.

工作日的平均车流量为(17 405±3 107)辆,早高峰(7:00～9:00)与晚高峰(17:00～19:00)的车流量共占全天车流量的(43.0±2.1)%;周末的平均车流量为(15 429±591)辆,早、晚高峰车流量占全天的(37.9±0.8)%.隧道内的车速日变化情况则与车流量相反,呈现夜高日低、周末日间波动较大的变化趋势.隧道内的平均车速为(41.04±8.80) km/h,在凌晨 3:00 出现高值(59.88±2.54) km/h,在 17:00 出现最低值(31.35±4.13) km/h.车速和车流量的变化趋势与宋爱楠等(2023)、张启钧等(2023)在天津五经路隧道观测到的机动车车流量变化相似.对车流量和车速进行相关性分析,工作日(图 3d)回归结果显示车速与车流量呈现负相关,皮尔逊相关系数为−0.42,拟合优度 R^2=0.18,周末(图 3c)回归结果同样呈现负相关,皮尔逊相关系数为−0.35,R^2=0.12.整体的变化趋势表明车流量和车速呈现出负相关关系,而较低的 R^2 表明车流量对车速的解释性不足,仅用车流量这一个因素来解释车速的变化是远远不够的.

2.2　单一车型和车队整体排放因子对比

2.2.1　机动车单车平均排放因子　CO、NO、NO_2、NO_x、SO_2、BC 和 $PM_{2.5}$ 的单车排放因子(图 4)分别为(1 064.9±479.8)、(496.5±209.3)、(55.5±30.4)、(578.6±267.6)、(6.3±2.2)、(3.3±1.5)和(37.7±19.2) mg/(km·辆).对比其他隧道实验的结果,CO 的排放因子低于 2014 年 Smit *et al.*(2017)在澳大利亚 Clem Jones-CLEM7 隧道(1.4±0.08) g/(km·辆)和 2017 年 Luo *et al.*(2020)在陕西秦岭 3 号隧道(3.9±1.7) g/(km·辆)观测的实验结果.对于 BC 的排放因子,本研究与天津五经路隧道的测定结果相比,低于 Ho *et al.* (2023)、Zhang *et al.*(2021)、Raparthi *et al.*(2021)的隧道观测结果(分别为 5.40、4.9 和 11.6 mg/(km·辆)),但略高于张启钧等(2023)测得的(2.62±0.60) mg/(km·辆)和 Liu *et al.*(2023)测得的(1.09±0.49) mg/(km·辆).对于细颗粒物,本研究所得到的 $PM_{2.5}$ 排放因子与 Huang *et al.*(2017a)在上海延安东路的观测结果(34±23.5) mg/(km·辆)相近,且远低于前人在珠江隧道得到的结果(Dai *et al.*, 2015, 92.4 mg/(km·辆); Zhang *et al.*, 2015, 82.7 mg/(km·辆)),但高于 2014 年 Clem Jones-CLEM7 的观测结果(15±2) mg/(km·辆)和前人在天津五经路隧道 2017 年和 2019 年开展的隧道观测结果(9.3±1.2)和(8.4±4.3) mg/(km·辆)(宋爱楠等, 2023).

表 2 总结了已发表的隧道实验中相应污染物的单车排放因子,2017 年秦岭 3 号隧道(Luo *et al.*, 2020)由于其为重型车占比较大(69%～82%)的高

