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Comprehending particulate matter dynamics in transit-oriented developments: Traffic as a generator and design as a captivator

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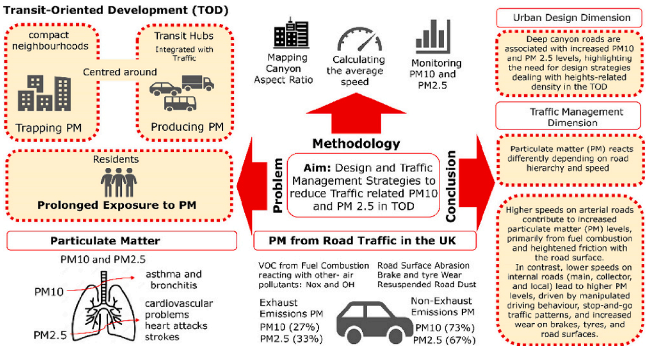
HIGHLIGHTS

- TOD Diverse activities can draw traffic and associated PM stemming from vehicles' exhaust and non-exhaust emissions.
- Deep TOD Street Canyons could act as a container and trapper for traffic-induced PM, especially in condensed TOD.
- The correlation between vehicle speed and PM levels in TODs is not straightforward and depends more on driving behaviour.
- Existing legislation falls short in addressing traffic-related PM from Non-exhaust sources, creating a regulatory gap.

GRAPHICAL ABSTRACT



Deep canyon roads are associated with increased PM10 and PM 2.5 levels, highlighting the need for design strategies dealing with heights-related density in the TOD

Particulate matter (PM) reacts differently depending on road hierarchy and speed

Higher speeds on arterial roads contribute to increased particulate matter (PM) levels, primarily from fuel combustion and heightened friction with the road surface.
In contrast, lower speeds on internal roads (main, collector, and local) lead to higher PM levels, driven by manipulated driving behaviour, stop-and-go traffic patterns, and increased wear on brakes, tyres, and road surfaces.

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ABSTRACT

In Transit-Oriented Development (TOD), the close integration of residential structures with community activities and traffic heightens residents' exposure to traffic-related pollutants. Despite traffic being a primary source of particulate matter (PM), the compact design of TODs, together with the impact of urban heat island (UHI), increases the likelihood of trapping emitted PM from traffic, leading to heightened exposure of TOD residents to PM. Although PM originates from two distinct sources in road traffic, exhaust and non-exhaust emissions (NEE), current legislation addressing traffic-related PM from non-exhaust emissions sources remains limited. This paper focuses on two TOD typologies in Manchester City—Manchester Piccadilly and East Didsbury—to understand the roles of TOD traffic as a PM generator and TOD place design as a PM container and trapper. The investigation aims to establish correlations between street design canyon ratios, vehicular Speed, and PM10/PM2.5, providing design guidance and effective traffic management strategies to control PM emissions within TODs. Through mapping the canyon ratio and utilising the Breezometer API for PM monitoring, the paper revealed elevated PM levels in both TOD areas, exceeding World Health Organization (WHO) recommendations, particularly for PM2.5. Correlation analysis between canyon configuration and PM2.5/PM10 highlighted the importance of considering building heights and avoiding the creation of deep canyons in TOD design to minimise the limited dispersion of PM. Leveraging UK road statistics and the PTV Group API for vehicle speed calculations, the paper studied the average speeds on the TOD roads concerning PM. Contrary to conventional assumption, the correlation analyses have revealed a noteworthy association shift between vehicular speed and PM concentrations. A

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positive correlation existed between speed increase and PM increases on arterial roads. However, a negative correlation emerged on main, collector, and local streets, indicating that PM levels rise for both PM10 and PM2.5 as Speed decreases. These findings challenge the traditional assumption that higher Speed leads to increased emissions, highlighting the potential impact of NEE on PM concentrations. This paper calls for thorough design considerations and traffic management strategies in TOD, especially in dense areas, considering building height, optimising traffic flow, and enhancing compromised air quality associated with vehicular emissions.

1. Literature review

Vehicles and urban traffic pose a persistent threat to the health of city residents, particularly impacting vulnerable groups such as children and older people. Ongoing research efforts strive to understand traffic-related pollutants' nature and atmospheric behaviour to enact targeted control measures. Particulate matter (PM) emerges as a prominent concern among these pollutants, recognised as a significant threat to air quality and public health, contributing to seven million premature deaths annually (Dubey et al., 2016; Kowalska et al., 2019; WHO, 2014). Notably, exposure to PM concentrations exceeding World Health Organization (WHO) guidelines led to 238,000 premature deaths in Europe in 2021 (EEA, 2022).

1.1. *Understanding particulate matter: sources, impact on air quality, and health*

Particulate matter (PM), known as particle pollution, constitutes a complex mixture of airborne particles and liquid droplets, encompassing acids (such as nitrates and sulfates), ammonium, water, black carbon, organic chemicals, metals, and soil material (Dubey et al., 2016; EPA, 2023a). The Environmental Protection Agency (EPA) classifies particle pollution into two main categories: coarse particles (PM10) with diameters ranging from 2.5 to 10 μm, typically found near roadways and dusty industries, and fine particles (PM2.5) with diameters <2.5 μm, commonly present in smoke and haze (EPA, 2023b; Hopke et al., 2020; Mazzei et al., 2008).

PM is classified as a “primary” pollutant when it is emitted directly from the source, such as vehicles, open burning, wildfires, residential combustion, and industrial activities (EPA, 2023b; Schauer et al., 1996; Sharma and Mandal, 2023; Viana et al., 2008). Conversely, it is termed “secondary” pollutants when formed in the atmosphere through chemical reactions involving gases such as sulfur dioxide (SO_2) and nitrogen oxides (NOX) with specific organic compounds (Daellenbach et al., 2020; Hopke et al., 2020; Schauer et al., 1996; Viana et al., 2008).

Human activities release PM into the air through various processes, including domestic combustion, road transport, and industrial combustion (Alastuey et al., 2006; Sharma and Mandal, 2023). Domestic combustion, such as wood-burning stoves or fireplaces, contributes to the emission of fine particles. Road transport releases PM, especially vehicles with internal combustion engines (Mazzei et al., 2008; Mukherjee and Agrawal, 2017). Industrial combustions, such as those in power plants and manufacturing facilities, are significant sources of airborne particles (Karagulian et al., 2015; Mukherjee and Agrawal, 2017). These diverse sources collectively contribute to the presence of PM in the atmosphere, impacting air quality and potentially posing health risks (Dominici et al., 2010; EEA, 2022; Manisalidis et al., 2020).

The UK National Atmospheric Emissions Inventory (2018) found that road transport accounted for the predominant source of PM2.5, contributing to 28.98 % of PM2.5 in the air, whereas domestic combustion was the primary source of PM10, constituting 27.28 % of total PM10 emissions in the air (NAEI, 2018) (Fig. 1). In addition, road transport was found to contribute to 12.90 % of PM10 emissions, as shown in Fig. 1 (DEFRA, 2023).

The UK Air Quality Expert Group (2019) forecasted that, in this way, without implementing measures to limit NEEs, NEEs will account for 94 % of all PM10 emissions and 90 % of PM2.5 emissions from road transport in the UK by 2030.

Inhalation of PM10 can result in respiratory issues, particularly among individuals with pre-existing conditions such as asthma and bronchitis (Alemayehu et al., 2020; Bell et al., 2013; Kim et al., 2015). These particles can deeply penetrate the respiratory system, causing inflammation, irritation, and impaired lung function. Prolonged exposure to PM is associated with systemic health effects, including an increased likelihood of lung cancer and reduced lung development in children (Cassee et al., 2013; Fussell et al., 2022; Gerlofs-Nijland et al., 2019).

Moreover, fine particles with diameters of ≤2.5 μm, known as PM2.5, pose even more significant health risks as they can reach the deeper regions of the lungs and even enter the bloodstream (Alemayehu et al., 2020; Kim et al., 2015; Mukherjee and Agrawal, 2017; US EPA, 2019). The inhalation of PM2.5 is linked to cardiovascular problems, including an elevated risk of heart attacks, strokes, and other cardiovascular diseases (DEFRA, 2019a, 2019b; Miller and Newby, 2020). The World Health Organization (WHO) indicates that ischemic heart disease (IHD) stands as the leading cause of premature mortality in Europe, with approximately 48 % of this mortality associated with PM2.5 (Tarín-Carrasco et al., 2021). Additionally, PM deposition can have adverse environmental impacts, such as damage to vegetation, pollution of soil and water resources, and harm to wildlife (WHO, 2021).

PM particles' toxicity varies based on size, composition, and sources (Dadvand et al., 2013; Sunyer et al., 2006). Fine particles, especially PM2.5, demand particular attention due to their ability to penetrate deeply into the respiratory system and potentially enter the bloodstream (Cassee et al., 2013; Fussell et al., 2022). The detrimental health effects associated with PM underscore the importance of reducing exposure by implementing air quality regulations and emission control strategies (Al-Kindi et al., 2020; Arias-Pérez et al., 2020).

1.2. *Particulate matter from road traffic*

Concentrating on particulate matter stemming from traffic, it is predominantly associated with vehicular activities on the road. The

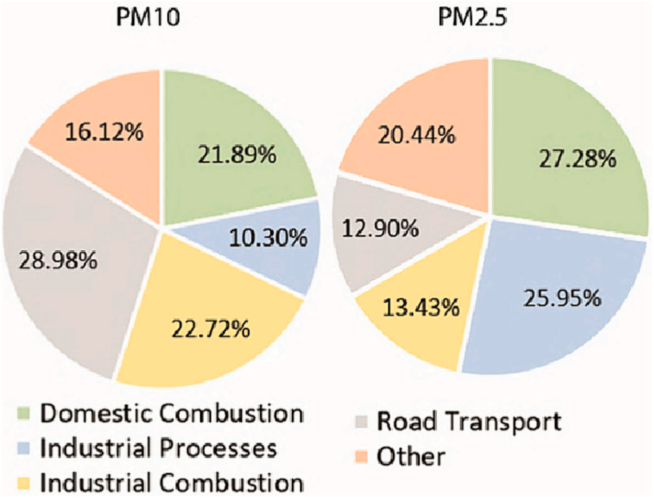


Fig. 1. Particulate matter PM 10 and PM 2.5 sources in the UK (NAEI, 2018).

quantity of PM emissions released by a vehicle is influenced by several factors, including vehicle weight, the material composition of brakes, tyres, and roads, the presence of dust on road surfaces, and driving styles (Katherine, 2020; Philip et al., 2017). PM is emitted directly from exhaust emissions originating from fuel combustion in vehicle engines through the emission of volatile organic compounds (VOC) that combine with other pollutants in the air, such as nitrogen oxides (NOx) and hydroxyl radicals (OH), forming PM (Reşitoğlu et al., 2015).

