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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 1064.9 ± 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^{-1} 辆$^{-1}$；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 mg km^{-1}. 隧道内周末的日车流量为工作日的 88.6%，工作日除 $PM_{2.5}$ 外的污染物的排放因子是周末的 1.0 ~ 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；大气污染物；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

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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 1064.9 ± 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^{-1} veh^{-1} 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 mg km^{-1} 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; Atmospheric Pollutants; Dynamic Emission Factors; 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; Tan et al., 2017; 邵龙义等, 2018; Wang et al., 2020; 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., 2017; Huang et al., 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)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，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)和 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)修正了《指南》的标准排放因子后进行清单的计算，而潘玉瑾等人也指出基于《指南》的排放因子估算成为清单构建的最大的不确定性来源.Shah and Zeeshan(2016)采用 IVE 模型进行清单的编制时指出，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，模型估算这一方法除了会引入较大不确定性外，

模型的输入数据难以获取也对模型应用至区域排放清单构建提出挑战(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., 2022; 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，但是不能完全对真实情景下道路排放进行表征(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世界的排放情况的排放测试方法(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., 2022).隧道实验最早由 Pierson 和 Brachaczek 提出(Pierson and Brachaczek, 1983)，基于质量平衡的原理，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.(2018)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 DV 对总排放贡献的 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(United States Environmental Protection Agency, 2025)、COPERT(European Environment Agency, 2019)、EMFAC(California Air Resources Board, 2021)、IVE(International Sustainable Systems Research Center, 2009)，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 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)的研究指出，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)和宋晓伟等(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，缺乏作为模型中技术分布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，模型估算因依赖难以完备获取的本地化数据，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的问题制约.基于此，本研究选择一条市区内隧道，通过 $PM_{2.5}$、CO、NO、NO_2、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(图 1).隧道全长 1500 m，为单向通行的双车道，限速 60 km h^{-1}，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，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 天工作日、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.

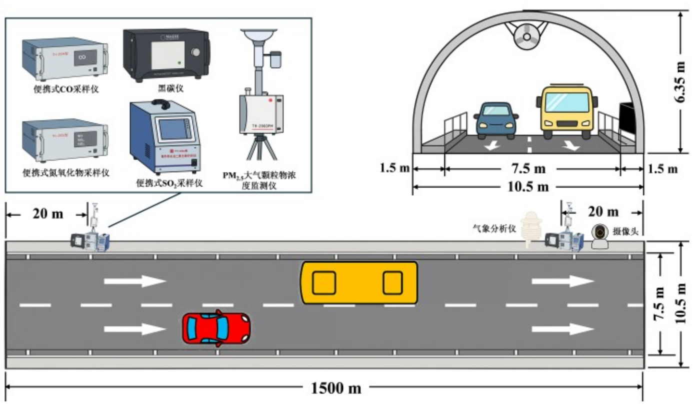


图 1 隧道实验采样示意图
Fig.1 Layout of Sampling Configuration and Detail of the Tunnel

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，黑碳仪通过对石英滤纸带上采集到的BC对光透射的衰减量反推出BC的质量浓度(Drinovec et al., 2015).对于$PM_{2.5}$浓度的观测，采用以连续 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).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.

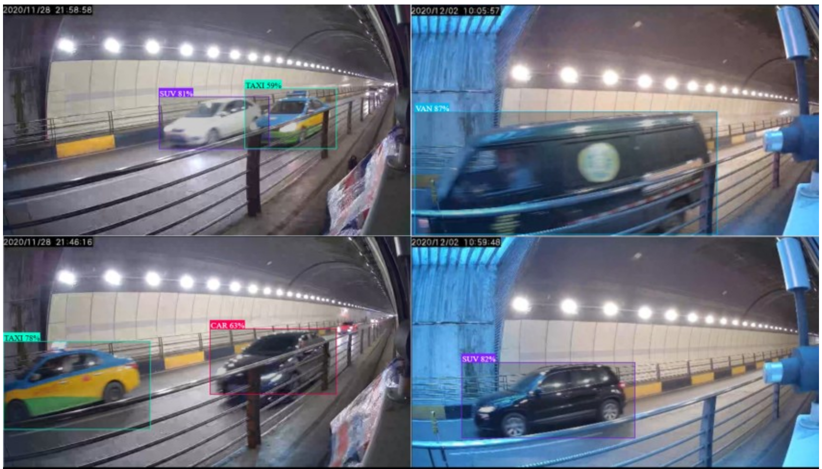
利用时间分辨率为 1 min 的气象分析仪(WS600，德国 Lufft)对隧道内的气象数据进行检测.本实验在隧道出口处采样点设置监控摄像头(MJSXJ02CM，上海创米科技有限公司)对隧道内机动车同行进行录制，为后续车辆识别和分析提供车流量的视频素材.

