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**Low-Emission Strategies in a vehicular traffic context:
A case study on San Salvario, Turin**

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ABSTRACT

Air pollution is a growing environmental problem, and emissions from vehicular traffic in large cities have a significant impact. Numerous strategies have been implemented in major cities to make urban areas more sustainable and livable. This study focuses on implementing an emission mitigation strategies – a new 30 zone - in Turin, specifically within the San Salvario district. The aim is to evaluate its effectiveness using two different softwares. The COPERT program was used for an initial analysis, using the typical vehicular fleet compositions of the area, while SUMO was used to further investigate the relationship between emissions and driving style, comparing only cars with different fuel and Euro standard. Both of the programs were used to compare a baseline scenario, where vehicles travel at a typical urban speed, with a scenario where speed is reduced to 30 km/h. COPERT's results highlight how speed reduction is not enough to actually reduce emissions; as a matter of fact, the analyzed pollutants show an higher value at a lower speed. This is influenced by the model used by COPERT, that doesn't allow to take into account the precise road configuration in this thesis' case study but employs a generic urban context. In SUMO, instead, it's possible to implement the road network of a specific area, as to analyze the behavior of a vehicle considering every urban element of the analyzed area. The results show that simply reducing speed is not enough to lower traffic emissions, as these are heavily influenced by typical urban factors like braking/acceleration, driving style, and road configuration. Implementing a new 30 Zone can be effective if it promotes a more fluid and less aggressive driving style which in some cases is only possible with an appropriate road configuration.

1. Vehicular Traffic Emissions and Air Pollution

1.1 Problem Overview

One of the main environmental challenges in the context of urban areas is atmospheric pollution. Today, with increasing urbanization and a greater reliance on private transportation, vehicular traffic has become one of the most significant sources of pollutant emissions into the atmosphere. This phenomenon not only affects air quality but also has negative effects on climate and ecosystems, including human health.

Vehicular traffic generates various types of pollutant emissions that can be classified into two main categories: combustion emission and non-exhaust emissions.

1.1.1 Combustion emission

This category of emissions directly results from the exothermic chemical reactions occurring during fuel combustion (gasoline, diesel, gaseous fuels) within the internal combustion engines of vehicles. The main atmospheric pollutants and greenhouse gases generated by this process include:

- **Carbon dioxide (CO₂):** the primary greenhouse gas produced in quantities directly proportional to fuel consumption. According to the European Environment Agency, the transport sector is responsible for approximately a quarter of total CO₂ emissions in Europe, with emissions increasing by 33.5% over the last three decades [1]. Specifically, road transport accounts for 71.7% of the CO₂ emitted into the atmosphere [1].

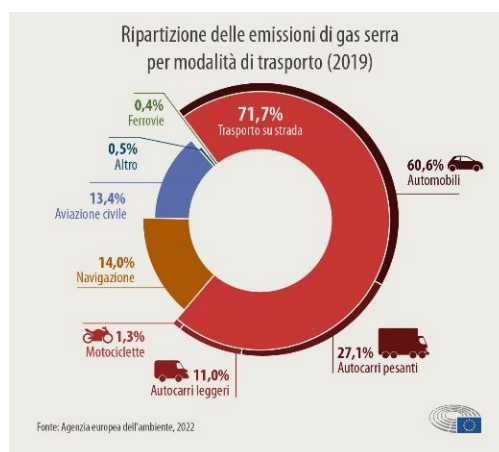


Fig. 1: Sources of traffic pollution in UE, categorized by transport mode [1]

In the graphical representation above, we can find a breakdown of greenhouse gas emissions by transport mode that shows that road transport is the most polluting mode. More specifically, passengers' cars are responsible for the largest share (60,6%), followed by heavy-duty vehicles (27,1%), light-duty vehicles (11%), and motorcycles (1,3%). Maritime and civil aviation complete the ranking, according to estimates from the European Environment Agency [1].

- **Nitrogen oxides (NOx):** they originate from the reaction between nitrogen and oxygen in the air at high temperatures and contribute to the formation of secondary particulate matter and tropospheric ozone. Diesel vehicles, in particular, emit higher levels of nitrogen oxides compared to gasoline-powered vehicles, primarily due to the higher combustion temperatures characteristic of diesel engines [2].
- **Carbon monoxide (CO):** a toxic gas produced by incomplete combustion, more common at low speeds and during engine start-up [3].
- **Unburnt hydrocarbons (VOCs):** precursors of tropospheric ozone.
- **Fine particulate matter (PM10 and PM2.5):** produced by incomplete combustion (especially in diesel engines).

1.1.2 Non-exhaust emission

Urban vehicles can also contribute to increase air pollution through physical and mechanical processes that release particles in the atmosphere. It is in fact possible to refer to a different type of **particulate matter (PM)**, originating from non-exhaust sources such as brake, tire, clutch, and road surface wear, as well as the resuspension of road dust due to vehicle movement [4].

Brake systems, for example, can be composed of various materials, often abrasive in nature to enhance friction. This friction, deliberately induced to enable braking, is considered a primary contributor to the release of particles of varying sizes into the environment. These emissions are particularly concentrated near intersections, traffic lights, and pedestrian crossings [4].

The contribution of brake wear to PM emissions varies significantly depending on the driving environment. In urban areas, where braking events are more frequent and intense, brake wear can account for 16–55% by mass of PM10 emissions, while on highways this figure drops to approximately 3% [4] due to fewer braking opportunities.

Similarly, tire wear is another major contributor to particulate emissions. This wear is mainly caused by shear forces between the tire tread and the road surface [4]. These interactions can alter the chemical

composition of the emitted particles and contribute approximately 5–30% of total non-exhaust PM₁₀ emissions [4]. While larger particles typically remain on the road surface, smaller particles can become airborne and contribute to ambient PM levels [5].

A key factor influencing non-exhaust emissions is the context in which the vehicle operates. In urban environments, such emissions are generally higher due to road designs that necessitate frequent and abrupt braking and acceleration. Moreover, particle generation is influenced by road type [4]: clearly, unpaved roads release more particles than paved roads, but even the material composition of paved surfaces can significantly affect particle generation.