Urban road materials, mainly asphalt, possess the capacity to absorb heat, thereby playing a role in the emission of particulate matter. Wide roadways surrounded by compact structures, such as those found in Transit-Oriented Developments (TODs), are more susceptible to elevated and trapped particulate matter. As solar heat warms road surface materials, like asphalt, release VOCs. These VOCs originate not only from the road surface but also accumulate from VOCs emitted during fuel combustion in vehicle engines. Following photochemical reactions in the atmosphere (see Fig. 2), these VOCs interact with other pollutants on the road, such as nitrogen oxides (NOx) and hydroxyl radicals (OH), in the presence of sunlight, resulting in the formation of secondary organic aerosols (SOAs). These SOAs, complex organic compounds, subsequently condense into tiny particles, contributing to overall PM levels, including PM2.5 and PM10.

While road traffic PM is formed due to chemical reactions from vehicle exhaust emissions, it is predominantly derived from non-exhaust emissions.

Non-exhaust emissions (NEE) refer to particulate matter and other pollutants emitted from sources other than the vehicle's exhaust system (Amato et al., 2020; Katherine, 2020). These emissions can originate from various sources other than the vehicle's tailpipe; non-exhaust emissions result from wear and tear on vehicle components and interactions between the vehicle and the road environment (Daellenbach et al., 2020; DEFRA, 2023; Katherine, 2020).

Studies revealed that non-exhaust PM2.5 and PM10 emissions surpass exhaust emissions as a significant component of road traffic emissions. According to the UK National Atmospheric Emissions Inventory (2018), PM emissions from NEE, including tyre wear, brake wear, and road wear, substantially increased between 2000 and 2018. Specifically, NEE accounted for 26 % of the total road traffic PM2.5 emissions in 2000, escalating to 67 % in 2018. Similarly, NEE contribution to road traffic PM10 rose from 39 % in 2000 to 73 % in 2018 (see Graphical abstract) (Lin et al., 2022; NAEI, 2018).

Non-Exhaust Emissions particulate matter comes from four different sources:

- Tyre wear: It is a significant contributor to PM emissions in the context of road traffic (Alves et al., 2020). As vehicles traverse road surfaces, the friction between the tyres and the asphalt leads to the tyre's abrasion, releasing small rubber particles into the atmosphere (Baensch-Baltruschat et al., 2020; Knight et al., 2020). Larger particles accumulate on the road and are eventually washed off by rain or road sweeping and washing. Conversely, particles with a diameter of <10 mm remain suspended in the air, becoming airborne (Alves et al., 2020; Baensch-Baltruschat et al., 2020; Knight et al., 2020). These tyre wear particles are a form of "microplastic" since they originate from the rubber abrasion of tyres (Knight et al., 2020). Consequently, tyre wear particles can potentially contribute to microplastic levels in the environment (DEFRA, 2019a, 2019b).
- Resuspended road dust: Whentyre wear and road surface abrasion occur, and possibly large particles (>10 mm) are emitted into the atmosphere (Casotti Rienda and Alves, 2021). These particles tend to deposit and accumulate on the road surface. However, if they are not subsequently washed away, they may undergo further grinding with accelerated passing vehicles, forming smaller particles (Alshetty and Nagendra, 2022; Casotti Rienda and Alves, 2021). These fine particles contribute to the overall concentration of fine particulate matter (PM < 10 mm) in the air.
- Road surface wear: During the friction between vehicle tyres and road surfaces, both the tyres and the road surfaces get abraded (Järlskog et al., 2022). This abrasion process generates fragmented particulate matter that volatilises into the atmosphere (Harrison et al., 2021; Järlskog et al., 2022).
- Brake wear: The braking process also releases PM emissions. When a vehicle comes to a stop, the brake pads exert pressure on the rotating disc or drum to bring it to a halt (Woo et al., 2021). This process generates significant friction, resulting in the abrasion of both the brake pads and the rotating disc (Tarasiuk et al., 2020; Woo et al., 2021). Consequently, this abrasion releases particulate matter into the surrounding air (Woo et al., 2021). The extent and composition of brake-induced PM emissions can vary depending on factors such as brake pad material, driving conditions, and vehicle type (Woo et al., 2021).

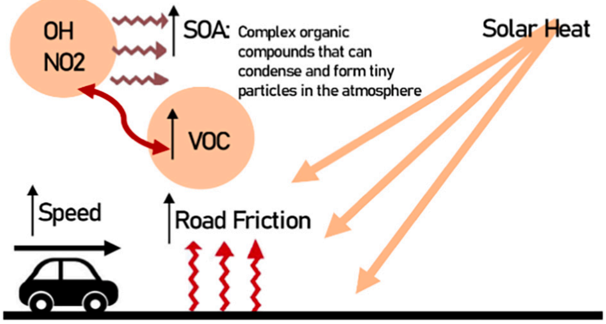


Fig. 2. PM originating from VOC emitted by vehicle engines and road surface.

In the UK, non-exhaust emissions (NEE) were found to contribute to PM2.5, with 37 % originating from resuspended road dust, 31 % from road wear, 27 % from tyre wear, and 5 % from brake wear (Lin et al., 2022). Additionally, NEE PM10 consists of 58 % resuspended road dust, 22 % from road wear, 15 % from tyre wear, and 5 % from brake wear (Lin et al., 2022).

Although the risk posed by non-exhaust emissions in increasing particulate matter (PM) from road traffic is well recognised, current legislation to reduce such emissions, particularly those generated by non-exhaust sources, remains limited (Amato et al., 2020; DEFRA, 2019a, 2019b). For example, the Euro emissions standards, established by the European Union (EU) to regulate pollutants emitted by vehicles, have primarily focused on pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) from exhaust sources (DieselNet, 2020; Infineum, 2023).

From the release of Euro 1 in 1992 to the current Euro 6 standards established in 2014 and still in effect, legislation predominantly focused on addressing PM emissions from diesel vehicles' exhaust emissions (DieselNet, 2020; Tzamkiozis et al., 2010). There was even limited consideration given to PM emissions from the exhausts of petrol vehicles until Euro 5 in 2009, when specific PM exhaust emission legislation for petrol vehicles started to emerge, a trend that continued with Euro 6 in 2014 and beyond (DieselNet, 2020; Lähde et al., 2022).

A potential solution lies in the forthcoming Euro 7 standards, which are expected to be implemented in 2025. These standards represent a significant step forward. They are anticipated to include the first legislation specifically targeting PM emissions from non-exhaust sources related to road traffic, such as those originating from tyres and brakes (European Parliament, 2024; Infineum, 2023; Krobot et al., 2023). This development is particularly crucial with the increasing prevalence of electric vehicles, which also generate non-exhaust PM emissions (Krobot et al., 2023).

1.3. Heavy vehicles and particulate matter

While Electric Vehicles (EVs) have emerged as a promising solution for reducing exhaust emissions, their benefits regarding NEE are not as straightforward.

In response to the growing need for transportation and its environmental repercussions, electric vehicles are frequently considered as a solution to reduce both greenhouse gas emissions and exhaust pollutants generated by road transport (Amato et al., 2020). However, many studies highlighted that while electric vehicles can eliminate exhaust emissions, they may not substantially reduce non-exhaust emissions (Amato et al., 2020; Bomey, 2023; Choi and Koo, 2021; Mastoi et al., 2022). Despite new regenerative braking systems that reduce brake wear, electric vehicles still significantly contribute to the non-exhaust emissions of PM through tyre wear, road wear, and road dust resuspension (Bomey, 2023; Choi and Koo, 2021). Interestingly, the heavy batteries in electric vehicles, especially those with greater autonomy, can make them weigh more than their conventional counterparts, leading to potential challenges in achieving significant non-exhaust emissions reductions (Choi and Koo, 2021).

A prime illustration of this weight disparity is evident in the 2023 GMC Hummer EV, a full-size pickup that surpasses 9000 pounds (4082.331 kg), primarily attributed to its hefty 2900-pound (1315.418 kg) battery (Bomey, 2023). In contrast, the 2023 GMC Sierra gasoline vehicle, also a full-size pickup, weighs <6000 pounds (2721.554 kg) (Bomey, 2023). This increased weight in EVs contributes to elevated friction with road surfaces during acceleration and braking processes.

In addition, the increased weight of EVs impacts various aspects of vehicle performance, including acceleration, handling, and energy consumption. This heavier weight intensifies the abrasion of tyres and road surfaces, resulting in more significant particulate matter emissions from tyre and road wear (Mastoi et al., 2022). Lightweight electric vehicles (EVs) were found to emit approximately 11–13 % less PM2.5 than their internal combustion engine vehicle (ICEV) counterparts (Amato et al., 2020). However, heavier-weight EVs emit an estimated 3–8 % more PM2.5 than ICEVs (Amato et al., 2020). Without specific policies targeting non-exhaust emissions, the increasing consumer preference for larger and more autonomous EVs may lead to a rise in PM2.5 emissions in the future, particularly with the adoption of heavier electric vehicles (Amato et al., 2020; Bomey, 2023; DEFRA, 2019a, 2019b).

In short, heavier vehicles significantly generate PM through NEE, resulting from heightened friction between these vehicles and the road surface and causing substantial friction, increasing tyre wear and road surface abrasion. Building upon the same concept, public transport vehicles, characterised by their inherent weight and larger dimensions to accommodate larger passenger capacities, amplify the potential for non-exhaust emissions PM, contributing to heightened PM levels in urban developments centred around transportation hubs, such as Transit-Oriented Developments (TODs). TODs are planned to create high-density neighbourhoods around public transport stations, promoting public transportation dependency and mitigating traffic-related pollution (ITDP, 2017) (Fig. 3). The intensified mass and size of public transport vehicles and their supposed higher flow in the TOD pose a risk for elevated traffic-related PM in those areas. This highlights the crucial need for addressing and mitigating the impact of such emissions in planning and managing traffic, especially in areas clustered around public transportation hubs such as TOD, as part of broader efforts to create sustainable and environmentally conscious urban spaces.

1.4. Transit-oriented development and particulate matter

Whether classified as primary or secondary, originating from exhaust or non-exhaust sources, particulate matter poses significant threats to human health and the environment. Specifically examining urban development surrounding public transport stations, the allure of these hubs attracts traffic and associated pollutants, heightening exposure to various pollutants, including PM.

While urban development around public transportation aims to promote environmentally friendly practices by encouraging public transportation over private vehicles, the accompanying commercial core in these areas often attracts commuters, increasing traffic and pollution (Dittmar and Ohland, 2004; Higgins and Kanaroglou, 2018). One of these urban developments is Transit-Oriented Development (TOD), which emerged as a concept in 1993, advocating for sustainable urban development around public transportation (Calthorpe, 1993). TOD emphasises the creation of self-sufficient neighbourhoods within a 600-meter radius of transportation hubs, offering community facilities, jobs, and diverse housing options to minimise commuting needs and promote sustainable modes of transportation (Fig. 3) (Chen, 2010; Renne et al., 2016; Tse, 2020).