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别，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 × 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 × 2.35 m 矩形区域作为与像素距离作为参照的锚点，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 分钟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 算法参数设置为：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.



[redacted]

图 2 车辆识别界面和流程图
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；采样点间距 L(km)可以得到机动车的车队平均排放因子(公式(1))，将污染物总质量以通过的车辆数 N(辆)，便可以得到单车的排放因子(公式(2))(Pierson et al., 1996).

[redacted] (1)

[redacted] (2)

式中，EF_{fleet} 为机动车车队整体排放因子，单位为 g km^{-1}，$EF_{\text{individual}}$ 为机动车单车平均排放因子，单位为 mg km^{-1} 辆$^{-1}$，A 为隧道横截面积 m^2，T 为采样时长 s，v 为风速 m s^{-1}.

1.4.2 分车型排放因子

本研究采用排放强度比值的方法，对通过公式(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)和 Deng et al.(2015)的研究，将车辆类型划分为 DV、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.

表 1 污染物排放因子比值参考表
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	0.0015
DV	0.45	0.3	0.3	0.3	0.03	0.0225	0.03
R	0.53	6	6	6	1.5	3.75	20

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

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.

[redacted] (3)

[redacted] (4)

式中，大型车和小型车的排放因子分别为 EF_{DV} 与 EF_{GV}，单位为 mg km^{-1} 辆$^{-1}$ 或 g km^{-1}；大型车和小型车的通行量分别为 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 2128 组 CO、NO、NO_2、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 1852 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 3-a、图 3-b 所示，日平均车流量为 16664 ± 2878 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 17405 ± 3107 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 15429 ± 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^{-1}，在凌晨 3:00 出现高值 59.88 ± 2.54 km h^{-1}，在 17:00 出现最低值 31.35 ± 4.13 km h^{-1}.车速和车流量的变化趋势与宋爱楠等(2023)和张启钧等(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 3-d)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 3-c)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.