1.2 Environmental and Health Impacts of Pollution

The data on passenger cars relative to demographic size in Italy is consistent with other European Union countries in terms of the number of buses per 1,000 inhabitants, and slightly above the European average for passenger cars, with **600 vehicles per 1,000 inhabitants** [15]. These data confirm the significant presence of vehicles within urban environments, which is closely linked to the increasing emissions of atmospheric pollutants. These pollutants can be classified into local-effect pollutants, such as NO_x, CO, VOCs, and PM, or climate-altering pollutants, such as CO₂. [15]

1.2.1 Consequences on Human Health

Air pollution from road traffic is known to have significantly more detrimental health effects than non-combustion sources [13].

Particulate matter (PM) is a highly heterogeneous mixture of solid and liquid particles that can be directly emitted into the atmosphere (primary particulate matter) or formed through gas-solid reactions in the atmosphere (secondary particulate matter). Its toxicity depends on physical characteristics, particle size, and chemical composition. PM can penetrate the respiratory tract, reaching the bronchiolar epithelium and pulmonary alveoli, where it can enter the bloodstream. More specifically, fine particulate matter is even more toxic because it contains nitrates, sulfates, acids, and metals adsorbed onto their surfaces [14]. Furthermore, these particles can be inhaled more deeply into the lungs, penetrate more easily into indoor environments, and travel over long distances [12].

Children are particularly vulnerable to more serious health issues, as their lungs are still developing and their higher metabolic rate leads to a faster breathing rate [15].

In terms of local-effect pollutants, nitrogen oxides (NO_x) are present initially as NO, which then forms NO₂. Exposure to NO₂ increases the risk of respiratory problems, particularly in children with asthma [14]. Carbon monoxide (CO) is an odorless gas produced by the incomplete combustion of carbon, which can impair oxygen delivery to various organs, including the heart, brain, and other tissues [14].

1.2.2 Environmental Effects

Regarding the spatial scale of traffic and environmental impacts, a distinction can be made between urban and non-urban (or higher) scales. A prevalent local environmental issue is the increasing acidification, which leads to a decline in environmental quality and the degradation of cultural heritage [18].

The increase in NO_x and VOCs and their interactions significantly elevate ozone levels in the atmosphere, as well as acid rain and the deposition of acidic particles over long distances. Photochemical oxidants, such as ozone, impair visibility, cause damage to forest ecosystems, thin-leaved plants, and rubber products, and can severely hinder the growth of certain crops. Acid deposition is linked to widespread forest decline, particularly above the cloud line in temperate regions. It contributes to material corrosion, structural damage to monuments and buildings, degradation of sensitive aquatic ecosystems, and the loss of freshwater fisheries [20].

Carbon dioxide emissions are almost directly proportional to fuel consumption, every kilogram of fuel consumed by a motor vehicle releases approximately **3 kg of carbon dioxide** into the atmosphere [20]. Motor vehicles significantly contribute to CO₂ and CFC emissions, the two primary drivers of the greenhouse effect. Without measures to reduce fossil fuel consumption, the growth in greenhouse gases could result in a global temperature increase of 2°C above pre-industrial levels by 2025 and 4°C by the end of the century [20].

Such a drastic temperature rise would lead to significant and catastrophic phenomena, including rising sea levels causing flooding, changes in water balance and rainfall patterns, more extreme climates, biodiversity loss, and a reduction in food supply. In urban areas, the impact of automotive pollutants on air quality tends to be more pronounced than their share of emissions on a regional or global scale. For instance, in city centers, road traffic accounts for up to 90% to 95% of CO emissions and a major share of particulate matter [20].

The effects of air pollution extend beyond human health and the environment to also affect building materials. The deposition of atmospheric pollutants on surfaces is one of the most significant causes of material degradation [19].

1.3 Current Regulations and Legal Thresholds

In response to the growing concern over air pollution and its adverse impacts on public health and the environment, various international and regional institutions have established regulatory frameworks aimed at monitoring and controlling pollutant concentrations in ambient air. Among the most influential entities in this domain are the European Union (EU) and the World Health Organization (WHO), which have set legal limits and guideline values, respectively, for key pollutants such as particulate matter (PM₁₀ and PM_{2.5}), nitrogen dioxide (NO₂), ozone (O₃), and sulfur dioxide (SO₂).

While the WHO provides scientifically grounded recommendations based on the latest health evidence, the EU enforces binding directives that member states are legally required to comply with. These standards are central to environmental policymaking and play a crucial role in shaping national strategies to mitigate vehicular emissions and improve air quality.

1.3.1 European Emission Standards

The European Union defined vehicle emission standards target air pollution from exhaust gases, brake and tyre abrasion, through a series of directives and limits starting from 1992. These regulating stages known as Euro categories are referred to as Euro 1, Euro 2, Euro3, Euro 4, Euro 5 and Euro 6, aiming to reduce vehicle pollution by imposing limits for different types of pollutants (CO, HC, NOx, PM).

The following is a summary list of the standards which became more strictly over the years [59]:

- **Euro 0 (1992):** These were highly polluting vehicles that used lead gasoline and were not equipped with an exhaust gas filtering system.
- **Euro 1 (1993):** This regulation mandated the use of a catalytic converter in all new vehicles and required the use of unleaded fuel.
- **Euro 2 (1997):** This standard improved control within the catalytic converter, allowing for lower emission limits compared to the Euro 1 class.
- **Euro 3 (2001):** A new homologation test was introduced, and emission levels for hydrocarbons (HC) and nitrogen oxides (NOx) were reduced further from the Euro 2 class.
- **Euro 4 (2006):** This standard brought about additional reductions in emissions compared to Euro 3.
- **Euro 5 (2011):** This class included further NOx reductions for petrol vehicles and a significant reduction in particulate matter compared to previous standards, making the use of a diesel particulate filter (DPF) mandatory.

- **Euro 6 (2015):** While the limits for petrol vehicles remained the same, this standard introduced further reductions for diesel vehicles. Euro 6 vehicles are categorized by their year of registration (2016, 2017-2019, 2020) and fall under different phases of the regulation (Euro 6c, Euro 6d-temp, Euro 6d). Although these phases have the same emission limits, they enforce increasingly strict control procedures and testing conditions.