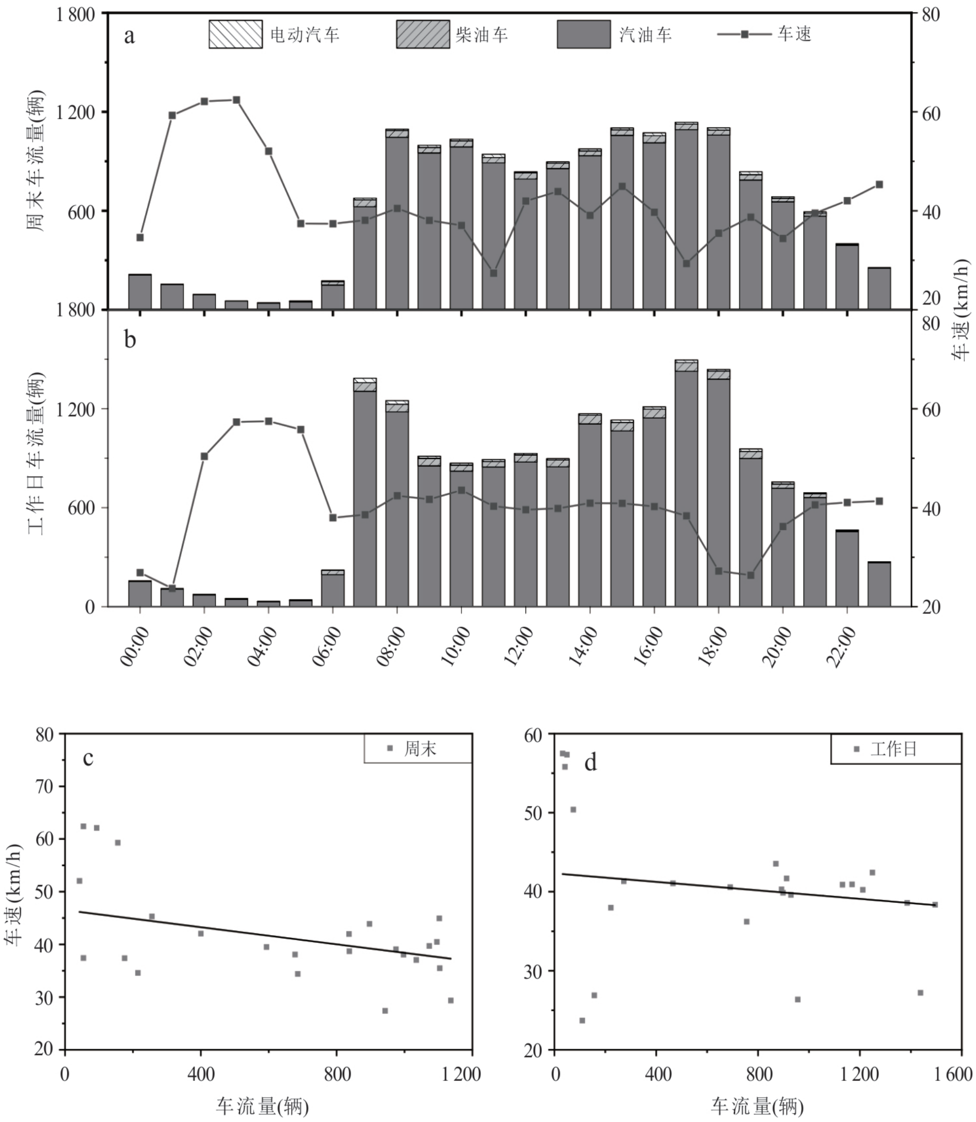

图3 观测期间隧道内车流量和车速日变化特征

Fig.3 Diurnal variation of traffic volume and vehicle speed inside the tunnel during the observation period

a、b.周末和工作日车速与车流量变化；c、d.周末和工作日车速与车流量相关性

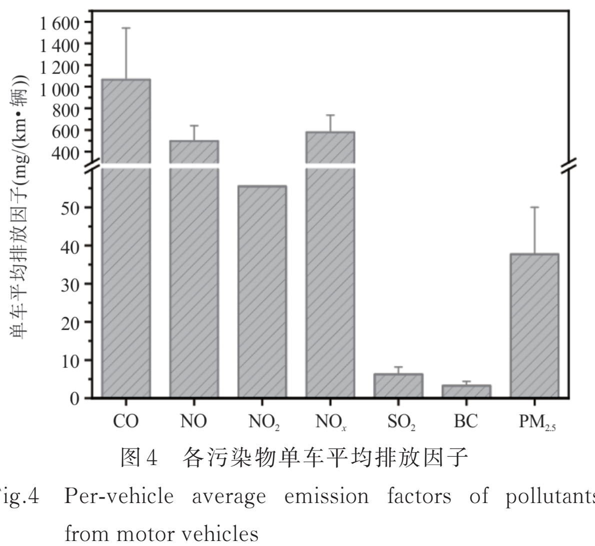

图4 各污染物单车平均排放因子

Fig.4 Per-vehicle average emission factors of pollutants from motor vehicles

速公路隧道，致使排放因子高出同时期的隧道实验单车排放因子（Song *et al.*，2018b）的均值13.8～111.5倍，表明车队车型构成会对隧道实验的排放因子产生显著影响.与其他地区的隧道实验相比，2019年印度执行的机动车标准为Bharat Stage IV（对标我国国IV标准），而我国此时执行更为严格的国V标准，这也使得2019年印度孟买Eastern Freeway隧道机动车的污染排放因子较本研究高出了13.6%～71.7%（Raparthi *et al.*，2021）.前人在天津五经路隧道于2017年和2019年均开展了隧道观测实验（Song *et al.*，2018b；宋爱楠等，2023），相较同时期的在上海（Huang *et al.*，2017a）和宜昌（本研究）的研究结果，其排放因子呈现较低水平，这可能

表 2　不同地区隧道实验得到的机动车大气污染物单车排放因子对比

Table 2　Comparison of emission factors from different tunnel studies

地点	年份	CO	NO	NO_2	NO_x	SO_2	BC	$PM_{2.5}$	参考文献
甘肃	1995	41.86	-	-	3.88	-	-	-	邓顺熙和董小林,2000
西安	1996	33.28	-	-	4.60	-	-	-	邓顺熙等, 2000a
成都	1996	28.73	-	-	4.65	-	-	-	邓顺熙等, 2000b
广州	1999	15.40	-	-	1.38	0.14	-	-	王伯光, 2001
香港	2004	1.84	-	-	0.88	-	-	0.13	Cheng *et al.*, 2006
台湾	2005	1.89	-	-	0.73	0.02	-	-	Chiang *et al.*, 2007
天津	2010	0.28	0.062	0.020	0.084	-	-	0.009 2	Song *et al.*, 2018b
Braga(Portugal)	2013	4.09	0.61	0.29	1.18	-	0.005	0.133	Alves *et al.*, 2015
广州	2014	3.10	-	-	1.29	0.020 7	-	0.082 7	Zhang *et al.*, 2015
香港	2015	1.80	1.33	0.24	1.58	-	-	0.025	Wang *et al.*, 2021b
上海	2016	1.84	-	-	0.4	-	-	0.034	Huang *et al.*, 2017a
天津	2017	0.28	0.062	0.020	0.084	-	-	0.009 2	Song *et al.*, 2018b
西安-汉中	2017	3.88	4.31	1.56	9.37	0.09	-	-	Luo *et al.*, 2020
郑州	2019	1.49	0.051	0.006 7	0.086	0.00	-	-	王雯楠等, 2024
天津	2019	0.41	-	-	0.080	-	-	0.009 3	宋爱楠等, 2023
Mumbai(India)	2019	1.60	-	0.147	-	-	0.012	0.044	Raparthi *et al.*, 2021
宜昌	2020	1.06	0.48	0.053	0.55	0.006 3	0.003 4	0.038	本研究

注:“-”表示无数据; 单位:g/(km·辆).