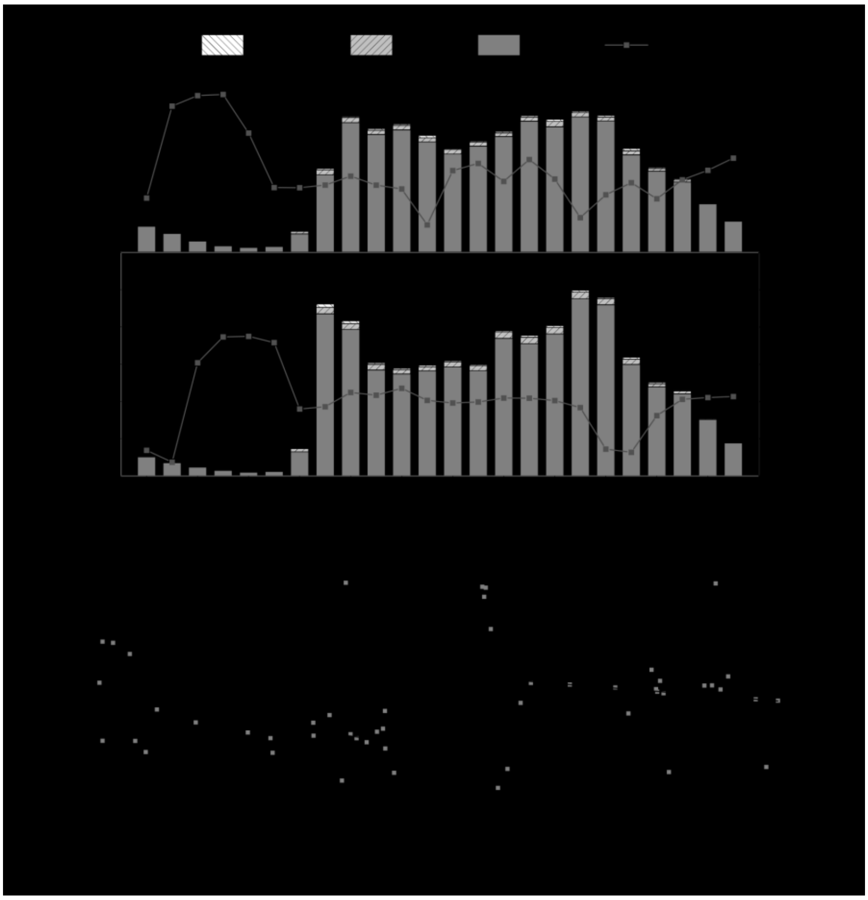


图 3 观测期间隧道内车流量和车速日变化特征 (a 和 b.周末和工作日车速与车流量变化；c 和 d.周末和工作日车速与车流量相关性)
Fig.3 Diurnal Variation of Traffic Volume and Vehicle Speed Inside the Tunnel During the Observation Period (a.& b.: Variation of traffic speed and volume on weekends and weekdays; c & d: Correlation between traffic speed and volume on weekends and weekdays)

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 1064.9 ± 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^{-1} 辆$^{-1}$. 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 veh^{-1} km^{-1})和 2017 年 Luo et al.(2020)在陕西秦岭 3 号隧道(3.9 ± 1.7 g veh^{-1} km^{-1})开展的观测实验结果.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 2017 年 Ho et al. (2023)、2019 年 Zhang et al.(2021)和 2019 年 Raparthi et al.(2021)的隧道观测结果(5.40、4.9 和 11.6 mg km^{-1} 辆$^{-1}$)，但略高于 2019 年张启钧等(2023)测得的 2.62 ± 0.60 mg km^{-1} 辆$^{-1}$ 和 Liu et al.(2023)测得的 1.09 ± 0.49 mg km^{-1} 辆$^{-1}$.对于细颗粒物，本研究所得到的 $PM_{2.5}$ 的排放因子与 Huang et al.(2017a) 2016 年于上海延安东路的观测结果 34 ± 23.5 mg veh^{-1} km^{-1} 相近，且远低于 2014 年在珠江隧道观得出的 92.4 和 82.7 mg km^{-1} 辆$^{-1}$(Dai et al., 2015; Zhang et al., 2015)，但高于 2014 年 Clem Jones-CLEM7 的观测结果 15 ± 2

mg km^{-1} 辆$^{-1}$和天津五经路隧道在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^{-1} 辆$^{-1}$(宋爱楠等, 2023).

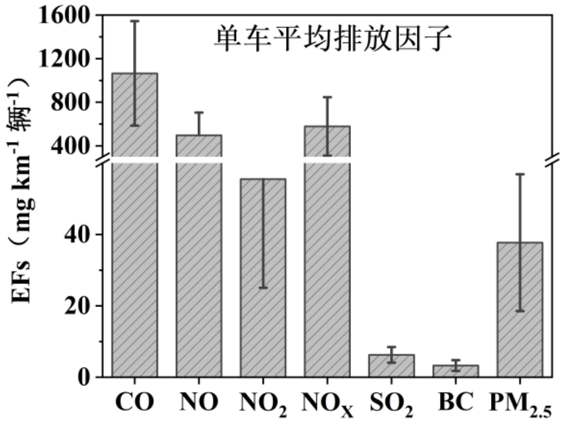


图 4 各污染物单车平均排放因子(单位：mg km^{-1} 辆$^{-1}$)
Fig.4 Per-Vehicle Average Emission Factors of Pollutants from Motor Vehicles (Unit: mg km^{-1} veh^{-1})

表 2 总结了已发表的有关于隧道实验的研究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%)的高速公路隧道，致使排放因子高出同时期的排放因子(Song et al, 2018)的均值约 13.8 ~ 111.5 倍，表明车队车型构成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).天津五经路隧道在2017年和2019年均开展了隧道观测实验(Song et al., 2018; 宋爱楠等, 2023)，相较同时期的结果，其排放因子呈现较低水平，这可能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(Yazdani and Frey, 2014).相较于 90 年代的隧道实验观测结果(邓顺熙等, 2000a; 邓顺熙等, 2000b; 邓顺熙等, 2000c; 王伯光等, 2001)，本研究 CO 和 NO_X 排放因子下降幅度可达最高 97.5%和 88.2%.