Under laboratory conditions, a test is performed to ensure that new vehicle models comply with the current Euro standards [79]. If the test is passed, vehicles are approved to be sold in Europe and other countries that adopt the same regulations. However, not all the zones are subjected to the same Euro Standard: there can be some specific areas with higher level of pollution, such as large cities, where is mandatory to circulate with a specific Euro standard vehicle, named Low Emission Zone (LEZ) and differ from city to city, according to the grade of pollution. The standard is also dependent on the fuel type [80], because petrol and diesel vehicles produce different types of emissions.

The positive effect of these standards is certified by numerous studies, for example SMMT registered a -63% and -82% CO reduction in petrol and diesel vehicle respectively since 1993, -84% of NOX since 2001 and -96% in PM since 1993 [80].

1.4 Electric Vehicles as a Sustainable Alternative

At this stage, it is evident that both exhaust and non-exhaust emissions from vehicles represent major contributors to air pollution, with road transport being one of the leading sources of ambient atmospheric contamination. In recent years, this issue has been the focus of increasing political and regulatory attention, aimed at identifying viable solutions that do not compromise the convenience and comfort associated with road-based mobility. One of the most significant developments in this context is the transition to electric vehicles (EVs) as potential replacements for internal combustion engine vehicles (ICEVs), particularly to eliminate tailpipe emissions. However, while EVs eliminate exhaust emissions during operation, they still produce non-exhaust emissions. Therefore, a comprehensive assessment must consider the entire life cycle of electric vehicles in order to accurately evaluate their overall environmental impact.

The study *“Impact of the Spread of Electric and Hydrogen Vehicles on PM10 Concentrations in Emilia-Romagna”* [6] assessed the potential effects of vehicle fleet electrification by comparing a pre-pandemic baseline scenario (2019) with a projected future scenario for 2030. In this future scenario, a significant share of internal combustion engine vehicles (ICEVs) is replaced by battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs). The results indicate a projected 52.4% reduction

in total annual PM₁₀ emissions from exhaust sources by 2030, relative to 2019 levels. However, it is important to note that both the fleet renewal rate and the market penetration of electric propulsion technologies are based on average estimates and subject to uncertainties. While it is reasonable to expect that a newer vehicle fleet will contribute to lower exhaust emissions of particulate matter and other pollutants, similar levels of certainty cannot be applied to projections of non-exhaust emissions, such as those from brake, tire, and road wear.

In general, non-exhaust emissions are strongly influenced by vehicle weight [12] as the magnitude of friction-related forces depends on both the coefficient of friction and the normal force, both of which are directly related to vehicle mass. On average, electric vehicles are approximately 24% heavier than their internal combustion engine counterparts [7]. According to findings by Simons (2013), an increase in vehicle mass of 280 kg leads to an estimated rise in PM₁₀ emissions of 1.1 mg per vehicle-kilometre (mg/vkm) for tire wear, 1.1 mg/vkm for brake wear, and 1.4 mg/vkm for road surface wear. [12]

Comparing the weight and performance of electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) is complex, as EVs often do not align neatly with conventional vehicle categories [8]. Additionally, EVs incorporate unique features not typically found in ICEVs. For instance, EVs use low rolling resistance tires to extend driving range, though there is debate over whether these wear out more quickly or last longer than standard tires. Regenerative braking, another EV-specific technology, significantly reduces brake wear and associated particulate emissions. Various studies estimate reductions in brake wear emissions between 50% and 95%, making regenerative braking an effective strategy that could benefit all vehicle types [9][10][11]

While electric vehicles (EVs) are typically more expensive and heavier than their internal combustion engine (ICEVs) counterparts, which can lead to increased PM emissions from tire, brake, and road abrasion, they still represent an excellent alternative and a viable replacement for an ICEVs fleet.

The primary advantage of EVs is their complete elimination of tailpipe emissions, including major pollutants like CO₂, NO_x, and PM. This makes them a crucial solution for improving urban air quality and significantly reducing the overall environmental impact of transportation. Despite the challenges related to weight and cost, their zero-emission performance in terms of exhaust fumes positions them as a key technology for a more sustainable future.

However, a comprehensive analysis of the sustainability of electric vehicles would require a deeper examination of the entire lifecycle of the car and its components. This topic, while crucial for a complete understanding, falls outside the scope of the present thesis

2. Strategies for Low-Emission Urban Transport

Urban air quality is increasingly compromised by the growing number of vehicles on the road, making transport a major contributor to environmental degradation in cities. In response, promoting sustainable mobility has emerged as a key strategy to balance mobility needs with environmental protection and public health concerns [21].

Governments have responded with a wide range of measures aimed at reducing transport emissions. These include:

- Reducing vehicle numbers and travel distances, for instance by encouraging public transport use and non-motorized travel modes;
- Implementing traffic control through speed regulations, coordinated traffic signals, and optimization;
- Enhancing vehicle energy efficiency, particularly through the adoption of electric and hybrid vehicles;
- Encouraging a shift to alternative fuels;
- Managing motorization more effectively through urban planning and regulation.

In Italy, these strategies have taken shape both nationally and locally. At the national level, eco-incentives support the purchase of low-emission vehicles and the scrapping of older, high-emission models. Locally, cities have implemented different measures [21] such as:

- Paid parking zones (“blue lines”),
- Limited Traffic Zones (ZTLs),
- Low Emission Zones,
- Vehicle restrictions,
- Pedestrianized areas,
- Expanded cycling networks,
- Improved public transport,
- Shared mobility services like bike-sharing and car-sharing.

A key legislative step was the **Ministerial Decree of March 27, 1998**, which mandates municipalities to develop sustainable mobility strategies by reducing reliance on private cars and promoting collective transportation [22].

Yet, despite various interventions, many urban and non-urban areas in Italy continue to fail to meet EU air quality standards. This indicates that regulatory action alone is insufficient. Lasting progress requires pairing regulations with clean, energy-efficient technologies capable of significantly reducing emissions. Additionally, stronger enforcement and expanded incentives are critical to facilitate the transition.

A valuable conceptual model for analyzing sustainable transport strategies is **the AVOID-SHIFT-IMPROVE (ASI) framework**. One of the earliest attempts to apply such a framework was the Environmentally Sustainable Transport (EST) project conducted by the OECD (2000). While pioneering, its general approach proved impractical for real-world application.