Since TOD calls for incorporating traffic and residents in high-density neighbourhoods, assessing its performance regarding air pollution, including PM, is critical. In particular, compact urban spaces, such as TODs, increase the risk of trapping pollutants, limiting their dispersion (Yuan et al., 2021). Thus, this paper seeks to understand traffic performance within TODs and the concentration of traffic-related PM on the TOD-designed streets to formulate strategies for effectively regulating traffic within TODs and mitigating PM levels.

TOD nodes vary depending on the urban community they serve, adapting to factors such as scale, context, and the structure of the public transportation network. This leads to the classification of TOD into Center TOD, District TOD, and Corridor TOD (CapMetro, 2021; Kamruzzaman et al., 2014; Taki and Maatouk, 2018). The Centre TOD refers to developing a transit-oriented community around a major transit hub

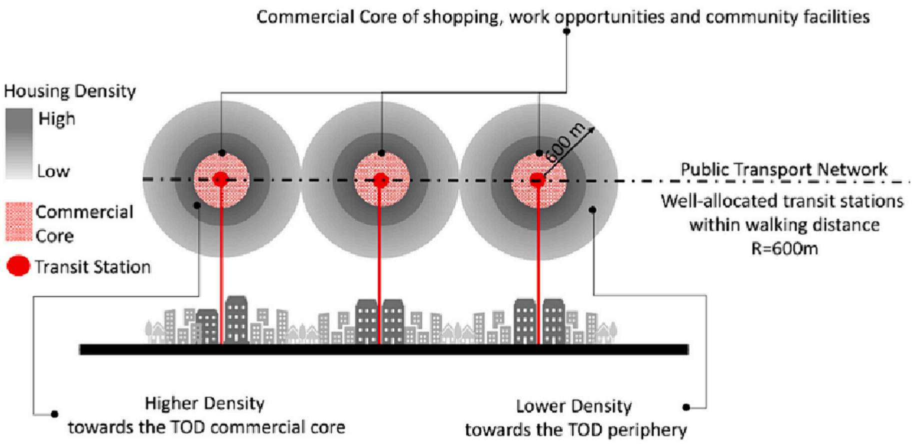


Fig. 3. Transit-Oriented Development (TOD) Network and Urban Structure.

or station (Yang and Song, 2021). It features high-density development with a mix of residential, commercial, and institutional buildings around the public transport station (Yang and Song, 2021). District TOD refers to developing transit-oriented neighbourhoods or districts, typically within walking distance of a local transit station. It encourages medium-density development, typically consisting of residential, commercial, and office buildings within a walkable radius (600 m) of transit stations (Phani Kumar et al., 2020). The corridor TOD focuses on development along a transit corridor, such as a Bus Rapid Transit (BRT), tram, light rail transit, or railway route. The corridor typology serves as the spine for transit accessibility and development opportunities. It encourages mixed-use development, with higher densities closer to the transit stations and gradually decreasing densities as you move away from the stations along the corridor (Huang et al., 2018; Phani Kumar et al., 2020).

It is evident that TOD at higher levels, particularly those centred around regional and central transit hubs, typically host a dense population. To accommodate this influx of residents, the layout of these TOD nodes features compact and high-density urban structure characterising. However, this condensed arrangement creates a deep canyon on roads, which could have a noteworthy impact on microclimates and air quality. The enclosed spaces created by dense urban areas can potentially trap air pollutants, influencing the overall air quality within the TOD environment. As the canyon depth increases (building heights/street width), streets are more susceptible to trapping various forms of pollution, consequently prolonging residents' exposure to pollutants such as particulate matter (PM). Since TOD's higher levels emphasise the development of compact neighbourhoods around public transportation, the likelihood of deeper road canyons is higher, intensifying the potential for PM entrapment.

Hence, the study seeks to comprehend the influence of TOD's urban density in terms of street canyons on the heightened trapping of PM. The study encompasses both traffic and urban design dimensions, examining their collective impact on traffic-related PM and the entrapment of these pollutants in the TOD.

The paper examines particulate matter (PM) concentrations in two TOD typologies in Manchester City. Specifically, one typology encompasses a high-level centre TOD, while the other represents a district neighbourhood TOD. The focus of the analysis extends to both the configuration of urban structures and traffic dynamics. The primary objective of this study is to investigate the correlation between canyon aspect ratio, traffic speed, and the levels of PM10 and PM2.5 within the two distinct TOD typologies, understanding how TOD density influences the trapping of pollutants and how the traffic impacts PM concentration in the TOD.

The literature review emphasises the imperative need to study PM as a significant air pollutant with adverse health effects, highlighting the dominant role of road transport in PM emissions, mainly from non-exhaust sources like tyre wear, brake wear, and road wear. It also addresses the complex relationship between Electric Vehicles (EVs) as well as highly weighted public transportation vehicles and PM emissions, emphasising challenges related to their increased weight and non-exhaust contributions, especially in TOD areas. The subsequent sections of the paper delve into presenting case studies and the criteria for their selection, detailing the adopted methodology, discussing the research results, and concluding with recommendations for fostering more sustainable TOD in addressing PM concerns.

2. Manchester TODs as case studies

This paper's selected TOD study areas are situated within Manchester City (Fig. 4), part of the Greater Manchester metropolitan area in the UK, encompassing a population of 552,000 and spreading over 45 mile^2 (ONS, 2022). Analysing Manchester TODs is driven by its challenging traffic congestion, which ranks it among the UK's most congested cities, presenting it as an intriguing case study (Davies, 2022).

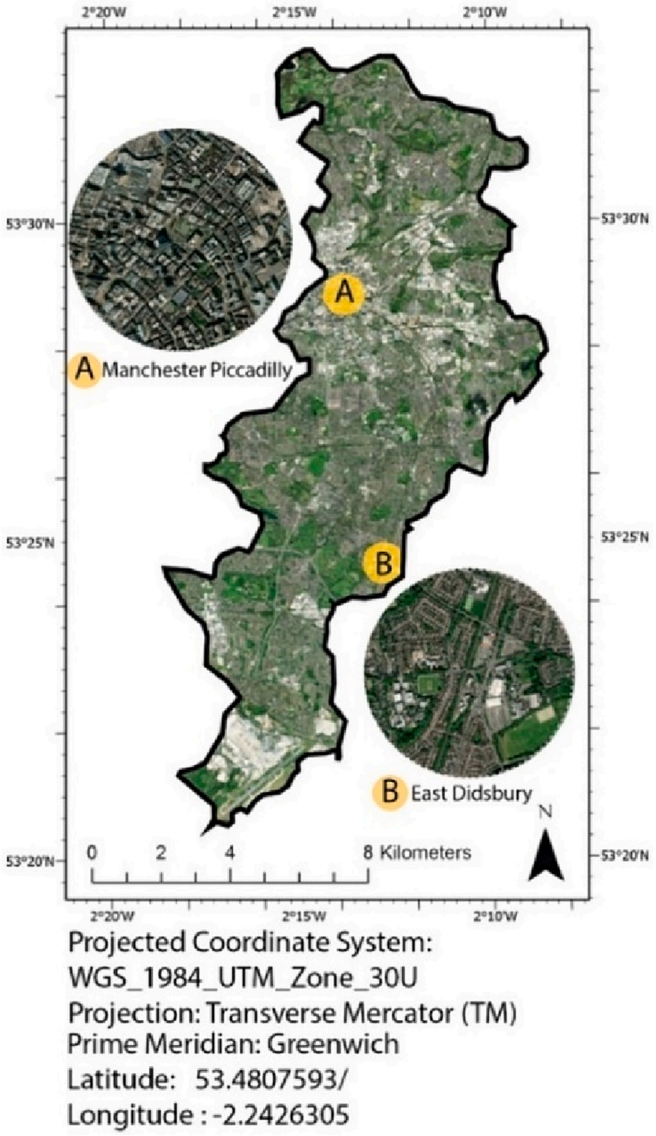


Fig. 4. The selected TOD areas within Manchester for the analysis.

New research from the National Infrastructure Commission reveals that Manchester experiences the most severe congestion outside London, coming second with 84 h of delay per driver (Davies, 2022). While London faces the highest congestion levels in England, Manchester leads the list of cities outside London, followed by Liverpool and Birmingham (Davies, 2022; Serda et al., 2013; Roberts, 2023; Szemraj et al., 2023; Wilkinson, 2018).

In addition, Manchester is the most polluted city in the UK's air pollution, ranking first among the top five most polluted UK cities: Nottingham, London, Cardiff, and Birmingham (Mortimer, 2023).

Furthermore, by examining pollution levels in Manchester through Breezometer and the UK emissions interactive map, it becomes evident that PM2.5 and PM10 emerge as the city's most significant and widespread pollutants (Breezometer, 2023).

The chosen case studies for this paper, Manchester Piccadilly and East Didsbury, represent distinct TOD typologies in Manchester City, offering diverse urban contexts and densities to examine the interplay between canyon design, transportation patterns and particulate matter emissions.

Manchester Piccadilly is a centre TOD allocated around the Piccadilly Garden transport hub, featuring a compact, mixed-use structure with diverse land uses (Gould et al., 2017; Shen et al., 2023; Symons et al., 2002). In contrast, East Didsbury represents a district TOD approximately 5 miles south of Manchester city centre, centred around East Didsbury railway station, showcasing a medium-density development pattern with a more limited range of land uses (Knowles and Binder, 2017; Symons et al., 2002).

The selection of diverse case studies enhances the research by providing a deeper understanding of the varied dynamics associated with different TOD typologies and scales on traffic and pollution.

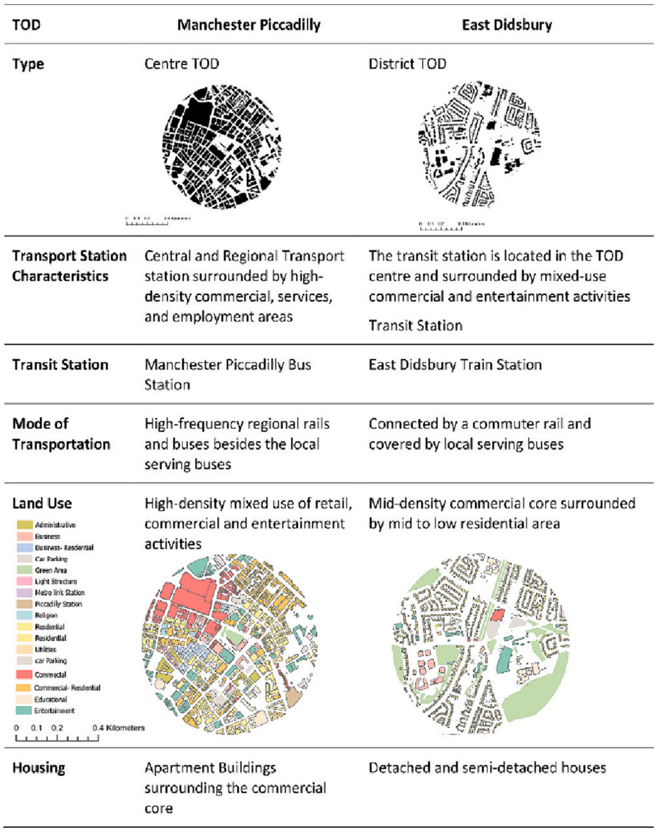
3. Data collection layers and research methodology

The paper examined PM levels in the two selected case studies, to correlate PM10/PM2.5 concentrations to the street canyon ratio and the average traffic speed on the roads, employing a comprehensive analysis based on three layers of data collection (see Fig. 6).