表 2 不同城市隧道实验得到的机动车大气污染物单车排放因子对比(单位：g km^{-1} 辆$^{-1}$)
Table 2 Comparison of emission factors from different tunnel studies (unit: g km^{-1} 辆$^{-1}$)

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, 2000a)
西安	1996	33.28	-	-	4.60	-	-	-	(邓顺熙, 2000b)
成都	1996	28.73	-	-	4.65	-	-	-	(邓顺熙等, 2000c)
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	-	-	0.0092	(Song et al, 2018)
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	0.0207	-	0.0827	(Zhang et al., 2015)
香港	2015	1.80	1.33	0.24	1.58	-	-	0.025	(Wang et al., 2021)
上海	2016	1.84	-	-	0.4	-	-	0.034	(Huang et al., 2017)
天津	2017	0.28	0.062	0.020	0.084	-	-	0.0092	(Song et al., 2018)
西安一汉中	2017	3.88	4.31	1.56	9.37	0.09	-	-	(Luo wt al., 2020)
郑州	2019	1.49	0.051	0.0067	0.086	0.00	-	-	(王雯楠等, 2024)
天津	2019	0.41	-	-	0.080	-	-	0.0093	(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	0.0063	0.0034	0.038	本研究

-：无数据

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(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 ppm)对三元催化转化器(TWC)催化剂的毒化作用，减排进入平台期(CO～1.8 $g·km^{-1}$ 辆$^{-1}$; NO_X～0.8 $g·km^{-1}$ 辆$^{-1}$).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 ppm)，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(SCR)，推动 NO_X 从 2013 年 0.227 $g·km^{-1}$ 辆$^{-1}$ (Deng et al., 2015)降至 2017 年 0.084 $g·km^{-1}$ 辆$^{-1}$ (Song et al., 2018)；2019 年国六 a 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 $g·km^{-1}$ 辆$^{-1}$. 燃油硫含量作为关键控制指标，从国I/II阶段的限值 2000 mg kg^{-1}，逐步降至国IV/V(约 2014 年)的 50 乃至 10 mg kg^{-1}，并在国VI阶段(约 2020 年)稳定维持在 10 mg kg^{-1} 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^{-1} 辆$^{-1}$；随着国IV/V标准油品的普及，2014 年降至 0.0207 g km^{-1} 辆$^{-1}$，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 0.0063 g km^{-1} 辆$^{-1}$，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.

图 5 我国近 30 年隧道实验排放因子变化趋势(单位: g km^{-1} 辆$^{-1}$)
Fig. 5 Trends in Tunnel-Based Vehicle Emission Factors in China Over the Past 30 Years (Unit: g km^{-1} veh^{-1})
(1 邓顺熙等, 2000a; 2 邓顺熙等, 2000b; 3 邓顺熙等, 2000c; 4 王伯光, 2001; 5 Cheng et al., 2006; 6 Chiang et al., 2007; 7 Song et al., 2018; 8 Zhang et al., 2015; 9 Deng et al., 2015; 10 Zhang et al., 2020; 11 Wang et al., 2021b 12 Huang et al., 2017a; 13 Song et al., 2018a; 14 Luo et al., 2020; 15 宋爱楠等, 2023; 16 本研究)

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图 6 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 mg km^{-1}.在前人开展的隧道实测研究中，Kristensson et al.(2004)于 1998 年在瑞典 Söderleds 隧道测得混合车流车队整体 CO 和 NO_X 排放因子分别为 5.27 ± 0.10、1.36 ± 0.03 g km^{-1}. Martins et al.(2006)、Pérez-Martínez et al.(2014)和 Nogueira et al.(2021)分别于 2004 年、2010 年和 2018 年在巴西圣保罗的 Jânio Quadros 隧道开展隧道实验，三年的车队排放因子呈不断下降的趋势(CO: 14.6 ~ 5.8 ~ 2.5 g km^{-1}; NO_X: 1.6 ~ 0.3 ~ 0.14 g km^{-1}) Lin et al.(2019)在高雄开展的对于 DV 的基于 PEMS 的实验得到了 $PM_{2.5}$、CO 和 NO_X 排放因子，分别为 2.01、12.3 和 0.552 g km^{-1}; O’Driscoll et al.(2016)开展的 PEMS 实验得出市区内 NO_2 排放因子为(0.36 ± 0.36) g km^{-1}. 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减降低了气态污染物的排放(Wen et al., 2023).对于实验方法的差异，隧道实验反映的是混合车流在相对稳定的城市交通状态下的平均排放特征，受交通流状态和隧道通风条件影响；而 PEMS 研究的是包含加速、爬坡等高负荷工况的单车排气口排放特征，往往得到更高的排放因子(Khan et al., 2020).因此，本研究排放因子低于部分现有研究，是政策技术进步以及实验方法差异等因素综合作用的结果.