To address this gap, the WCTRS SIG11 initiated the CUTE (Comparative study on Urban Transport and the Environment) project. CUTE proposed a two-axis classification matrix for low-carbon transport measures, distinguishing between strategies (e.g., reduce car use) and the instruments used to implement them [46]. These were ultimately condensed into the ASI approach:

- **AVOID:** Reduce the need for motorized travel;
- **SHIFT:** Move travel demand to low-carbon modes;
- **IMPROVE:** Enhance energy efficiency and reduce emissions per kilometer.

AVOID measures are often implemented via land-use planning aimed at creating compact urban forms to reduce unnecessary travel. For instance, in Japan, railway companies have actively developed towns around train lines to both encourage public transit use and reduce urban sprawl [46]. These policies also aim to protect green spaces and improve accessibility to natural areas.

SHIFT strategies aim to reduce car dependency through [46]:

- Improved public transport (though alone it may not fully resolve congestion issues);
- Promotion of active travel modes like cycling and walking, supported by bike-sharing schemes and dedicated infrastructure (e.g., bicycle-parking);
- Traffic control measures, which also support AVOID goals, such as vehicle exclusion zones near public transport hubs, enhancing pedestrian access;
- Economic instruments like road pricing, to internalize the environmental costs of driving.

IMPROVE focuses on technological upgrades and is more dependent on a country's level of development. These strategies include [46]:

- Emission standards for vehicles (e.g., EU's EURO standards and Directive 1999/30/EC);
- Fuel shift from gasoline to electricity and other low-carbon alternatives;
- Deployment of Low-Emission Vehicles (LEVs), including:
 - Hybrid Vehicles (HVs), which reduce gasoline use by combining internal combustion with electric propulsion;
 - Battery Electric Vehicles (BEVs), which eliminate tailpipe emissions entirely.

In Europe, LEV penetration has been supported by zonal access restrictions in city centers, where only vehicles meeting certain emission standards are allowed, such as in Environmental Zones.

The transition toward low-emission urban transport systems requires a comprehensive and multi-dimensional approach. While overarching strategies such as AVOID–SHIFT–IMPROVE provide a useful framework, their practical implementation depends on a variety of policy tools, technological innovations, and urban planning solutions.

In the following paragraphs, there will be analyzed some of the main strategies adopted to reduce atmospheric emissions from road traffic, using as case studies several model cities that have **implemented these strategies and achieved interesting results.**

2.1 Pedestrianized Areas

Pedestrianization involves transforming congested urban areas and streets into zones exclusively for foot traffic. While the primary aim is to **create spaces reserved for pedestrians**, most implementations allow access for emergency vehicles (ambulances, police, fire trucks) to maintain essential services. The specific degree of vehicle restriction often depends on the type and purpose of the pedestrianized area.

This urban planning strategy has been widely adopted by cities globally to tackle a range of transport-related issues. By removing or severely limiting private vehicles, pedestrianization directly contributes to:

- **Reduced Congestion:** Alleviating traffic jams and improving flow in surrounding areas.

- **Enhanced Safety:** Significantly decreasing the incidence of crashes and injuries involving pedestrians and vehicles.
- **Environmental Improvement:** Lowering air and noise pollution levels, leading to a healthier and more pleasant urban environment.
- **Improved Walkability and Liveability:** Encouraging walking and cycling, promoting physical activity, and making cities more attractive and enjoyable for residents and visitors alike.
- **Community Building:** Fostering a greater sense of community by providing public spaces for social interaction and events.

2.1.1 Benefits of Pedestrianization

A core benefit of pedestrianization initiatives lies in their ability to discourage reliance on motorized-vehicle-friendly infrastructure, thereby actively reducing car dependency [47]. A compelling example of this comes from Vienna, where a comprehensive pedestrianization design led to a remarkable 34% growth in railway transport usage and a 53% increase in bus travelers [48].

Beyond shifting transportation modes, pedestrianized zones create safer streets where citizens feel more secure. They also foster greater face-to-face social interactions and communication, transforming public spaces into vibrant community hubs.

Furthermore, pedestrianization offers a low-cost and sustainable approach to heritage preservation. It effectively limits the encroachment of heritage land by parking lots and other transport infrastructure projects like road widening or flyover construction [47].

In addition to heritage preservation, pedestrianization proves highly effective in urban redevelopment. By managing traffic more effectively, the quality of buildings can significantly improve. Planners gain the freedom to focus on the aesthetic design of pedestrian streets without the disruptive presence of heavy motorized traffic. This allows for the revelation of diverse and specific cultural characteristics of pedestrian areas, ultimately enhancing community livability. Reclaimed land can then be repurposed for urban renewal projects, such as parks, public amenities, and community spaces, further enriching the urban fabric.

2.1.2 Environmental Impacts: Chester Case Study

Numerous studies have explored the environmental impacts of pedestrianization, with the majority reporting positive outcomes regarding pollution reduction. A particularly interesting study is the one focused on the city of Chester [49], a historic city in northwest England with a population of approximately 78,000. To assess the impact of pedestrianization, researchers utilized transport models such as SATURN and SATCHMO to estimate traffic characteristics within Chester's road network. Following the implementation of the pedestrianization scheme, traffic was diverted from the newly pedestrianized roads and reassigned across the remaining network.

The simulation of post-pedestrianization traffic conditions involved modifying the road network data file to ensure no motor vehicles would travel on the now-closed roads. Bus routes were also removed from these pedestrianized areas. Subsequently, an emission model was developed to analyze key traffic-related pollutants: CO, HC, NO_x, CO₂, and PM. The results, as shown in the table below, provide a clear picture of environmental changes.