This quantitative research utilised three thorough data collection layers (Fig. 5). The initial layer of the data collection involved assessing the PM10 and PM2.5 levels on the roads. The second level involved mapping the road hierarchies and the canyon aspect ratio in the two study areas. Transitioning to the third layer, the research delved into studying the traffic volume and Speed within the TOD roads. Lastly, the study conducted a correlational analysis, establishing connections between the canyon aspect ratio, the average traffic speed and the levels of PM10 and PM2.5. This multifaceted approach provided valuable insights into the intricate relationship among these variables within the specific context of TODs.

3.1. Layer I: air quality monitoring: PM10 and PM2.5

The research monitored PM10 and PM2.5 pollutants using the BreezoMeter API platform. The primary distinction between the conventional approach reliant on air quality monitoring stations and the BreezoMeter framework lies in their respective methodologies for air quality assessment.



TOD	Manchester Piccadilly	East Didsbury
Type	Centre TOD	District TOD
Transport Station Characteristics	Central and Regional Transport station surrounded by high-density commercial, services, and employment areas	The transit station is located in the TOD centre and surrounded by mixed-use commercial and entertainment activities Transit Station
Transit Station	Manchester Piccadilly Bus Station	East Didsbury Train Station
Mode of Transportation	High-frequency regional rails and buses besides the local serving buses	Connected by a commuter rail and covered by local serving buses
Land Use Administrative Business Business- Residential Car Parking Green Area Light Structure Metro link Station Piccadilly Station Religion Residential Residential Utilities car Parking Commecial Commercial- Residential Educational Entertainment 0 0.1 0.2 0.4 Kilometers	High-density mixed use of retail, commercial and entertainment activities	Mid-density commercial core surrounded by mid to low residential area
Housing	Apartment Buildings surrounding the commercial core	Detached and semi-detached houses

Fig. 5. TOD typology and characteristics in Manchester Piccadilly and East Didsbury.

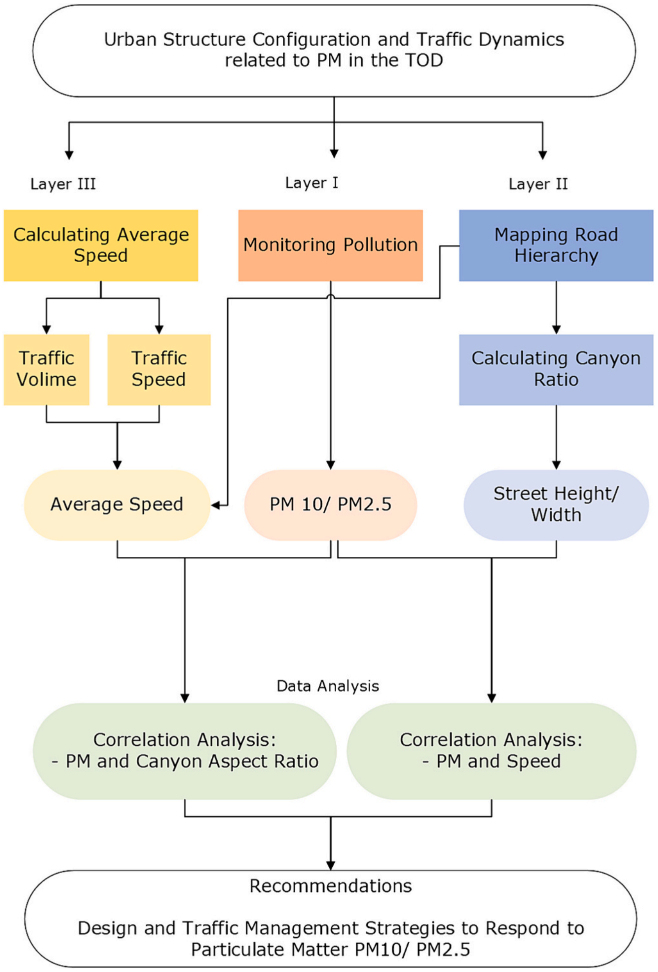


Fig. 6. The research methodology.

While traditional methods typically rely on data gathered from stationary measuring stations covering their immediate vicinity, BreezoMeter adopts a comprehensive approach by aggregating global data from diverse sources, including weather reports, traffic patterns, GPS data, and measurements from monitoring stations worldwide (Adamec et al., 2020; Breezometer, 2024). This accumulation of vast datasets, often referred to as Big Data, undergoes meticulous verification processes on dedicated servers before being utilised to construct a comprehensive air quality index (Breezometer, 2024).

Therefore, BreezoMeter's approach facilitates research across broader geographical regions rather than being confined to specific monitoring points around air quality monitoring stations. Consequently, the BreezoMeter platform was utilised in many traffic-related air quality studies, including studying PM levels (Adamec et al., 2020; Blagoiev et al., 2018; Bunds et al., 2019; Rana, 2022; Thomas et al., 2018; Vital et al., 2021).

The data aggregation process begins with BreezoMeter sourcing information from many channels, including government monitoring devices, alternative air quality monitors, satellites, and GPS systems (Copernicus, 2022). Subsequently, this data undergoes rigorous hourly validation checks, totalling a substantial 1.6 terabytes of data to ensure accuracy. Once validated, the dataset is organised to generate an impressive 420 million geographical data points (Nunes, 2019; van de Rhoer, 2017).

Using proprietary dispersion algorithms and machine learning techniques, BreezoMeter conducts approximately 7.1 billion compound

Table 1
Weather conditions on the selected days.

Date	High temp. °C	Low temp. °C	Wind speed Mph	Prevalent wind direction
06.04.2023	11	9	5.07	N
29.04.2023	11	9	4.97	N
31.10.2023	12	11	4.72	N
22.10.2023	12	8	4.19	NW

calculations to model pollutant dispersion accurately (Adamec et al., 2020). These algorithms account for various factors such as weather patterns, traffic flow dynamics, and geographical characteristics, resulting in precise air quality measurements tailored to specific locations and prevailing environmental conditions (Breezometer, 2024; Copernicus, 2022; van de Rhoer, 2017).

The culmination of this meticulous process yields ultra-accurate and hyperlocal air quality data, which is disseminated through the BreezoMeter application and API (Adamec et al., 2020; Breezometer, 2024; Casotti Rienda and Alves, 2021; Copernicus, 2022). In the context of this study, researchers relied on the BreezoMeter API to access real-time air quality information for the selected case studies, highlighting the platform's utility in facilitating research endeavours.

HTML requests were made to API endpoints to retrieve pollutant data. Accordingly, the study captured PM10 and PM2.5 levels daily on the selected days in April and October on an hourly basis to calculate the average daily concentration. Choosing days in both April and October is justified due to the similar weather conditions the two months share (see Table 1). The selected days demonstrated nearly identical weather conditions, encompassing temperature, wind speed, and direction (Table 1). Furthermore, the study ensured that the chosen days displayed the "same as usual" indicator on BreezoMeter to use data that represented the actual and prevalent pollution behaviour as usual. By leveraging the collected data, the study comprehensively examined the impact of design dimensions in TOD on the entrapment of PM and the influence of traffic on generating PM.

3.2. Layer II: mapping the road hierarchies in the TOD and calculating the canyon ratio

The second level of the analysis involved mapping the road hierarchies in the two study areas, incorporating data on building height and street width. This facilitated the calculation of the canyon Aspect Ratio (Building Height/Street Width), which was then correlated with PM10/PM2.5 levels along TOD roads (M'Saouri El Bat et al., 2021; Oke, 1981). The goal was to comprehend the influence of street enclosure, specifically the canyon ratio, on PM concentration within the TOD areas.

The study employed ArcGIS Pro to map the road hierarchy within the two TODs, categorising roads into arterial, main, collector, and local (Roh et al., 2017; Tsigdinos et al., 2022). Arterial roads are considered major highways and serve as primary corridors for long-distance travel and connecting major destinations (Goto and Nakamura, 2016). Main roads facilitate travel within cities or towns, linking residential areas, commercial districts, and local destinations (Goto and Nakamura, 2016; Roh et al., 2017). Collector roads act as intermediaries between local streets and main roads, efficiently distributing traffic (Roh et al., 2017). Local roads cater to local traffic needs within residential and small districts, prioritising safety and pedestrian-friendly environments (Roh et al., 2017).

By employing OpenStreetMap (OSM) and GIS mapping techniques, the research systematically mapped the road hierarchy and their associated widths in Manchester's Piccadilly and East Didsbury (Luo et al., 2019). Furthermore, height mapping was executed using high-precision data from the University of Edinburgh's EDINA, particularly the Digimap collection. These datasets offered the base for calculating the canyon aspect ratio, which is determined by averaging the height of both street sides relative to the street width along all roads within both TOD areas (EDINA, 2021).

3.3. Layer III: capturing traffic data for calculating traffic speed

The study utilised UK road statistics to compute traffic volume on the TOD roads, categorising it by vehicle types to two-wheeled motor vehicles, cars and taxis, buses and coaches, Light Goods Vehicles (LGVs), and Heavy Goods Vehicles (HGVs) (DFT, 2022b).

To capture real-time vehicle speeds, the research collaborated with the PTV Group and employed their PTV API, using the Routing API Traffic Mode (PTV, 2023). This API facilitated the monitoring of actual speed data on roads in the two TODs, allowing the retrieval of real-time average speeds for different vehicle types along defined routes (PTV, 2023). The system, responsive to JavaScript requests, provided JSON data, including distance and time information, allowing speed calculation (Chandan et al., 2017). Based on that, the study systematically observed hourly traffic speed, then mapped it on all roads in the study areas using ArcGIS Pro for the two weekdays (Thursday, April 6, 2023, and Tuesday, October 31, 2023) and the two weekends (Saturday, April 29, 2023, and Sunday, October 22, 2023). The selection of April and October, with similar weather conditions, aimed to represent everyday traffic situations, avoiding extreme weather events during winter and summer impacting traffic flow. This approach provided a stable environment for analysing inherent traffic patterns with consistent daylight hours and regular school attendance. Applying the "same as usual" traffic filter on Google Maps also ensured that the selected days represented the usual traffic in the study areas.

By observing hourly traffic speed, the research correlated the Speed with the hourly monitored levels of PM10 and PM2.5, providing valuable insights into the relationship between traffic patterns and particulate matter concentrations in the TOD.