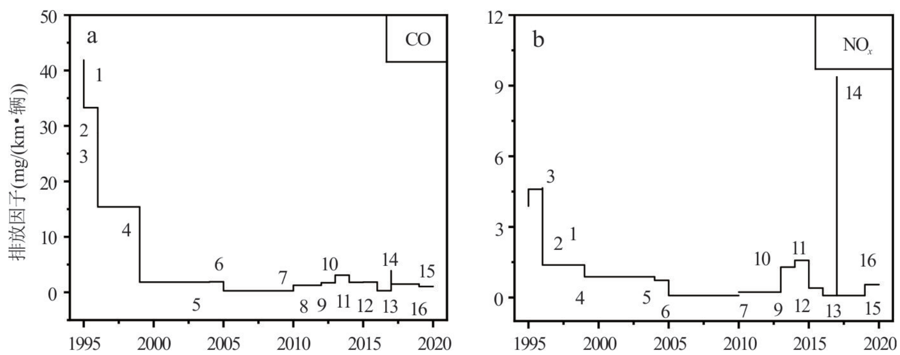

图 5　我国近 30 年隧道实验排放因子变化趋势

Fig.5　Trends in tunnel-based vehicle emission factors in China over the past 30 years

1 据邓顺熙和董小林(2000); 2 据邓顺熙等(2000a); 3 据邓顺熙等(2000b); 4 据王伯光(2001); 5 据 Cheng *et al.*(2006); 6 据 Chiang *et al.*(2007); 7 据 Song *et al.*(2018b); 8 据 Zhang *et al.*(2015); 9 据 Deng *et al.*(2015); 10 据 Zhang *et al.*(2020); 11 据 Wang *et al.*(2021b); 12 据 Huang *et al.*(2017a); 13 据 Song *et al.*(2018a); 14 据 Luo *et al.*(2020); 15 据宋爱楠等(2023); 16 据本研究

是由于五经路隧道为 2.3°的下坡,发动机输出功率较低造成排放降低(Boroujeni and Frey, 2014).相较于 20 世纪 90 年代的隧道实验观测结果(邓顺熙和董小林, 2000; 邓顺熙等, 2000a, 2000b; 王伯光等, 2001),本研究 CO 和 NO_x 排放因子下降幅度最高分别可达 97.5% 和 88.2%.

图 5 总结了 1995—2021 年我国开展隧道实验获得的机动车 CO 与 NO_x 单车排放因子变化趋势.在我国排放标准升级、油品净化与尾气后处理技术迭代的协同驱动下(Wu *et al.*, 2011),除个别年份的研究结果(如 2017 年的秦岭 3 号隧道)受车流量、构成影响外,排放因子呈现显著下降趋势.1996—2005 年,国Ⅰ、国Ⅱ标准的实施改善了燃烧效率,CO 和 NO_x 排放降幅分别达 93% 和 84%,受限于高硫燃油(>500 mg/kg)对三元催化转化器(three-way catalytic converter,TWC)催化剂的毒化作用,减排进入平台期(CO 约为 1.8 g/(km·辆); NO_x 约为 0.8 g/(km·辆)).2006—2012 年国Ⅲ标准实施,要求 DV 加装氧化催化器和废气再循环系统,并同步推行汽油脱硫(硫含量降至 150 mg/kg),实现 TWC 对 CO 的高效

转化，CO和NOx排放因子进一步降低85%和88%. 2013—2017年国Ⅳ、国Ⅴ标准强制DV加装选择性催化还原系统（selective catalytic reduction，SCR），推动NO_x从2013年0.227 g/(km·辆)(Deng *et al.*，2015)降至2017年0.084 g/(km·辆)(Song *et al.*，2018b)；2019年国VIa逐步实施，伴随新能源汽车的推广，本研究得出CO和NO_x的排放因子进一步降至1.06和0.55 g/(km·辆). 燃油硫含量作为关键控制指标，从国Ⅰ/Ⅱ阶段的限值2 000 mg/kg，逐步降至国Ⅳ/Ⅴ(约2014年)的50乃至10 mg/kg，并在国Ⅵ阶段(约2020年)稳定维持在10 mg/kg以下. 燃油硫含量管控政策的加严也反映在了机动车SO_2排放因子不断下降这一趋势中：1999年广州隧道实验测得的排放因子高达0.14 g/(km·辆)；随着国Ⅳ/Ⅴ标准油品的普及，2014年降至0.020 7 g/(km·辆)，降幅超过85%；至2020年国Ⅵ标准全面实施后，本研究获取的排放因子进一步降至0.006 3 g/(km·辆)，相比1999年下降了95.5%，体现了燃油提标对机动车SO_2排放的显著削减.

2.2.2 机动车车队整体排放因子 CO、NO、NO_2、NO_x、SO_2、BC和$PM_{2.5}$的机动车车队整体排放因子分别为(634.7±477.2)、(266.0±142.9)、(26.4±13.5)、(302.3±159.5)、(3.5±1.9)、(2.0±1.1)和(19.8±12.3) g/km(图6). 本研究观测期间，车队中GV占比远高于DV，且当前已全面实施的国Ⅴ标准和不断提高的车辆技术显著降低了气态污染物的排放(Wen *et al.*，2023).