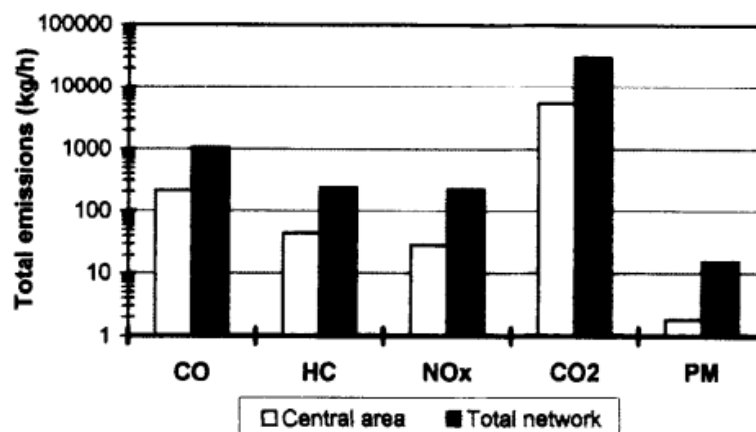


Fig 2: Comparison of emission values in the central area of Chester (pedestrianized area) and the rest of the city [49]

The figure illustrates a clear difference in total exhaust emissions between the central pedestrianized area and the broader urban network. While PM emissions are relatively low (under 2 kg/h in the center, just over 15 kg/h city-wide), CO₂ emissions are significantly higher, exceeding 5300 kg/h in the central area and 30.600 kg/h across the entire network. [49]. (-17.3% CO₂, -10% No_x, -13.3% PM)

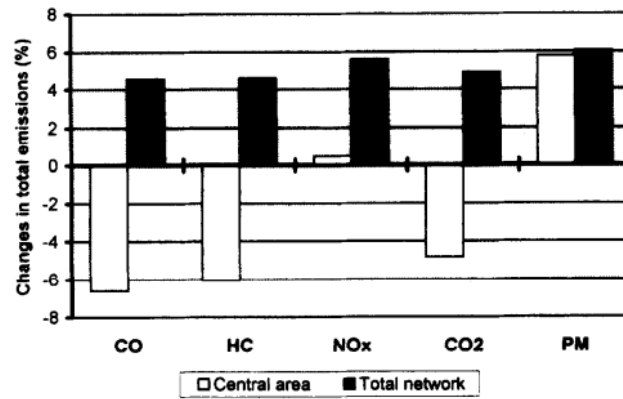


Fig. 3: Percentage changes in total emissions in the central area of Chester (pedestrianized area) and the rest of the city [49]

In general, there is a decreasing trend in terms of emissions after pedestrianization. Although no emissions are produced in the pedestrianized roads, some traffic has been re-diverted to other roads still in the central area and thus contributing to offset the environmental gains which would be obtained within the city centre. However, the apparent increase in average levels of PM concentrations was caused by the re-routing of buses from the roads closed to traffic, which produce large amount of PM non-exhaust emission due to their weight [47].

In addition, the figure below illustrates the percentage changes after pedestrianization for four traffic indicators in the Chester road network:

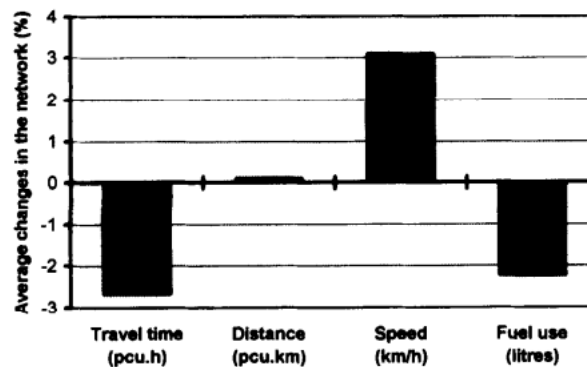


Fig. 4: Percentage changes in travel time, distance, speed and fuel use after pedestrianization [49]

Even with a slight increase in total distance traveled across the network, average traffic speed in Chester improved by about 3%, and total travel time decreased by just under 3%. This indicates freer-flowing traffic. The Chester pedestrianization scheme also yielded economic benefits by reducing overall fuel consumption throughout the network [47].

Furthermore, banning motor vehicles significantly reduces air pollutants, directly benefiting public health by improving lung and respiratory systems. Breathing cleaner air leads to numerous health advantages and offers protection against severe lung diseases.

This is evident from the discussion that Pedestrianization of a street or an area of the city provides multiple benefits across society. Pedestrianization is low cost, high benefit, easy and fast to implement, sustainable and long-lasting solution. As an indirect positive effect, pedestrianized areas become very attractive for bicyclists because of improvement in traffic safety and perceived safety [47].

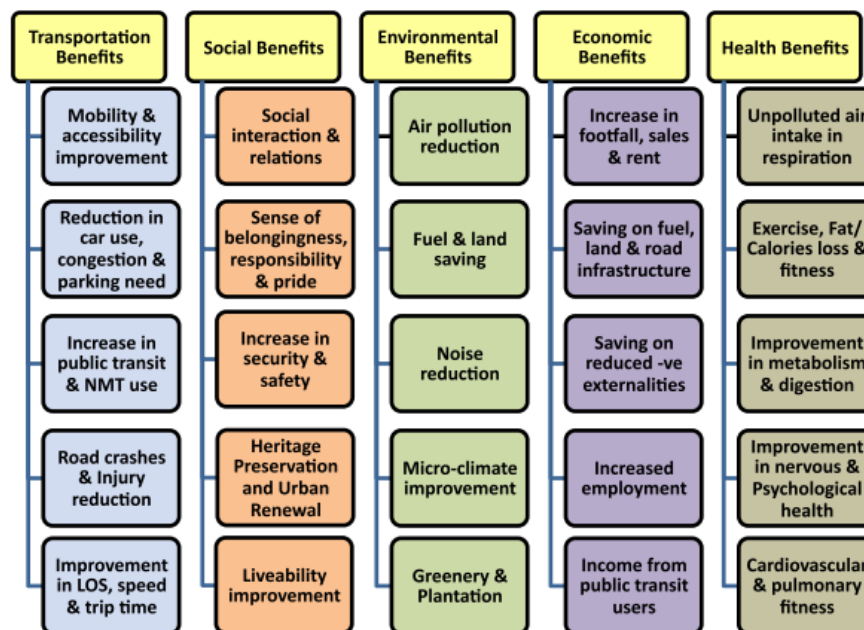


Fig. 4: Benefits of pedestrianization [47]

2.2 Low Emission Zones

Low emission zones (LEZs) are an effective tool for restricting traffic for one or more specific vehicle categories within a defined area. The main difference from a Limited Traffic Zone (ZTL) is that LEZs restrict access based on a vehicle's type and pollution class, unlike a ZTL, which may restrict all vehicles. This strategy is successful because it is accompanied by a gradual increase in newer, less polluting vehicles, and it is a local, city-based measure that is easily adapted to any urban context. In fact, every LEZ implementation is different from city to city, depending on the local context and the available tools.