Capturing data on the volume and Speed of each vehicle category on the roads of the two study areas facilitated the research in computing the average Speed for each road. This enabled the establishment of correlations between vehicle speed and particulate matter concentrations (PM10 and PM2.5). The findings aim to provide insights for efficient traffic management in the TOD, specifically addressing particulate matter concerns.

3.4. Data analysis: SPSS correlation analysis

Using SPSS correlational analysis, specifically Pearson Correlation analysis, the research established correlations between PM concentrations, the Canyon Aspect Ratio (CAR), and the relationship between PM and average road speeds in the two study areas. This statistical approach assesses the strength and direction of linear relationships between the continuous variables, yielding a correlation coefficient within the -1 to 1 range to quantify the degree of association (Tarasiuk et al., 2020; Tong et al., 2018). Following data cleansing to remove outliers, the analysis facilitated an understanding the impact of traffic speed and street design on PM10 and PM2.5 levels within TOD, offering valuable insights for the design and traffic management strategies to mitigate PM concentrations in TOD environments.

4. Results and discussion

Monitoring Particulate Matter (PM10 and PM2.5) in Manchester's Piccadilly and East Didsbury areas revealed significant exceedance of the World Health Organization's recommended levels. Notably, PM2.5 levels were higher than their recommended levels compared to PM10, posing a more significant risk due to their greater ability to penetrate the respiratory system deeply.

Data analysis from April and October indicated consistent results, with discernible differences between weekdays and weekends. All Manchester Piccadilly exceeded the WHO recommendations for PM2.5

(15 μg/m^3) on weekdays, ranging from 21.32 to 34.57 μg/m^3. Weekend levels were slightly lower, with 98.89–99.01 % of the area recording PM2.5 readings averaging between 15.11 and 30.34 μg/m^3, surpassing the 15 μg/m^3 WHO threshold.

71.23–72.33 % of Manchester Piccadilly roads experienced high PM10 on weekdays, exceeding the WHO-recommended 45 μg/m^3 level, fluctuating from 45.22 to 62.55 μg/m^3. However, on weekends, 20.21–23.77 % of the area displayed PM10 levels below the WHO threshold, ranging between 45.52 and 60.16 μg/m^3 (Fig. 7).

Similar to Manchester Piccadilly, East Didsbury also experienced elevated levels of PM10 and PM2.5, surpassing the WHO-recommended levels. PM2.5 levels in East Didsbury exceeded the WHO 15 μg/m^3 recommended level, ranging between 33.39–38.27 μg/m^3 on weekdays and 18.12–27.63 μg/m^3 on weekends. Additionally, PM10 levels surpassed the WHO 45 μg/m^3 recommended threshold, ranging between 47.98 and 56.53 μg/m^3. Notably, East Didsbury TOD did not show any high level of PM10 on weekdays, where readings ranged between 25.93 and 40.00 μg/m^3 on weekends (Fig. 8).

Given that the selected days for analysis exhibited nearly similar identical weather conditions, including consistent wind direction, Speed, and temperature (Table 1), the discernible contrast in PM2.5 and PM10 levels between weekdays and weekends in both areas implies the potential impact of traffic-related sources on PM. Weekday observations revealed elevated PM2.5/PM10 levels compared to the lower weekend readings. This discrepancy can be attributed to the heightened impact of traffic emissions during weekdays, arising from a potential increase in both traffic volume and associated emissions. In contrast, weekends showcased decreased PM levels, aligning with the expected reduction in traffic volume during that time. This consistent pattern emphasises the significant role of traffic-related sources in shaping air quality in the analysed regions.

Exceeding the PM readings beyond the WHO thresholds in the study areas emphasises the necessity to delve into the behaviour of PM2.5 and PM10 in relation to street design and traffic movement in the TOD. Understanding how PM levels fluctuate in correlation with canyon aspect ratio and traffic patterns is crucial for informing TOD initiatives

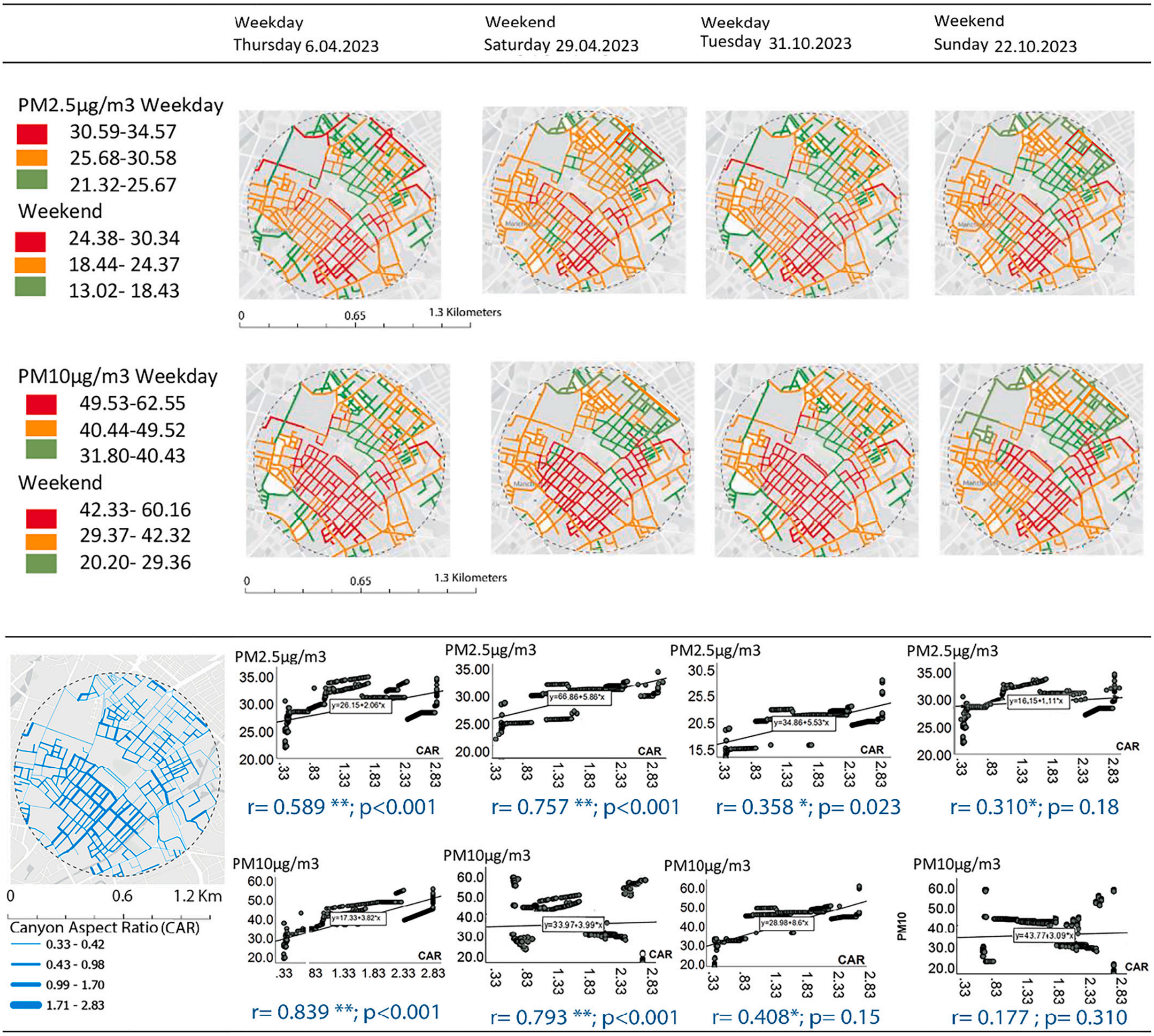


Fig. 7. Mapping CAR, PM10, PM2.5 in Manchester Piccadilly TOD and their correlation analysis.

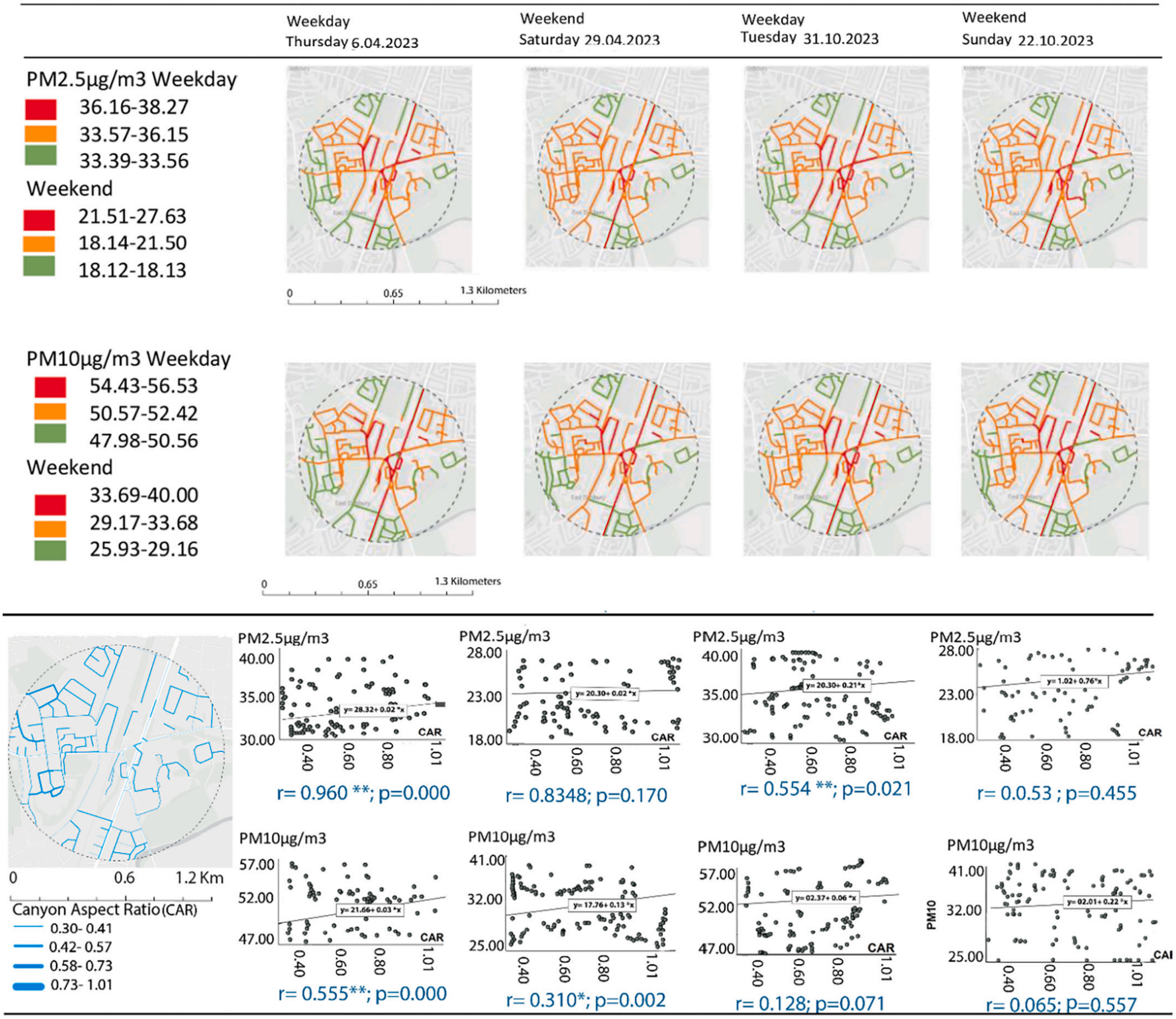


Fig. 8. Mapping CAR, PM10, PM2.5 in East Didsbury TOD and their correlation analysis.

on considering TOD planning and regulating traffic movements for mitigating PM. This is especially important considering that TOD residents residing in areas designed around transport hubs and traffic may be more susceptible to the adverse effects of particulate matter pollutants.