2.3 工作日和周末机动车排放因子对比

在实验观测期内，周末的日车流量较工作日降低了11.4%，对于这两种不同情景，各污染物单车排放因子和车队整体排放因子的变化趋势基本呈现工作日高于周末的特点(表3). 这在CO的排放情况上较为明显，其单车排放因子是周末的1.48倍，NO、NO_2、NO_x与BC同样呈现出工作日略高于周末的情况，工作日的单车排放因子是周末的1.0～1.2倍，$PM_{2.5}$的排放因子则呈现周末为工作日的1.11倍. 由于城市中的$PM_{2.5}$来源较为广泛(如工业、二次无机盐、区域传输和机动车排放等)，对比采样期的宜昌市站点监测数据可发现，采样期内周末的$PM_{2.5}$浓度(88.7 μg/m^3)显著高于工作日(73.3 μg/m^3)，因此周末$PM_{2.5}$排放因子的升高可能归因于实验开展期间周末的城市背景值较高，进而对隧道内的观测产生影响. 这一现象也与Hua *et al.*(2021)于2014—2018年的冬季在北京34个站点观测出的“节假日效应”结果相类似，周日$PM_{2.5}$浓度较周中的平均值高出5%，节假日则高出22%，而NO_2则无显著变化甚至下降. 车队整体的CO、NO、NO_2、NO_x、SO_2、BC和$PM_{2.5}$排放因子均为工作日高于周末，工作日的整体排放因子分别是周末的1.32～2.40倍. Wang *et al.*(2021a)基于CMAQ建模和拥堵数据得出在华北和华南地区交通排放的污染物呈现周末低于工作日的现象，其中$PM_{2.5}$的总减少量可达6.0 μg/m^3.

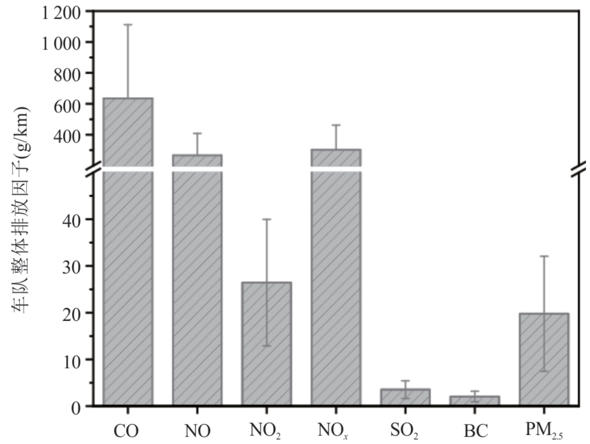

图6 各污染物车队整体排放因子

Fig.6 Fleet-averaged emission factors for various pollutants

表3 工作日和周末的平均排放因子

Table 3 Average emission factors on weekdays and weekends

时间情景	排放因子	单位	CO	NO	NO_2	NO_x	SO_2	BC	$PM_{2.5}$
工作日	单车	mg/(km·辆)	1409.5	508.1	60.5	581.2	6.7	3.3	35.8
	车队	g/km	757.8	252.0	28.6	288.6	3.9	2.0	17.9
周末	单车	mg/(km·辆)	720.2	484.9	50.5	576.0	5.8	3.2	39.6
	车队	g/km	512.9	146.4	13.9	159.9	1.6	1.1	13.6

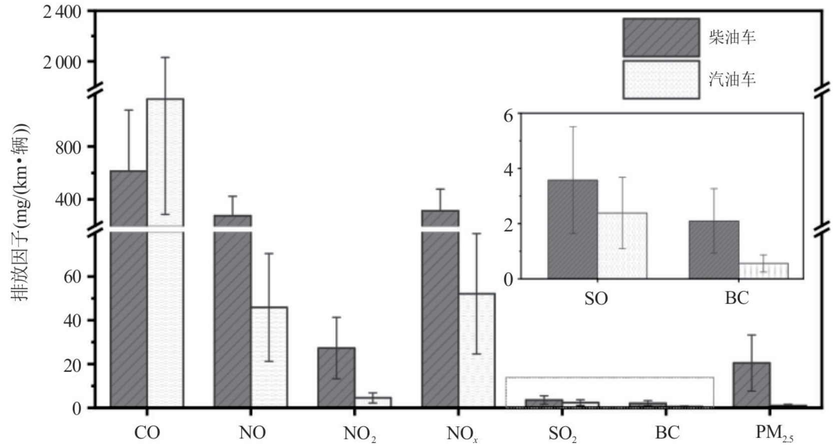

图7　各污染物机动车分车型排放因子

Fig.7　Emission factors of different pollutants by vehicle type

2.4　轻型GV和重型DV排放因子

基于单车排放因子的分析结果，DV与GV（图7）在各污染物排放因子上呈现明显差异．DV的NO和NO_x的排放因子分别达2 703.22和631.29 mg/(km·辆)，而GV则分别为450.54和105.22 mg/(km·辆)．与之相反的是CO的排放因子，GV的CO排放因子是DV的1.9倍，二者平均情境下CO排放因子分别为1 159.05与613.61 mg/(km·辆)，这可能是由于GV在城市道路环境中，特别是交通拥堵的高峰时段，发动机处于怠速工况，汽油的不完全燃烧产物CO的排放增加．对于颗粒物的排放情况，DV和GV的单车平均$PM_{2.5}$排放因子分别为55.74和2.79 mg/(km·辆)，而BC的排放因子DV和GV分别为3.31和0.88 mg/(km·辆)．$PM_{2.5}$和BC的不同车型排放因子对比，也反映出重型车辆对于城市颗粒物污染的影响较为显著．