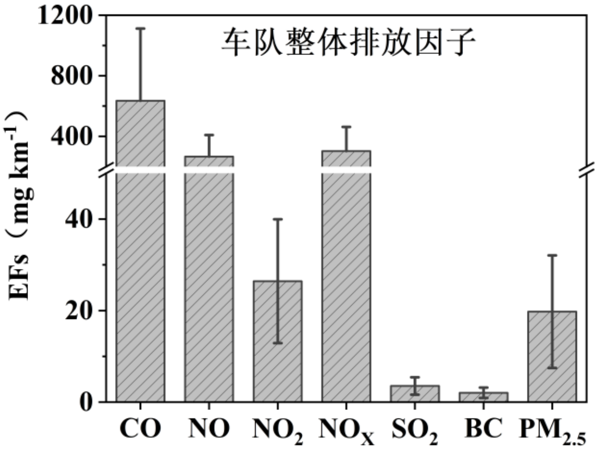


图 6 各污染物车队整体排放因子(单位：g km^{-1})
Fig.6 Fleet-Averaged Emission Factors for Various Pollutants (Unit: g·km^{-1})

2.3 工作日和周末机动车排放因子对比

在实验观测期间内，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.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 $PM_{2.5}$ 的来源较为广泛(如工业、二次无机盐、区域传输和机动车排放等)，对比采样期间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，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，包括了因子分别是周末的 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}.

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^{-1} 辆$^{-1}$	1409.5	508.1	60.5	581.2	6.7	3.3	35.8
	车队	g km^{-1}	757.8	252.0	28.6	288.6	3.9	2.0	17.9
周末	单车	mg km^{-1} 辆$^{-1}$	720.2	484.9	50.5	576.0	5.8	3.2	39.6
	车队	g km^{-1}	512.9	146.4	13.9	159.9	1.6	1.1	13.6

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 在平均情境下 NO 和 NO_X 的排放因子分别达 2703.22 和 631.29 mg km^{-1} 辆$^{-1}$，而 GV 则分别为 450.54 和 105.22 mg km^{-1} 辆$^{-1}$.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，平均情境下排放因子分别为 1159.05 与 613.61 mg km^{-1} 辆$^{-1}$，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，大量机动车处于怠速工况，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^{-1} 辆$^{-1}$，而 BC 的排放因子 DV 和 GV 分别为 3.31 和 0.88 mg km^{-1} 辆$^{-1}$. $PM_{2.5}$ 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较为显著.

与国内外的研究进行对比分析，Chan and Ning (2005)于 2004 年在香港的遥感观测结果表明在 10 ~ 70 km h^{-1} 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开展的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^{-1} 辆$^{-1}$；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 $PM_{2.5}$ 的排放因子分别为 2.18 和 0.79、5.64 和 0.18 以及 0.15 和 0.01 g km^{-1} veh^{-1}，重型车对隧道内 CO、NO_X 和 $PM_{2.5}$ 的贡献率为 61.5%、94.8%和 89.3%，均远高于本研究结果. Pérez 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的特点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，燃料性质是各污染物排放的重要影响因素之一.