According to the French Agency for Ecological Transition (ADEME), LEZs accelerate the renewal of the vehicle fleet, which contributes to a greater reduction in air pollution [60]. They also have a positive impact on the climate and, therefore, on the greenhouse effect: CO₂ emissions from London's transport sector plummeted by 13% in just the first six months of the Ultra Low-Emission Zone (ULEZ) operation. Trend analysis shows that concentrations of NO₂ at roadside sites in the central zone in February 2020 are 39 µgm⁻³ less than in February 2017, when changes associated with the ULEZ began. This is a reduction of 44% [61]. Low emission zones also reduce motorized traffic: in London, the ULEZ helped reduce city traffic by between 3% and 9% in 2019 compared to the previous year [61].

The administration also plans to implement a zero-emission zone in central London by 2025, extending it to the city's inner urban belt (Inner London) by 2040 and to the rest of the city by 2050. Furthermore, the City of London produces regular reports on the ULEZ, thanks primarily to the adoption of real-time monitoring technologies (fixed and mobile cameras that read the license plates of vehicles entering the zone). The ULEZ also includes a congestion charge, which varies based on the vehicle's emission type and category, following the "polluter pays" principle [61].

As previously discussed, traffic-related air pollution has significant effects on human health. Consequently, reducing typical road traffic emissions by implementing LEZs also has positive health effects. The health damage caused by road transport has recently been shown to be much higher than initially thought with the Dieselgate scandal revealing the extent of widespread manipulation of car emission limits. Many of the recent cars approved under Euro 6 rules were found to emit up to 13 times the current NO_x legal limit when driven on the road [62].

LEZs were not only considered as the most effective measure in this regard but were also mandated by cost-benefit analyses. In terms of environmental quality, there is a comprehensive body of research that has studied the effectiveness of LEZs, summarized in the following table:

Location(s) of LEZ	Name of the scheme	Reduction of PM10	Reduction of PM2.5	Reduction of NO2 (or NOx if indicated)	Reduction of other pollutants	Remarks on the methodology	Reference (see full reference in annex 1)
5 EU Member States (Denmark, Germany, Netherlands, Italy and UK)	Environmental zones	Reduction of annual mean concentration of up to 7% in German LEZ	-	Reduction of annual mean concentration of up to 4% in German LEZ	Significant reduction of the traffic contribution to BC concentrations (15-17% in London) and total EC concentration (13-16% in Amsterdam, Berlin, Leipzig). Significant reduction of ratio of black carbon to PM10 in Milan.	Review of studies undertaken in 5 Member States. German LEZ found to be more effective in air pollution, probably because light-duty vehicles are also covered.	Holman, Claire, Harrison, Roy, Querol, Xavier, 2015
17 German cities	Environmental zones ('Umweltzonen')	-	-	4%	-	concentrations measured inside and outside LEZs in 17 German cities of 6 federal states (2005–2009)	Morfeld P, Groneberg D. A., Spallek M., 2014
19 German cities	Environmental zones ('Umweltzonen')	<5% at stations near traffic, ≤ 1% at all stations	-	-	-	Data on PM10 concentrations within and outside of LEZs from 19 German cities	Morfeld, P., Groneberg, D. A., Spallek, M., 2014
82 German cities	Environmental zones ('Umweltzonen')	up to 4% in city (up to 8% at stations with highest pollution)	-	-	-	difference-in-differences approach	Gehrsitz, Markus, 2017
137 German cities	Environmental zones ('Umweltzonen')	total reduction of 7.5 micrograms/m3 (stage 1 & stage 2 LEZ)	-	-	-	fixed effects panel data model for daily observations of PM10 concentrations from 2000 to 2009 with control, interaction, for local meteorological conditions and traffic volume	Malina, C. & Scheffler, F., 2015
Amsterdam, NL	Environmental zone ('milieuzone') for heavy-duty only	traffic contribution reduced by 5.8%	-	traffic contribution reduced by 4.9%	Traffic contribution to EC reduced by 12.9%	Analysis of differences between a street frequently used by heavy-duty vehicles and an urban background location	Panteliadis, Pavlos et al., 2014
Berlin, DE	Environmental zones ('Umweltzonen')	3%	-	7-10%	Black Carbon concentration reduced by 15%	analysis of the relative contribution of the source sectors and black carbon data one year after introduction of the LEZ	Lutz, M., 2009
Brussels, BE	LEZ (Zone à basses émissions)	-	6.4% of PM2.5 emitted by light-duty vehicles	4.7% of NOx emitted by light-duty vehicles	no significant reduction in pollutant concentrations	Estimation of traffic emissions based on vehicle fleet observed	Bruxelles Environnement, 2019
					observed yet at official stations	by camera data. Reduction estimated for 6 months of the LEZ equivalent to estimated reduction over 12 months before.	
Leipzig, DE	Environmental zones ('Umweltzonen')	no statistically significant reduction	-	-	decrease in BC and particle number concentration (diameter 50 to 100 nm) in the vicinity of roads	specialized measurements of ambient black carbon (BC) mass concentrations and particle number size distributions	Rasch, F. et al., 2013
Lisbon, PT	LEZ ('Zona de Emissões Reduzidas')	29% (zone 1), 23% (zone 2)	not significant	12% (zone 1), 22% (zone 2)	-	Temporal trends were determined with a linear regression between the annual average concentrations and time).	Santos, M. et al., 2013
Lisbon, PT	LEZ ('Zona de Emissões Reduzidas')	annual average concentration reduced by 23% between 2011 and 2013, reduction significantly stronger inside LEZ	-	annual average concentration reduced by 12% between 2011 and 2013, but no significant difference between inside and outside LEZ	-	Analysis of the air quality data before and after the LEZ phase 2	Ferreira, Francisco et al., 2015
London, UK	toxicity charge	Concentration reduced by 2.46–3.07% compared to just over 1% outside LEZ	-	no discernible differences	-	Evaluation of the introduction of London LEZ by comparing trends inside and outside LEZ	Ellison, R.B., Greaves, Stephen, Hensher, David, 2013
Madrid, ES	LEZ ('Madrid Central') with features of a Zero-Emission Zone (see below)	-	-	Average of official stations shows a 17% reduction vs. previous 9 years. Inside the LEZ, 32% reduction in June 2019 vs. 2018, and 13% compared to years with lowest pollution.	-	Analysis of official data for period since creation of the monitoring network	Ecologistas en Acción, 2019
Milan, IT	LEZ with charge for polluting vehicles in centre ('ecopass zone' that later became Area C)	no significant differences	no significant differences	-	black carbon contribution to PM10 decreased by 47% in the Ecopass zone compared to the no-restriction zone	measuring simultaneously black carbon and PM mass concentrations with fixed monitoring stations	Invernizzi, Giovanni et al., 2011
Munich, DE	Environmental zone ('Umweltzone')	13% at traffic stations (19.6 % in summer, and 6.8 % in winter)	-	-	-	analysis of the routinely collected PM10 mass concentrations data by a semiparametric regression model	Fensterer, Veronika et al., 2014