与国内外的研究进行对比分析，Chan and Ning (2005)在香港的遥感观测结果表明在10～70 km/h车速范围内，GV的CO排放强度是DV的3.4～15.5倍，而DV的NO排放强度则为GV的2.9～9.1倍．张启钧等(2023)基于多元线性回归得出天津五经路隧道实验中轻型车和重型车BC的排放因子分别为(1.51±0.24)和(56.9±15.2) mg/(km·辆)；Tu *et al.*(2025)在一条重型车占比较高(34%～56%)的高速公路隧道开展观测，重型车和轻型车的CO、NO_x和$PM_{2.5}$排放因子分别为2.18和0.79、5.64和0.18以及0.15和0.01 g/(km·辆)，重型车对隧道内CO、NO_x和$PM_{2.5}$的贡献率分别为61.5%、94.8%和89.3%，均远高于本研究结果．Pérez-Martínez *et al.*(2014)的隧道研究得出NO_x和PM_{10}的排放因子和HDV占比存在显著的线性关系(R^2分别为0.79和0.62)．本研究结果与以往研究结果均反映出相似的结论：较少的高排放车辆类型贡献了较多的PM和NO_x排放．且由于不同发动机类型和运行工况以及汽油和柴油的燃料特性，DV主要贡献PM、NO_x的排放，GV主要贡献CO的排放，燃料特性是各污染物排放的重要影响因素之一．

2.5　单车和车队的排放因子的实时变化

图8给出逐小时的单车排放因子，CO、NO、NO_2、NO_x、SO_2、$PM_{2.5}$和BC的平均单位车辆排放因子变化范围分别为528.5～2 636.7、273.4～1 002.1、13.8～123.2、308.6～1 287.1、3.3～10.9、5.5～77.7和0.77～6.90 mg/(km·辆)．

对比各小时机动车不同污染物的排放因子可以看出，单车不同污染物的排放因子均在凌晨(0：00～6：00)出现高值，CO、NO、NO_2、NO_x、SO_2、$PM_{2.5}$和BC在该时段出现的最高值分别是日间(7：00～23：00)平均值的2.5、3.5、3.4、3.4、2.0、2.5和3.0倍．该现象与隧道内大型货车和卡车仅能于22：00至次日6：00内通行的交通管制政策有关，隧道内0：00～6：00的DV占比是7：00～23：00时段的1.6倍，高排放的DV在车队中占比增高会造成各污染物单车的排放因子增高(Yang *et al.*, 2019)．这一现象也与2017年Song *et al.* (2018a)在天津五经路隧道的观测结果一致，凌晨(00：00～05：00)时段NO、NO_2、NO_x和CO的平均排放因子分别是日间时段(06：00～23：00)的2.8、1.8、2.1和2.5倍，而凌晨时段的重型车占比是日间时段的1.5倍．同样，Zhang