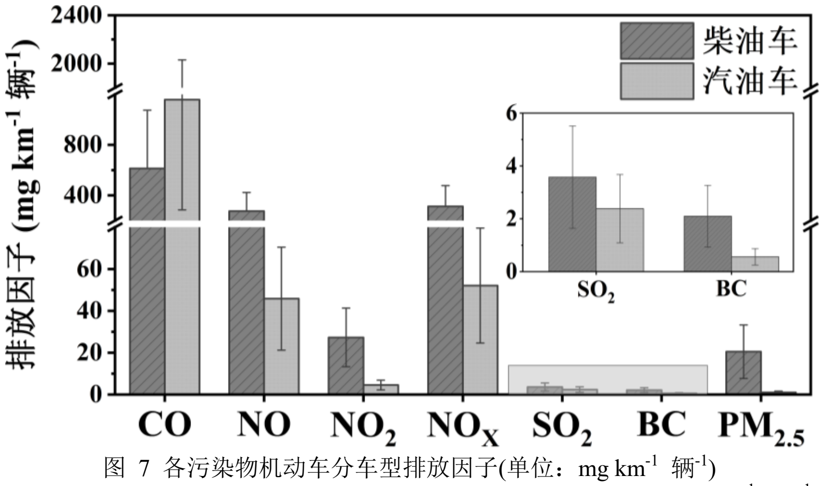


图 7 各污染物机动车分车型排放因子(单位：mg km^{-1} 辆$^{-1}$)
Fig.7 Emission Factors of Different Pollutants by Vehicle Type (Unit: mg·km^{-1}·veh^{-1})

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 ~ 2636.7、273.4 ~ 1002.1、13.8 ~ 123.2、308.6 ~ 1287.1、3.3 ~ 10.9、5.5 ~77.7 和 0.77 ~ 6.9 mg km^{-1} 辆$^{-1}$.

对比各小时机动车不同污染物的排放因子可以看出，单位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 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 年在天津五经路隧道的观测(Song et al., 2018)的结果显示，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 et al.(2015)在广州珠江隧道的实验结果与本研究表现一致，$PM_{2.5}$、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的观测得到 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^{-1} 辆$^{-1}$，也与本研究中氮氧化物小时排放因子变化趋势较为吻合.

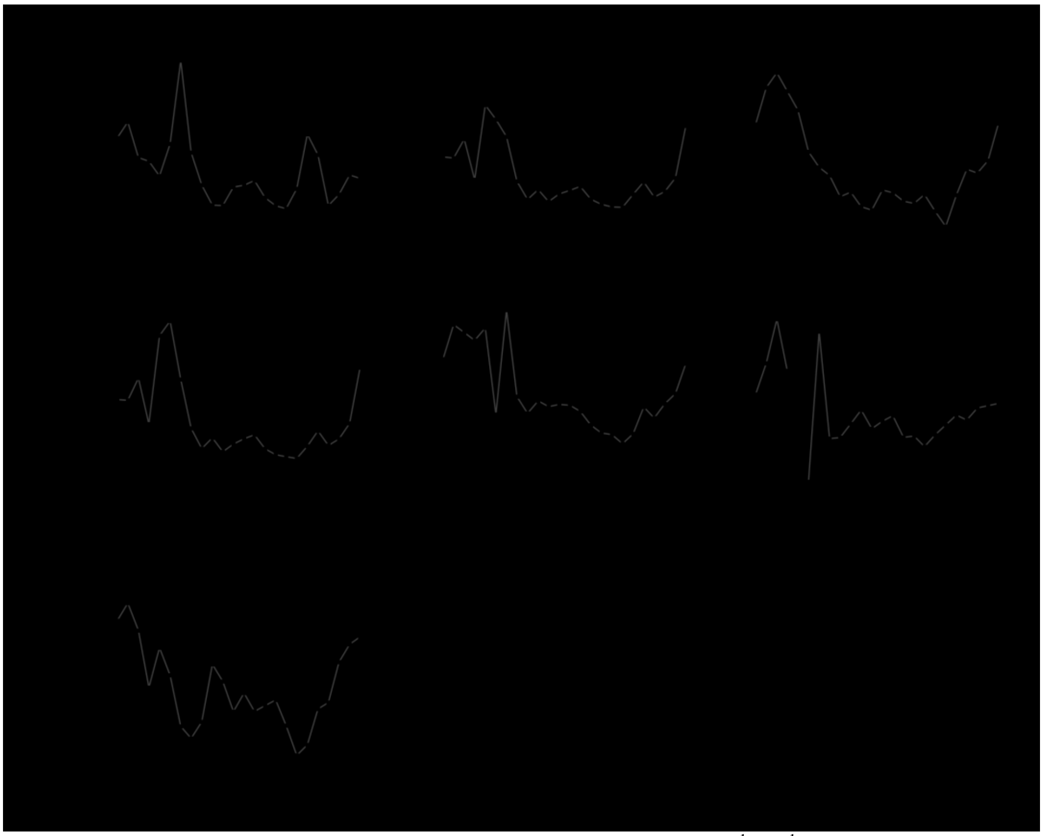


图 8 各污染物单车逐时排放因子(单位：mg km^{-1} 辆$^{-1}$)