Fig. 5: Studies on LEZ Effectiveness and Pollutant Reduction [62]

2.2.1 Madrid Case Study

While Low Emission Zones (LEZs) are a valuable tool for reducing traffic emissions, they are not considered a complete solution on their own. However, they represent an important project to consider in the urban redesign of a city aiming to be greener and more sustainable.

This has led to the development of Zero-Emission Zones (ZEZs). These are areas where access is granted only to zero-emission forms of mobility, such as electric cars, buses, and bikes. The European Commission has recognized ZEZs as a powerful tool for achieving air quality improvements [62].

A prime example is Madrid, which introduced the "Madrid Central Scheme" in 2018 to rapidly reduce emissions. The plan combines elements of both an LEZ and a ZEZ. It introduced a phased and location-based ban on vehicles with internal combustion engines, foreseeing a phase-out of diesel vehicles by 2024 and of petrol vehicles by 2030. There is a combination of elements of a LEZ and a ZEZ. Access and parking rights depend on the vehicle's emission class, and cars without a sticker cannot enter the zone. The city provides an "access guarantee" that the center can be reached via public transport, and special parking lots are also made available.

A report analyzing air quality in Madrid shows how the situation in 2019 differed from the years before the implementation of the Madrid Central scheme:

Estación	Promedio 2010-2018	2019	Diferencia	% Variación
Plaza del Carmen	46	36	-10	-22
Tres Olivos	34	25	-9	-26
Cuatro Caminos	46	38	-8	-17
Plaza de Castilla	45	37	-8	-18
Plaza de España	47	40	-7	-15
Ramón y Cajal	46	39	-7	-15
Barrio del Pilar	43	36	-7	-16
Castellana	41	34	-7	-17
Retiro	32	25	-7	-22
Arturo Soria	40	34	-6	-15
Plaza Elíptica	58	53	-5	-9
Urb. Embajada	43	38	-5	-12
Moratalaz	41	36	-5	-12
Méndez Alvaro	39	34	-5	-13
Farolillo	38	33	-5	-13
Escuelas Aguirre	55	51	-4	-7
Vallecas	40	36	-4	-10
Sanchinarro	35	31	-4	-11
Casa Campo	24	20	-4	-17
Villaverde	41	39	-2	-5
El Pardo	18	16	-2	-11
Barajas Pueblo	37	36	-1	-3
Ensanche de Vallecas	36	37	+1	+3
Juan Carlos I	24	26	+2	+8
RED	39	35	-4	-10

Fig. 6: Percentage change in air quality before (2010-2018) and after (2019) the implementation of the Madrid Central Scheme [63]

The table shows the annual average values of **NO₂** recorded between 2010 and 2019 at 24 stations in Madrid's air quality monitoring network. Values exceeding the annual limit of **40 µg/m³ of NO₂** are highlighted in red.

It's immediately clear that the number of stations that exceeded this limit drastically decreased in 2019, falling from 18 in 2010 to just 2 in 2019: the stations of Plaza Elíptica (53 µg/m³) and Escuelas Aguirre (51 µg/m³). The values recorded at all stations in 2019 also show a decrease, confirming the effectiveness of the project implemented by the city [63].

Nevertheless, LEZs can be seen as a necessary but not sufficient measure for addressing air quality and climate challenges. A combination of different initiatives with the same objective is instead more effective, as demonstrated by the case of Madrid.

2.3 The “30 Zones” Project

Sustainable urban mobility, however, is not solely about environmental performance. It also encompasses road safety, public health, the quality and accessibility of public space, and the alleviation of traffic congestion [23]. Urban redesign oriented toward these principles is particularly relevant in cities, which are the main sources and victims of traffic-related emissions. Among the most representative initiatives aligning with these goals is the implementation of “Zone 30” areas. These low-speed zones are designed to calm traffic, enhance safety, improve the quality of urban life, and encourage non-motorized modes of travel.

This type of intervention involves identifying one or more residential neighborhoods that suffer from issues such as traffic congestion, poor spatial quality, and high accident rates, with the goal of redesigning these areas to promote sustainable mobility. The new layout primarily includes reducing motor vehicle speeds to below 30 km/h and reallocating space to create new green areas, pedestrian zones, or cycling paths. This approach aims to enhance the quality of streets as public spaces, as suggested by Italian urban planner Matteo Donde.

Various studies have highlighted a strong correlation between speed limits and air quality. However, it is important to note that vehicle emissions are heavily influenced by multiple factors, including driving behavior and the composition of the vehicle fleet. In fact, reducing the average speed limit from 50 km/h to 30 km/h can lead to significantly different emission outcomes depending on the context [24].

For instance, the following four scenarios illustrate how crucial fleet composition is [24]:

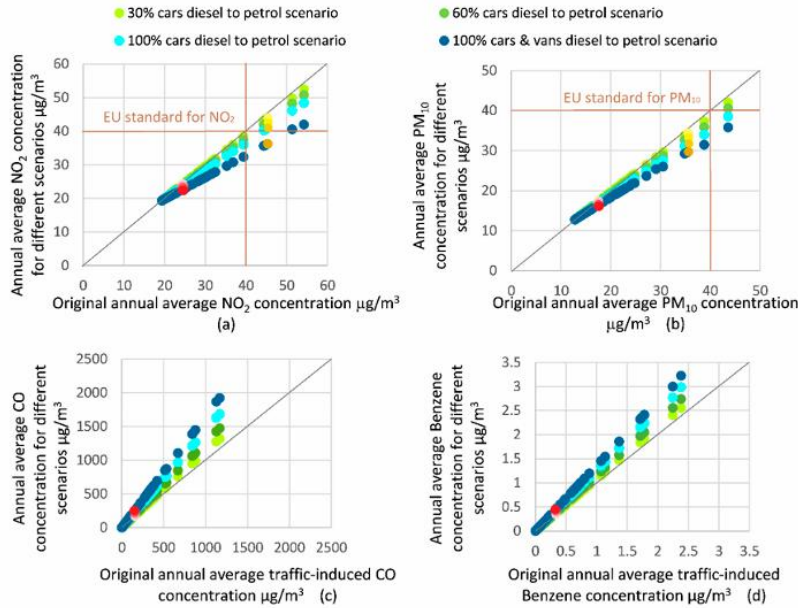


Fig. 7: Annual average pollutants concentration by varying fleet composition [24]