4.1. Canyon aspect ratio (CAR) and PM concentrations

The analysis of PM10 and PM2.5 levels across the road network in the two study areas revealed a noticeable correlation between street canyon aspect ratio (buildings height/street width) and PM concentrations in Manchester Piccadilly and East Didsbury (Figs. 7 and 8).

In Manchester Piccadilly, the results indicated a tendency for PM levels to increase with higher canyon aspect ratios (CAR), signifying taller buildings compared to road width. This positive correlation was statistically significant for PM2.5 levels and CAR throughout the four days of the analysis. As for PM10, the correlation reached significance on three out of the four days, excluding the selected weekend in October, where the association was positive but lacked statistical significance. The significance of the correlations rejected the null hypothesis and suggested a potential link between the canyon ratio and the limited dispersion or generation of PM in Manchester Piccadilly.

East Didsbury displayed a comparable pattern but with a less pronounced correlation. The region showed a noteworthy positive association between PM2.5 and the CAR during the selected weekdays in April and October, whereas no significant correlation was recorded on the weekends chosen for both months. Similarly, the correlation between PM10 and the CAR was positive, with significance observed only on April's analysed weekend and weekday. Conversely, the positive correlation on both the weekend and weekday of October lacked statistical significance.

Compared to East Didsbury, the stronger correlation between CAR and PM concentrations in Manchester Piccadilly could be attributed to the deeper canyons in that area. The consistently noted positive significant correlations in both regions confirm the direct influence of deep canyons in higher densities TOD on the heightened entrapment of PM pollutants.

4.2. Analysing traffic volume and vehicle composition

The analysis of traffic volume, using the 2022 Annual Average Daily Flow data, indicated a higher traffic volume in Manchester Piccadilly compared to East Didsbury (DFT, 2022a). Comparing the annual daily traffic volume in the area showed that Manchester Piccadilly exhibits a traffic volume of 23,679 motor vehicles on arterial roads, 2820 on main roads, 2533 on collector roads, and 1030 on local roads. In contrast, East Didsbury shows a traffic volume of 21,543 motor vehicles on arterial roads, 2343 on main roads, 1733 on collector roads, and 535 on local roads.

Further examination of vehicle types revealed a prevalence of private vehicles, cars, and taxis on the roads in both Manchester Piccadilly and East Didsbury across all four road categories (Fig. 9). In Manchester Piccadilly, cars and taxis constituted 83.083 % of vehicles on arterial roads, declining to 66.49 % on main roads, reducing further to 54.320 % on collector roads, and then rising again to 70.125 % on local roads. On the other side, East Didsbury displayed a significant lack of buses and coaches on its roads across the whole category. The absence of public transportation in East Didsbury was compensated by an increased share of private vehicles. Hence, ED showed a significant presence of cars and taxis, accounting for 74.82 % on collector roads and rising to 86.38 % on arterial roads, with main and local roads exhibiting percentages of 84.34 % and 83.96 %, respectively.

This prevalence of private vehicles on TOD roads and the limited presence of buses and coaches in road traffic, especially in East Didsbury, raise concerns about the effectiveness of the TOD in reducing car dependency and promoting sustainable commuting alternatives like public transportation dependency.

Based on the acquired traffic volume data, the study calculated the

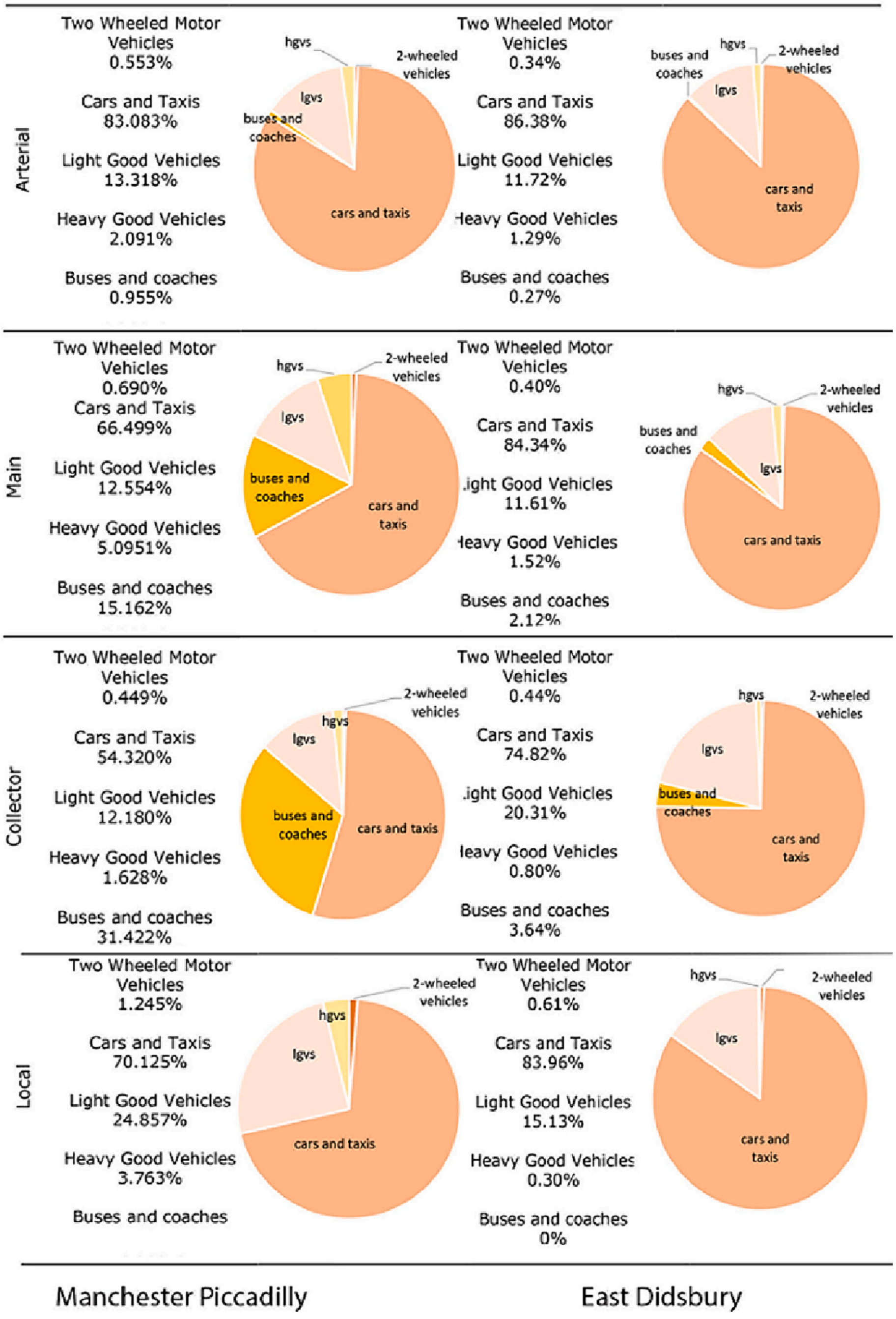


Fig. 9. Traffic volume in the two study areas.

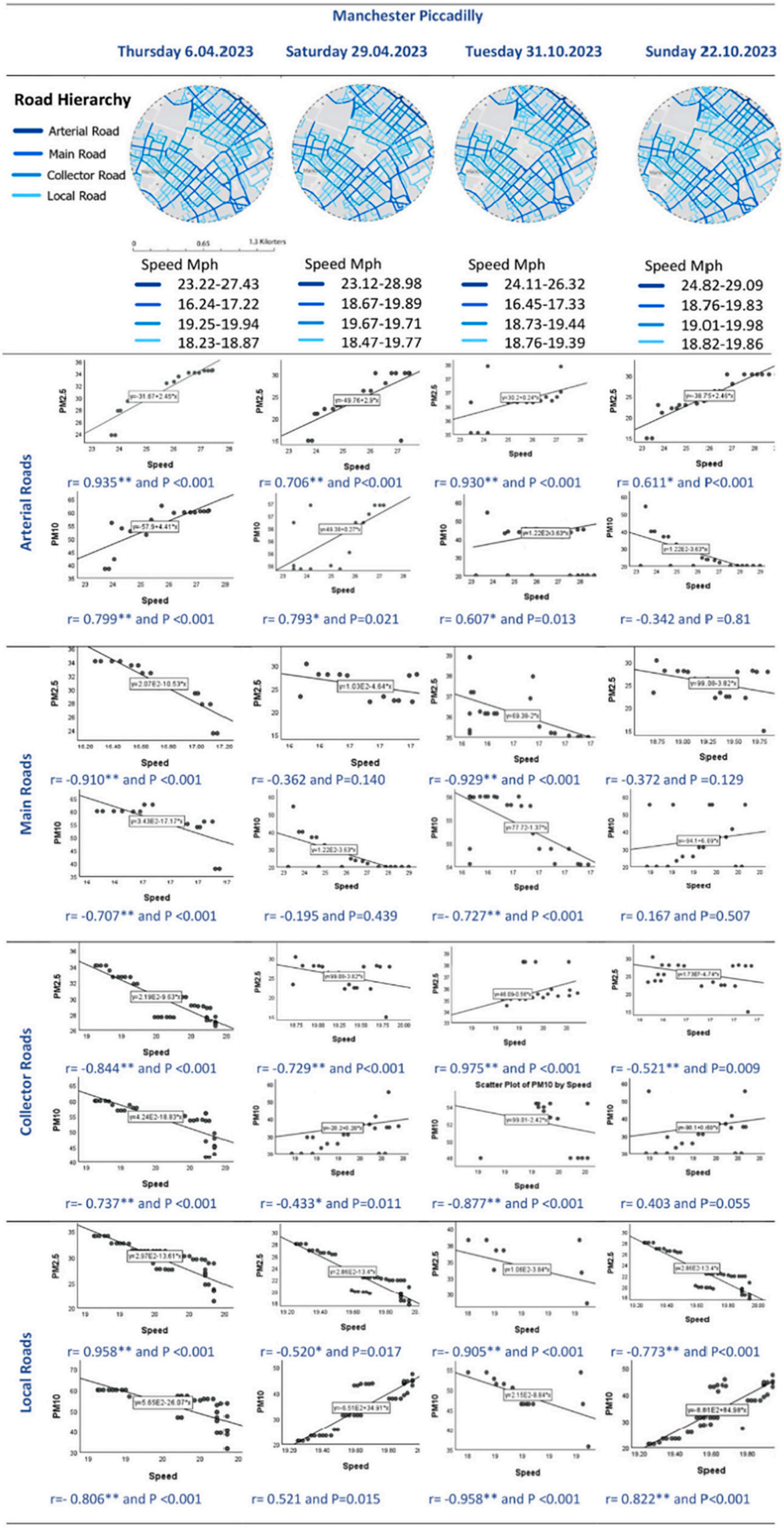


Fig. 10. Speed and particulate matter PM10 and PM2.5 correlations in Manchester Piccadilly TOD.