Fig.8 Hourly Dynamics of Per-Vehicle Emission Factors for Pollutants (Unit: mg km^{-1} veh^{-1})

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 ~ 2083.7、24.0 ~ 513.8、2.9 ~ 56.1、28.17 ~ 586.6、0.2 ~ 6.7、1.9 ~ 46.0 和 0.03 ~ 3.8 g km^{-1}.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，这可能由于高峰期的车辆通行密度增加，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)的研究同样指出昼间 06:00 ~ 11:00 和 12:00 ~ 17:00 的排放量平均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 1487.89 和 2083.69 g km^{-1}，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(小时平均车速低于 40 km h^{-1})，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)，NO、NO_X、SO_2和 BC 在 7:00 和 18:00 车队整体的排放因子达到峰值，分别 513.85、586.60、6.71 和 2.69 g km^{-1}与 481.4、519.32、5.08 和 3.83 g km^{-1}.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 年均排放浓度的增幅可达 3.5 μg m^{-3}、1.1 ppb、2.5 ppb 和 0.1 ppm. 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，分别为 56.11 和 42.24 g km^{-1}.该现象和 Gantt et al.(2021)的路边站的观测结果一致，即 NO_2增量的峰值(9 ppb)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高频变化无法捕捉，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.

图 9 各污染物车队整体逐时排放因子(单位: g km^{-1})

Fig. 9 Hourly Dynamics of Fleet-Averaged Emission Factors for Pollutants (Unit: g km^{-1})

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(单位时间通过的车辆总数)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.

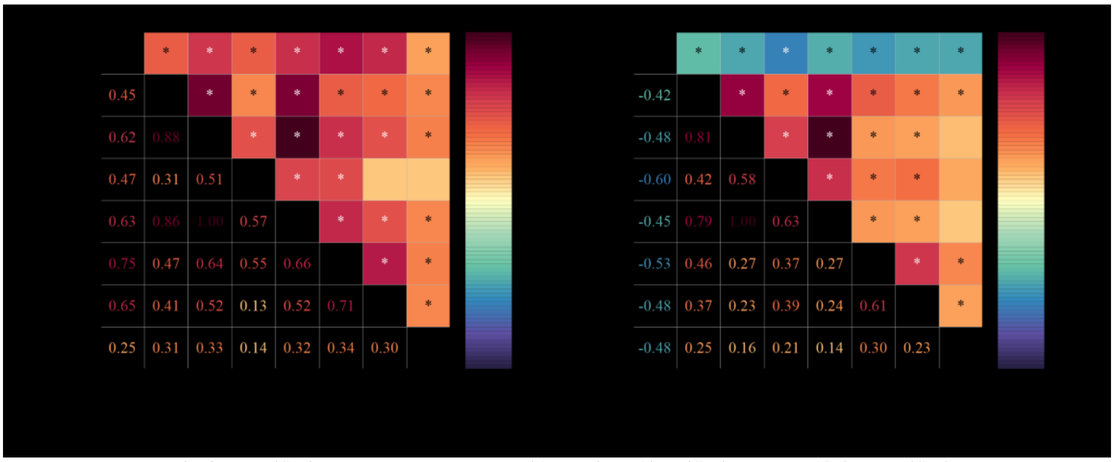


图 10 车流量与排放因子的 Pearson 相关性 (a.车队整体排放因子; b.单车平均排放因子)
Fig.10 Pearson correlation between Traffic Volume and Emission Factors (a. Fleet-Level Emission Factors; b. Per-Vehicle Average Emission Factors)

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^{-1} 辆$^{-1}$，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^{-1} 辆$^{-1}$；当平均车速为 10 ~ 20 km h^{-1} 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、等红灯等待行为等)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

本研究通过城市隧道内真实车流的实测方法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 16664 ± 2878 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 1064.9 ± 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^{-1} 辆$^{-1}$；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 mg km^{-1}.与前人研究比较结果表明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 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是其余时间平均值的 2.0 ~ 3.5 倍，这表明交通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则表现为正相关关系，NO、NO_X、SO_2 和 BC 的 Pearson 相关系数分别呈现低于-0.40 和高于 0.60.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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