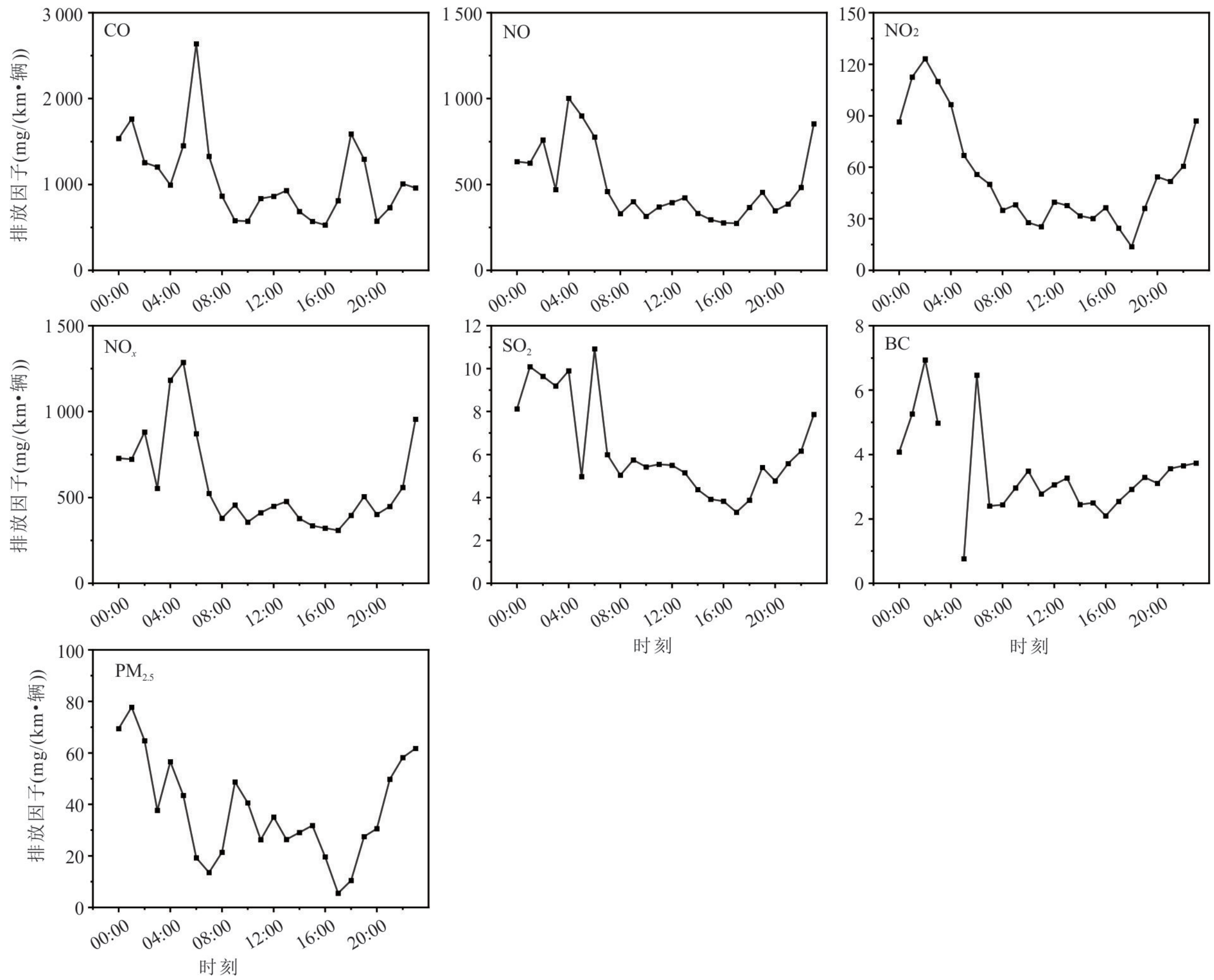

图8 各污染物单车逐时排放因子

Fig.8 Hourly dynamics of per-vehicle emission factors for pollutants

et al.(2015)在广州珠江隧道开展的实验结果也与本研究一致，$PM_{2.5}$、NO、NO_2、NO_x和CO在凌晨时段的排放因子分别是日间时段的4.7、2.8、1.8、2.1和2.5倍；严晗等(2014)于2009年在北京市典型道路观测得到BC在日间和夜间的排放因子分别为(9.3±1.2)和(29.5±11.1) mg/(km·辆)，也与本研究中氮氧化物小时排放因子变化趋势较为吻合.

图9给出了机动车车队整体的逐小时排放因子.对于车队整体而言，CO、NO、NO_2、NO_x、SO_2、$PM_{2.5}$和BC的排放因子变化范围分别为36.1～2 083.7、24.0～513.8、2.9～56.1、28.17～586.60、0.2～6.7、1.9～46.0和0.03～3.80 g/km.各污染物的车队整体排放量在早晚高峰时段(7:00～9:00;17:00～19:00)显著增加，峰值为全天平均值的1.8～3.3倍，这与单车排放因子呈现平缓甚至下降的变化趋势存在明显差异，这可能与高峰期的车辆通行密度增加有关，尽管单位车辆的排放因子未升高甚至略有下降，但大量车辆的累积效应仍增加了总体排放量.针对交通日变化的相关研究中，Jiang *et al*.(2021)在杭州市的观测结果表明，工作日CO、HC、NO_x和$PM_{2.5}$的排放在08:00和18:00分别出现峰值，是平均排放水平的2.2～3.4倍；Wang *et al*.(2014)的研究同样表明昼间06:00～11:00和12:00～17:00的排放量分别占全天排放量的41.0%和33.2%，而00:00～05:00和18:00～23:00的排放量仅分别占4.9%和20.9%.

CO的变化趋势最为显著，在7:00和18:00的排放因子分别达到了1 487.89和2 083.69 g/km，是全天平均排放因子的2.3倍和3.3倍，CO出现峰值归因于高峰时段的拥堵导致车速明显下降(平均车速低于40 km/h)，此时汽油燃烧不完全，在一定程度上增加了高峰时段CO的排放因子(谢岩等，2020).拥堵引起的频繁停车起步工况也会增加其他污染物的排放(Qiao *et al*., 2021)，车队整体的NO、