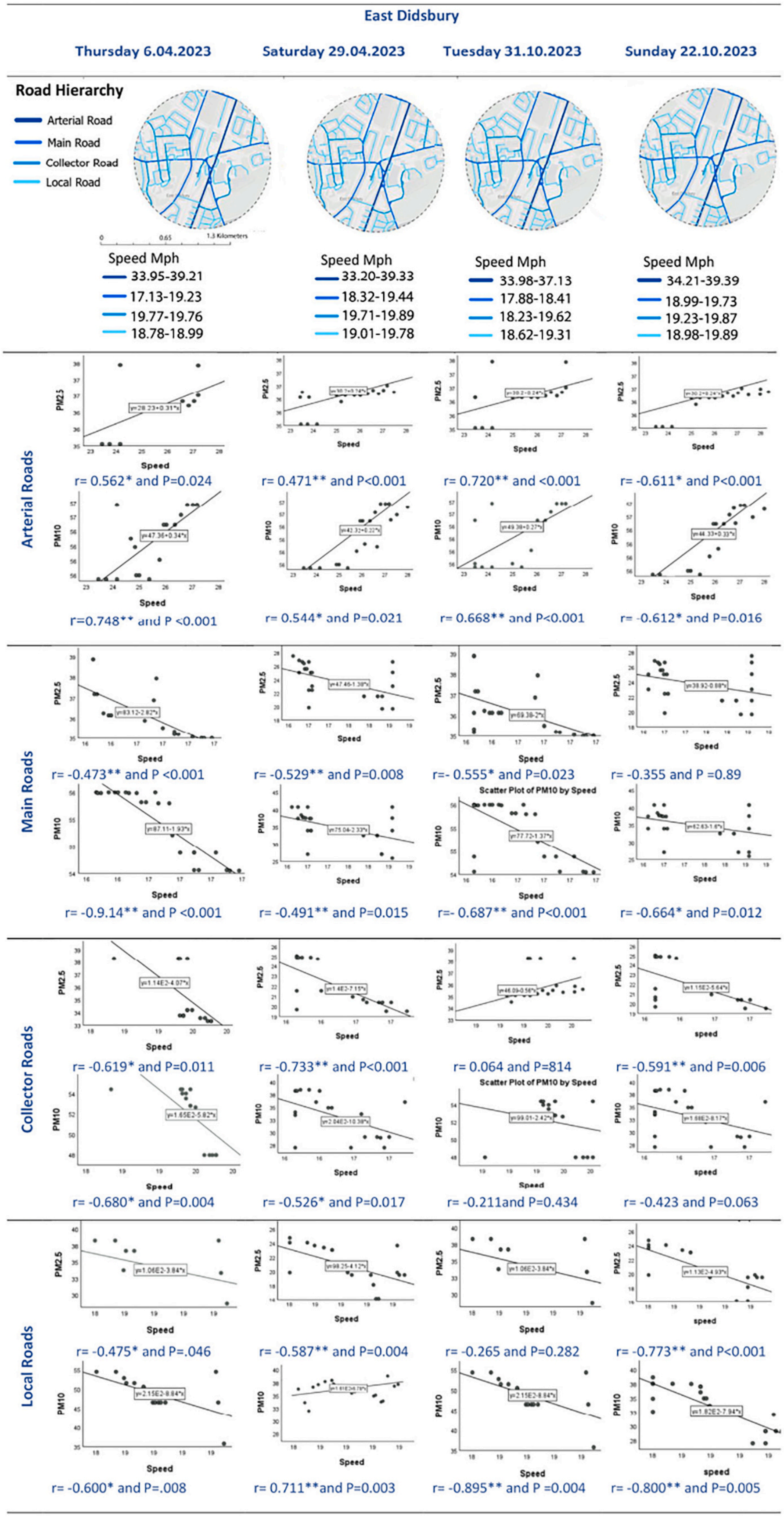


Fig. 11. Speed and particulate matter PM10 and PM2.5 correlations in East Didsbury TOD.

average speed of each road throughout the two areas by considering the actual Speed of each vehicle type and their respective volumes on the streets. This process aided in estimating the overall average speed for each road. The calculation of average speeds for roads in both study areas, coupled with the recorded concentrations of PM10 and PM2.5 on the four selected days, allowed for a comprehensive correlation analysis between road speed and PM2.5/PM10 along each road category of Manchester Piccadilly and East Didsbury.

4.2.1. *Traffic speed and PM on the TOD principal roadways: arterial roads*

In Manchester Piccadilly, the correlation analysis between PM2.5 and Speed on arterial roads over four days revealed a significant positive correlation—indicating that as Speed increased, so did PM2.5 concentrations consistently throughout the four days. Similarly, the correlation between Speed and PM10 exhibited a significant positive trend, except for one weekend day (Sunday, October 222,023), where an insignificant negative correlation was observed. Similarly, in East Didsbury, the correlation analysis mirrored that of Manchester Piccadilly, showcasing a significant positive relationship between PM2.5 and Speed on arterial roads throughout the four days. The PM10 correlation results echoed those of PM2.5, indicating a positive correlation with Speed. This analysis revealed a prevalent positive correlation between Speed and PM2.5/PM10 in the main arteries (Figs. 10 and 11).

4.2.2. *Traffic speed and PM on the TOD internal roads: main, collector, and local roads*

On the other hand, the internal roads, encompassing main, local, and secondary road hierarchies, exhibited diverse responses to PM in both East Didsbury and Manchester Piccadilly (Figs. 10 and 11). This study underscores the complex interplay of factors influencing PM emissions, emphasising the need for an understanding of how different driving scenarios can compromise TOD air quality.

Since the influence of Speed on PM generation is not consistently uniform and usually ascribed to driving behaviour, it is imperative to understand how driving style impacts PM, addressing both exhaust and non-exhaust emissions. Future research should delve specifically into this topic, exploring the impact of driving styles, including acceleration, deceleration, and manoeuvring. Additionally, it should examine how driving behaviour in interactions with other modes of transportation, such as pedestrian networks, cyclists, and public transport, contributes to elevated PM levels in Transit-Oriented Developments (TODs). Addressing these aspects enables a concerted effort to improve air quality in TOD urban areas and formulate effective traffic management strategies to mitigate PM-related traffic issues in TODs.

Across the four days for analysis in both study areas, a consistent negative correlation was observed between PM10/PM2.5 and Speed.

In Manchester Piccadilly, on the main roads, PM2.5 displayed a significant negative correlation throughout the four days. Although weekends also showed negative correlations, they lacked significant correlation. Similarly, on the main roads in Manchester Piccadilly, PM10 exhibited a negative correlation with Speed. Monitored weekdays in April and October displayed significant negative correlations, while weekends on Saturday, April 29, 2023, showed a negative but insignificant correlation, and Sunday, October 22, exhibited a positive and negligible correlation.

In East Didsbury, on the main roads, the correlation between PM2.5 and Speed was consistently negative on the weekdays in April and October and exhibited a significant negative correlation on the weekend in April. However, the correlation was negative but insignificant on the weekend of October. Focusing on PM10 and Speed on East Didsbury main roads, the findings revealed a consistently negative and significant correlation throughout the four days.

The analysis of main roads in Manchester Piccadilly and East Didsbury revealed a consistent negative correlation between vehicle speed and PM10 and PM2.5. This negative association is particularly prominent on weekdays, emphasising the impact of weekday traffic patterns on particulate matter concentrations.

Table 2
Potential impact of speed on traffic-related PM in TOD.

Arteries	**Reasons for heightened PM with high speed**	
	Exhaust emissions sources	**Non-exhaust emissions sources**
	Heightened fuel combustion in vehicle engines emitting VOCs	• Increased tyre abrasion due to heated tyres • Increased road surface abrasion due to higher friction • Air turbulence resuspending of road dust
Main, collector, and local	**Reasons for heightened PM with low speed**	
	Exhaust emissions sources	**Non-exhaust emissions sources**
	Incomplete fuel combustion in vehicle engines emitting VOCs	• Increased braking wear due to repeated stopping • Heightened tyre wear during the abrupt stopping and acceleration

Focusing on the collector roads in Manchester Piccadilly, they exhibited a consistent inverse relationship between PM2.5/PM10 and Speed. Notably, these roads displayed a significant negative correlation between PM2.5 and Speed over the four monitored days, except for a positive insignificant correlation between PM2.5 and Speed on the weekday of October. Additionally, there were significant negative correlations between PM10 and Speed on the selected weekdays in April and October and during the weekend in April. However, the correlation between PM10 and Speed turned positive and insignificant only during the weekend in October. These results showed that decreased Speed on the collector roads in Manchester Piccadilly was highly associated with heightened PM2.5/PM10 levels.

In April, East Didsbury collector roads exhibited a significant negative correlation between both PM2.5/PM10 and Speed on the monitored weekday and weekend. In October, the correlation was negative between PM2.5/PM10 and Speed, but they lacked significance except for a significant negative correlation observed on Sunday, October 22, between PM2.5 and Speed. Only a positive but insignificant correlation between PM10 and Speed on the collector roads of East Didsbury was observed on the analysed weekday of October. These findings indicated a strong association between reduced speeds on the collector roads in East Didsbury and elevated levels of PM2.5/PM10 (Table 2).

Analysing the data and shifting the focus to the local roads around Manchester Piccadilly, a clear and consistent negative correlation emerged between Speed and PM10 as well as PM2.5 over the four days. Notably, this correlation was significant, except for an insignificant positive correlation between PM10 and Speed on April 29, 2023. In contrast, the correlations observed on the local roads of East Didsbury were less significant and less consistent. Specifically, the positively significant correlation between PM10 and Speed emerged on the weekend of Sunday, April 29, 2023, and the insignificant negative correlation was noted on Tuesday, October 31, 2023, between PM2.5 and Speed.

4.2.3. *Comprehending the impact of vehicle speed on the PM levels*

The road speed and PM concentration results suggested that the relationship between vehicle speed and PM is not straightforward and could be influenced by both exhaust and non-exhaust emissions (Table 2). On main arteries, the research revealed a direct correlation between higher vehicular speeds and elevated PM levels, encompassing both PM10 and PM2.5. This observed positive correlation can be ascribed to the effect of higher speeds inducing elevated temperatures in the tyres, consequently leading to intensified tyre wear and road surface abrasion.