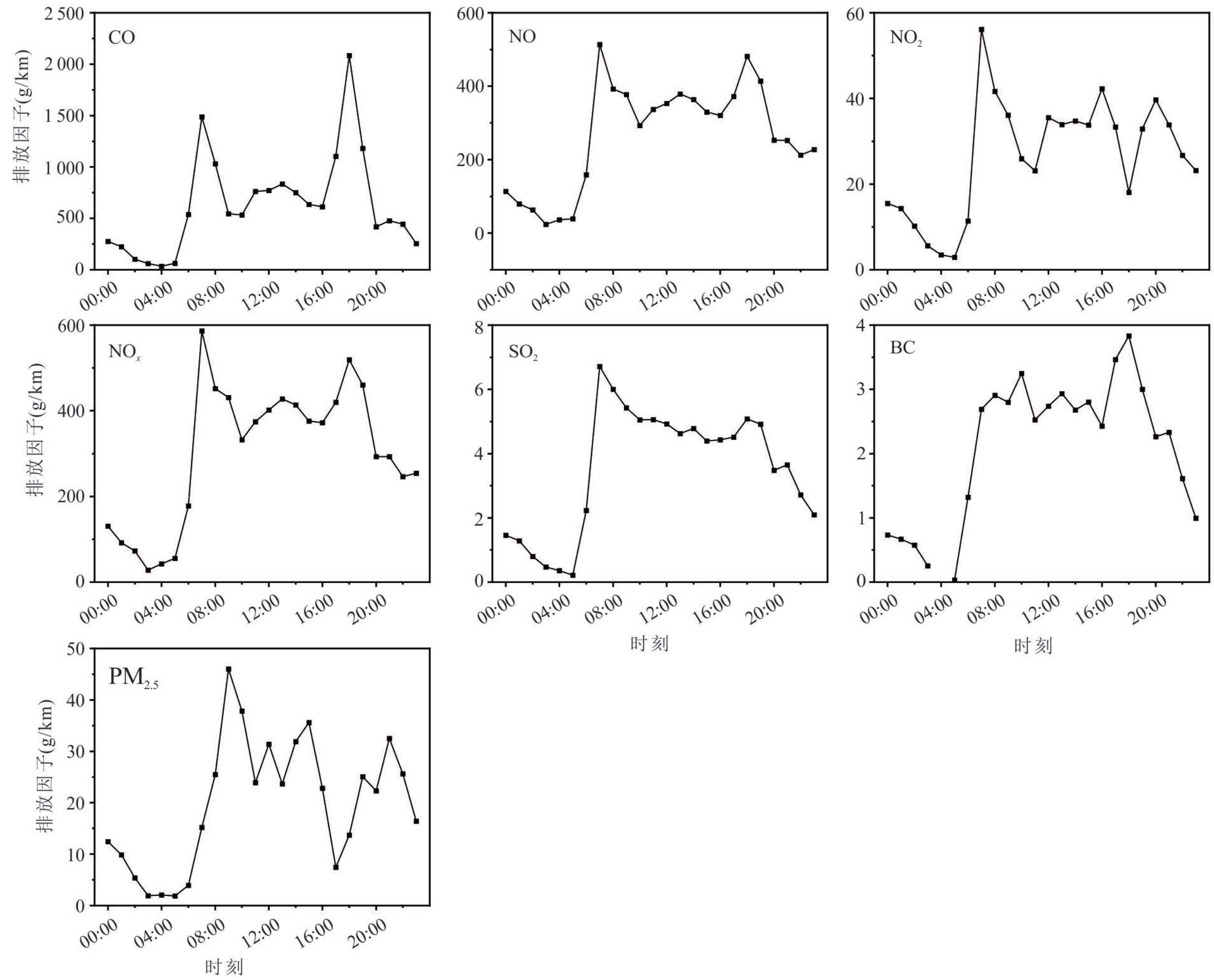

图 9　各污染物车队整体逐时排放因子

Fig.9　Hourly dynamics of fleet-averaged emission factors for pollutants

NO_x、SO_2和BC排放因子在7:00和18:00达到峰值,分别为513.85、586.60、6.71和2.69 g/km与481.4、519.32、5.08和3.83 g/km. Wang *et al.* (2023b)的模拟结果表明交通拥堵严重的情景下$PM_{2.5}$、O_3、NO_2与CO年均排放浓度的增长量可达3.5 μg/m³、1.1×10^{-9}、2.5×10^{-9}和0.1×10^{-6}. NO_2作为二次污染物,与NO和NO_x的变化趋势存在差异,其排放因子峰值出现在7:00和16:00,分别达56.11和42.24 g/km.该现象和Gantt *et al.*(2021)在路边站的观测结果一致,即NO_2增量的峰值(9×10^{-9})出现在当地时间14:00~16:00.此外,本研究的$PM_{2.5}$逐时排放因子在晚高峰时段缺失明显峰值,在昼间变化较为剧烈且无明显峰值,本研究中$PM_{2.5}$采样频率为1 h,时间抽样不足可能会因高频变化而无法捕捉,进而导致高交通流量时段峰值表征存在不足且存在较大波动.

2.6　机动车实时排放因子与车流量关系

由图10可以看出,车流量与不同排放因子的相关性呈现出明显差异.具体而言,车流量与单车排放因子呈负相关关系,相关系数均低于−0.40;而与车队整体排放因子则表现为正相关关系,其中NO、NO_x、SO_2和BC的相关系数均高于0.60.单车排放因子的下降可能与高车流量条件下较为稳定的驾驶工况有关.车流量增加表明车辆运行更为连续、平稳,频繁启停和急加速等工况减少,有助于提高燃油燃烧效率,从而降低单位里程的污染物排放;而车队整体排放因子的升高则源于上文所指出的交通流量增加所带来的累积效应,尽管单车排放有所减少,但单位时间内车辆总数增多,导致整体污染物排放量上升,特别是在封闭或半封闭的隧道环境中,污染物易发生聚集,加剧局地空气污染程度.

当前多数高时空分辨率机动车排放清单在时间分配策略上仍依赖于“EF×VKT”这一假设(Sun *et al.*, 2021; Feng *et al.*, 2023; Wang *et al.*, 2025).该方法虽能从活动水平数据上提升时空解析度,但

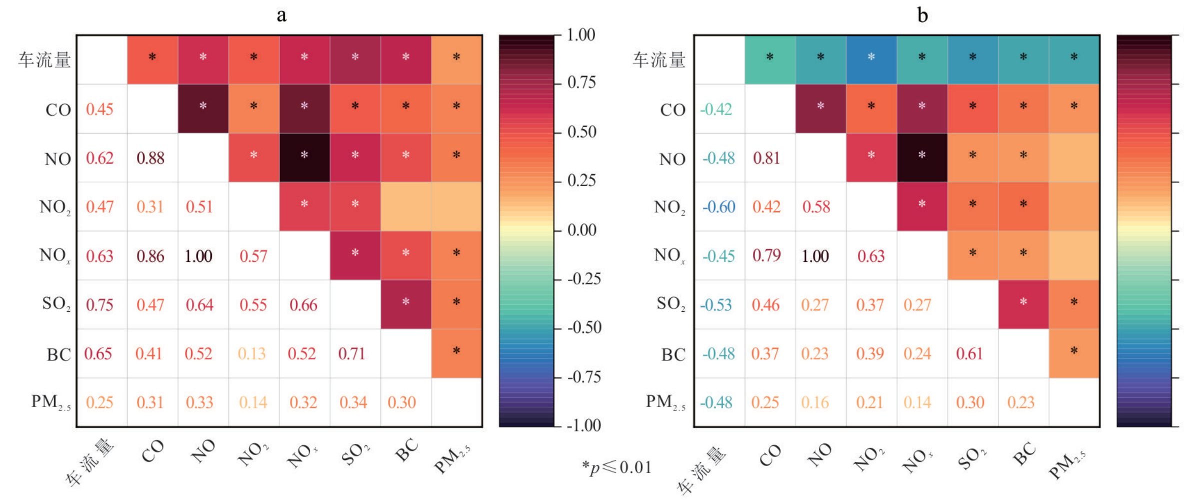

图 10 车流量与排放因子的 Pearson 相关性

Fig.10 Pearson correlation between traffic volume and emission factors

a. 车队整体排放因子；b. 单车平均排放因子

忽略了排放因子在不同时间、车队结构、交通状态下的动态演化，可能导致排放估算出现系统性偏差．不同实测方法（如底盘测功机、隧道实验、PEMS 等）因样本组成、采样位置、驾驶行为与环境条件差异表现出明显差异，单一的车流量指标无法捕捉排放因子的动态变化（Chen *et al.*, 2022）．其次，对车队的实地观测实验强调排放因子受道路结构、车队结构、驾驶行为与环境气象等诸多变量影响，是动态变化的，车流量无法综合替代上述因素．Deng *et al.*（2015）开展的隧道实验结果显示，坡度−3%～+3%的上海延安东路隧道内 CO 的排放因子为（1.266±0.89）～（3.974±2.19）g/(km·辆)，坡度−6%～+6%的长沙营盘隧道内 CO 和 NO_x 排放因子分别为（0.754±0.561）～（6.050±5.940）和（0.121±0.022）～（0.818±0.755）g/(km·辆)；当平均车速为 10～20 km/h 时，CO 的排放因子比高车速下高出约 50%，研究表明 CO 和 NO_x 的单车排放因子随道路坡度增大和车速降低而增大．此外，车辆驾驶行为（如加速度、红灯等待行为等）对 CO 等污染物排放因子的影响显著，这些行为特征并不由流量反映．Kendrick *et al.*（2015）在美国一主干道旁展开的监测结果表现出：NO_x 的浓度在早上时段和交通量有一定相关性（NO 的 R^2=0.10～0.45，NO_2 的 R^2=0.14～0.27），而到了傍晚时段几乎没有相关性（NO 和 NO_2 的 R^2=0.01～0.05），车流量虽为重要活动指标，但不能仅用车流量作为排放因子的时间代理变量，应引入基于驾驶状态、车种结构和实时交通数据的动态校正机制，以提升排放清单的科学性与政策适用性．

3 结论

本研究通过对城市隧道内的交通源排放开展实测获取了高时间分辨率机动车排放因子，并采用排放强度比值法实现了机动车排放因子的分车型解析．

（1）城市隧道的日平均车流量为（16 664±2 878）辆，其中 GV 占比最高，为 94.9%．在工作日时呈现显著的早晚高峰波动趋势，高峰时段的车流量占全天车流量的比例可达（43.0±2.1）%；隧道内的车流量和车速整体呈现负相关的趋势，皮尔逊相关系数为−0.42～−0.35，但 R^2 仅为 0.12～0.18，表明车流量对车速变化的解释程度不高．

（2）本研究观测得出的 CO、NO、NO_2、NO_x、SO_2、BC 和 $PM_{2.5}$ 的单车排放因子分别为（1 064.9±479.8）、（496.5±209.3）、（55.5±30.4）、（578.6±267.6）、（6.3±2.2）、（3.3±1.5）和（37.7±19.2）mg/(km·辆)；车队整体排放因子分别为（634.7±477.2）、（266.0±142.9）、（26.4±13.5）、（302.3±159.5）、（3.5±1.9）、（2.0±1.1）和（19.8±12.3）g/km．与前人研究对比，机动车的标准提升和减排技术优化对机动车排放的削减是显著的，相较 20 世纪 90 年代的研究结果部分污染物的排放因子降幅可达 88%～97%．

（3）观测期间，周末的日车流量较工作日降低了 11.4%，除 $PM_{2.5}$ 外工作日的排放因子为周末的 1.0～1.48 倍．隧道内单车污染物逐时排放因子呈现夜晚高、日间低的现象．隧道内凌晨的 DV 占比是其余时间的 1.6 倍，各污染物在凌晨时段呈现的单车排放因子最高值分别是其余时间平均值的 2.0～3.5 倍，这表

明车队的车型构成会对排放造成显著影响，在DV占比增高时，NO、NO_x和$PM_{2.5}$的排放也会随之增高.车队的污染物逐时排放因子呈现显著的双峰，早晚高峰期峰值为全天平均值的1.8～3.3倍.

（4）车流量与单车排放因子呈负相关关系，而与车队整体排放因子表现出正相关关系，车流量和单车排放因子与车队整体排放因子的NO、NO_x、SO_2和BC的Pearson相关系数分别呈现低于－0.40和车队整体高于0.60的现象，表明车流量作为排放因子的时间代理变量的解释性不足，应结合其他影响因素如驾驶状态、道路坡度等进行校正.

本研究获得的机动车排放大气污染物动态排放因子可为区域高精度排放清单构建提供基础数据支撑，本研究提出的基于图像识别技术的机动车分车型车流量识别可为后续研究提供借鉴.

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