In addition, at higher speeds, the fuel combustion is heightened, resulting in increased emissions of pollutants such as volatile organic compounds (VOCs). These VOCs, in turn, contribute to higher concentrations of airborne particulates, reinforcing the argument that higher speeds on arterial roads could escalate PM levels.

Additionally, the more significant air turbulence generated around a moving vehicle at higher speeds can stir up road dust, further contributing to increased particulate matter concentrations. The increased airflow around a moving vehicle can cause the resuspension of particulate matter settled on the road surface. This resuspended particulate matter can then be carried into the air, particularly in the vicinity of the arteries road.

The findings of this paper related to the positive association between PM and Speed on main arteries road align with the results of research funded by the Natural Environment Research Council (NERC) (Bartington and Lacey, 2023), which investigated PM concentrations on Welsh highways and emphasised the link between higher vehicle speeds and elevated PM levels, underscoring the substantial impact of increased Speed on arteries roads on the NEE.

Conversely, lower vehicular speeds, especially inside urban settings with frequent stops, starts, and idling, can unexpectedly increase PM levels. This phenomenon was evident in the observed internal roads within the two TODs, including the main, collector, and local roads. The heightened PM levels on these roads negatively correlated with Speed, suggesting that lower speeds could contribute to increased brake wear and, therefore, PM.

Given the complex dynamics of TOD, which encompasses multiple road intersections catering to diverse transportation modes like cycling, pedestrians, public transportation, and cars, the influence of low speeds on brake wear becomes particularly noteworthy.

Furthermore, tyre abrasion at lower speeds, particularly with stop-and-go driving behaviour, occurs due to the repeated cycles of acceleration and deceleration. As seen in stop-and-go driving, tyres experience increased friction against the road surface during frequent stops and starts. The continuous cycle of bringing the vehicle to a stop and then accelerating again can lead to heightened abrasion on the tyre tread. This process is exacerbated in urban settings of congested traffic conditions where drivers frequently need to stop at intersections or in slow-moving traffic. The repetitive nature of stop-and-go driving, even at lower speeds, contributes to tyre wear and abrasion over time.

Moreover, the idling characteristic of low-speed driving may further intensify the release of exhaust PM, such as VOCs, due to inefficient combustion in the vehicles' engines.

This a study underscores the complex interplay of factors influencing PM emissions, emphasising the need for an understanding of how different driving scenarios can compromise TOD air quality.

Since the influence of Speed on PM generation is not consistently uniform and usually ascribed to driving behaviour, it is imperative to understand how driving style impacts PM, addressing both exhaust and non-exhaust emissions. Future research should delve specifically into this topic, exploring the impact of driving styles, including acceleration, deceleration, and manoeuvring. Additionally, it should examine how driving behaviour in interactions with other modes of transportation, such as pedestrian networks, cyclists, and public transport, contributes to elevated PM levels in Transit-Oriented Developments (TODs). Addressing these aspects enables a concerted effort to improve air quality in TOD urban areas and formulate effective traffic management strategies to mitigate PM-related traffic issues in TODs.

5. Conclusion and recommendations

Manchester Piccadilly, serving as a regional transit-oriented development, distinguishes itself with a more condensed urban structure, a higher level of transportation hub activity, increased traffic, and greater integration of residents, activities, and traffic compared to East Didsbury, a district TOD characterised by medium urban density and a lower scale of public transportation serving the area. These distinctive characteristics significantly influence particulate matter (PM) concentrations and their traffic-related dynamics in TOD.

The analysis revealed that Manchester Piccadilly encompassed spreading roads exhibiting high concentrations of PM10 and PM2.5 that surpass the World Health Organization (WHO) limits, with PM2.5 demonstrating heightened intensity in both Manchester Piccadilly and East Didsbury compared to PM10.

The condensed structure and deeper street canyons of Manchester Piccadilly further contribute to the prolonged retention of PM, as stagnant air circulation is more likely to occur in this condensed area compared to the medium-density TOD of East Didsbury. The positive significant correlation between increased canyon aspect ratio and intensified PM concentrations rejected the null hypothesis and asserted the strong impact of deeper streets on PM retention. This finding underscores the considerable impact of street canyons on the entrapment of pollutants, revealing a crucial aspect of urban design that influences air quality in TODs.

The distinct characteristics of Manchester Piccadilly, marked by high density, taller buildings, and narrower roads, contribute to a more pronounced positive correlation between canyon aspect ratio and PM than East Didsbury. The heightened correlation in Manchester Piccadilly underscored the more significant role of deeper street canyons in the entrapment of PM, emphasising the need for a nuanced understanding of how specific urban features contribute to air quality challenges in different TOD contexts.

Recommendations stemming from this research highlight the importance of considering design dimensions, particularly the canyon aspect ratio, in the planning and development of TODs. Proposing wider roads relative to building height emerges as a practical strategy to mitigate PM concentrations. Therefore, building codes within TODs should include building height and density considerations derived by analysis to enhance air quality and reduce PM concentrations. Additionally, green spaces and vegetation should be incorporated into public spaces, acting as natural filters for particulate matter. By integrating these design considerations, TODs can achieve a balance between urban development and air quality, fostering healthier and more sustainable urban environments.

Given that a substantial portion of particulate matter in urban areas originates from road traffic, comprehending the correlation between PM and traffic patterns, particularly in terms of speed, became crucial. Analysing this correlation during weekends and weekdays showed that lower PM levels were more evident on weekdays compared to ends in both areas. This reduction in PM2.5/PM10 levels on weekends emphasised the association between PM concentrations and traffic intensity, where traffic is potentially higher on weekdays.

In this study, despite various particulate matter (PM) sources discussed in Sections 1.1 and 1.2, significant correlations were observed between total PM concentration and traffic speeds. These correlations highlight the association between traffic-related activities and PM levels in the study areas, offering valuable insights into the impact of vehicular emissions on local air quality.

The analysis showed that arterial roads exhibited a positive correlation, indicating that increased Speed is associated with higher PM levels stemming from the exhaust, such as VOC emissions and from non-exhaust emissions, such as tyre friction and road surface abrasion. Conversely, the correlations between main, collector, and local roads were negative, suggesting that PM10 and PM2.5 concentrations increase as speed decreases. This negative correlation could be influenced by driving behaviours in TODs, including abrupt stops, swift accelerations at intersections, and increased brake wear.

Furthermore, the observed correlations are more pronounced in Manchester Piccadilly compared to East Didsbury, with heightened significance on weekdays compared to weekends. This underscores the impact of traffic intensity on correlation strength, with more integrated traffic patterns in areas like Manchester Piccadilly leading to stronger correlations.

The shift from a positive correlation on arterial roads to a negative correlation on main, collector, and local roads for PM10 and PM2.5 in relation to vehicular speed challenges conventional expectations.

Contrary to conventional expectations, which predict a positive correlation between speed and pollutant levels owing to heightened exhaust emissions at higher speeds, the observed mix of negative and positive correlations between speed and particulate matter (PM) within each road category challenges this assumption. Increased PM levels at high speeds can be attributed to heightened tyre wear, road surface abrasion, and heightened fuel combustion in vehicle engines. Conversely, Elevated PM concentrations at lower speeds are linked to non-exhaust emissions resulting from brake wear and volatile organic compounds (VOCs) emitted during the incomplete combustion of fuel in vehicle engines. Consequently, these findings emphasised a strong association between road speed and traffic-related PM concentrations, highlighting the substantial role played by non-exhaust emissions in addition to exhaust emissions in exacerbating PM in the urban environment.

Hence, comprehensive traffic management strategies should deal with not only exhaust emissions but also non-exhaust emissions, especially those contributing to particulate matter. The streamlined organization of traffic within TODs can minimise the necessity for intersections, alterations in driving patterns, and unnecessary braking and acceleration. Consequently, this approach can mitigate particulate matter originating from non-exhaust emissions, thus alleviating prolonged exposure of TOD residents to elevated PM levels.

Higher TOD density exacerbates traffic integration and worsens the environmental situation, resulting in heightened particulate matter (PM) levels, such as in Manchester Picadilly. Consequently, a more cautious approach is imperative when dealing with higher degrees of TOD, such as centre TOD, where pronounced traffic integration, whether through public transportation or private vehicles, is anticipated. These results advocate for careful consideration and strategic planning when dealing with TODs, particularly in higher-density areas where traffic integration is more pronounced. In addition, Managing TOD should prioritise a sustainable commuting infrastructure that encourages walking and cycling over driving, mitigating environmental impact and fostering healthier and more sustainable living within TOD communities.

The study's findings significantly affect urban planning and air quality management in TODs. Addressing driving behaviours, optimising traffic flow, and considering road design and vehicle types can reduce particulate matter non-exhaust emissions and improve air quality in TOD areas.

6. Limitation and further research

The study's findings offer valuable insights into the relationship between traffic dynamics, street canyon effects, and PM levels within TOD areas; however, some limitations warrant consideration for future research.

1. Limited Duration of Analysis: The study's findings are based on data collected over only four days, comprising two days each in April and October. While these days were chosen to represent variations in traffic and air quality across weekdays and weekends, the narrow timeframe may not fully capture the complexity of traffic patterns and air quality dynamics throughout the year. Future research should extend the analysis to include multiple days across different seasons, accounting for weather conditions and traffic behaviour variations.
2. Limited Scope of Street Canyon Design: While the study examined the impact of street canyons on particulate matter (PM) levels, it did not account for the orientation of these canyons relative to wind direction and urban layout. Future research could incorporate live monitoring of PM levels and utilise simulation modelling techniques to analyse how street canyon orientation influences air pollutant dispersion. Investigating the implications of street canyon orientation on TOD design could provide valuable insights for urban planning and air quality management strategies.
3. Inability to Isolate Traffic-Related PM Levels: While Breezometer provides accurate data on local scales suitable for micro-level analysis, it is crucial to recognise that various sources can influence PM levels both within and outside the study areas. Furthermore, the significant correlations revealed in this study between traffic speed and total PM concentration in the air, the analysis could not extract PM levels specifically attributed to traffic sources. This limitation suggests the need for further research to employ advanced modelling techniques, such as simulating traffic flow considering different vehicle types and emissions profiles. Utilising tools like COPERT, developed by the European Environment Agency, could facilitate the estimation of emissions from road transport, aiding in identifying traffic-related PM levels within TOD areas.
4. Furthermore, while this study focused primarily on traffic-related factors, future research could explore the contributions of non-traffic sources to PM levels, either from traffic or any other sources, in more detail. By incorporating additional data sources and employing advanced modelling techniques, researchers can further elucidate the complex interplay between various emission sources and their respective impacts on PM concentrations.

CRediT authorship contribution statement

Esraa Elmarakby: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Hisham Elkadi:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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