This figure shows that changing the vehicle fleet composition, especially by replacing diesel cars and vans with petrol ones, can significantly reduce NO_2 and PM_{10} concentrations. The reductions reached up to 35% for NO_2 and 28% for PM_{10} on the most polluted streets, particularly where initial levels were highest. In some cases, this shift could bring pollution levels below EU limits. In short, it shows that increasing the proportion of petrol cars and vans would worsen traffic-related CO and Benzene pollution. In fact, replacing all diesel vehicles with petrol could increase CO by up to 65% and Benzene by up to 36%. This is the opposite of what would happen with NO_2 and PM_{10} .

On the other hand, during a complete trip through a city, the resulting total mass of pollutants emitted and the fuel consumed is not only a consequence of the average speed and acceleration, but also of the instantaneous engine conditions, which is a function of the driving style [26]. It is notable that aggressive driving resulted in a sharp increase of fuel consumption and emissions compared to normal driving [26].

To support this claim, an experiment was carried out using a light-duty passenger vehicle (Peugeot 406 2.0 HDI Break), which was driven under three different conditions reflecting distinct driving styles [25]:

- **Aggressive driving pattern**, with high acceleration and deceleration values, but not exceeding the maximum speed.
- **Normal driving pattern** following the surrounding vehicles, maintaining normal smooth accelerations and decelerations when braking.
- **Eco driving**, based on anticipation, regular speed, smooth accelerations and changing gear at low engine speed.

The following figure shows the percentage changes in fuel consumption and emissions of NO_x, CO, HC, and PM when comparing Eco driving and Aggressive driving styles to the Normal driving style:

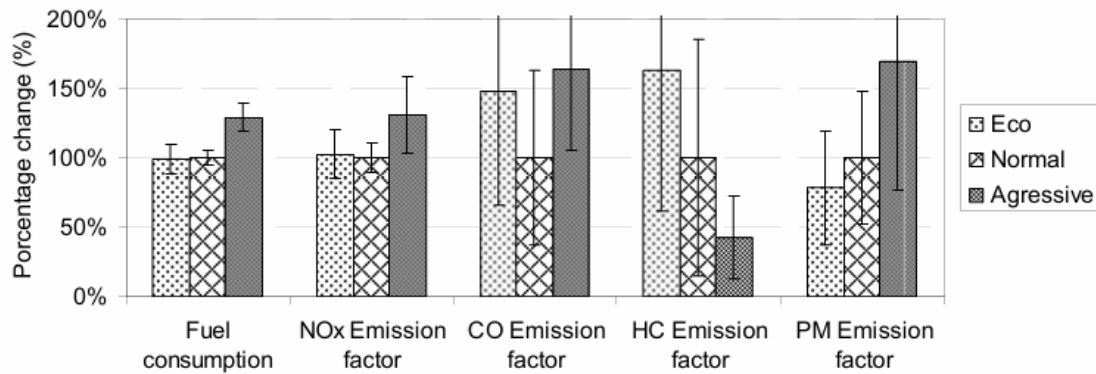


Fig. 8: Percentage changing in fuel consumption and pollutant emissions based on the driving style [25]

The results for fuel consumption and NO_x emissions align with typical vehicle and engine behavior, whereas the trends for other pollutants differ.

CO and HC emissions are higher under Eco driving conditions, likely due to lower oxidation catalyst temperatures, a drop of approximately 10% in average exhaust gas temperature was observed [25]. In contrast, the increase in CO emissions during aggressive driving is attributed to richer fuel/air mixtures during acceleration phases, while the lower HC emissions result from higher catalyst temperatures [25].

PM emissions are largely dependent on engine load, which explains their increase with more aggressive driving, a trend that aligns with expectations. The high variability (standard deviation) in CO, HC, and PM emissions is probably linked to the transient operating conditions of the turbocharger, which deviate significantly from its optimal design parameters [25].

So, in conclusion, this study has shown that lowering the speed limit on narrow, one-lane residential streets in city centers, also significantly reduces fuel consumption and, consequently, greenhouse gas emissions. The study found that emission factors for CO, NO_x, and PM generally decrease when speed limits are reduced from 50 km/h to 30 km/h. However, hydrocarbon (HC) emissions tend to increase under these lower speed conditions. Despite this, the researchers emphasize that in the context of European cities, the most critical pollutants are NO_x and PM, particularly due to the prevalence of diesel-powered vehicles. The study also highlights that driving behavior plays a key role in influencing both fuel consumption and pollutant emissions.

Overall, the findings suggest that implementing 30 km/h speed limits in selected residential areas of large urban centers can provide meaningful environmental benefits, not only by lowering fuel use but also by improving air quality.

Under normal driving behavior and typical traffic conditions, city routes were found to have the highest fuel consumption and emission levels, while ring roads and motorways showed the lowest values. In fact, fuel consumption in urban traffic was observed to be twice as high [26], demonstrating how road type also significantly impacts both fuel use and emissions.

This highlights the relevance of the "Zone 30" project, which involves redesigning urban areas to feature lower speed limits and improved street layouts. Such interventions are intended to encourage more sustainable driving behavior, characterized by fewer abrupt accelerations or braking and more consistent speeds. However, for this strategy to be truly effective, it should be accompanied by the selection of an appropriate vehicle fleet, one that is specifically chosen to further reduce emissions.

2.3.1 Road Safety

The health impacts of traffic emissions resulting from speed limit reductions should also be considered. Speed is the leading cause of fatal accidents in Italy, and 74% of all crashes occur on urban roads [32][33].

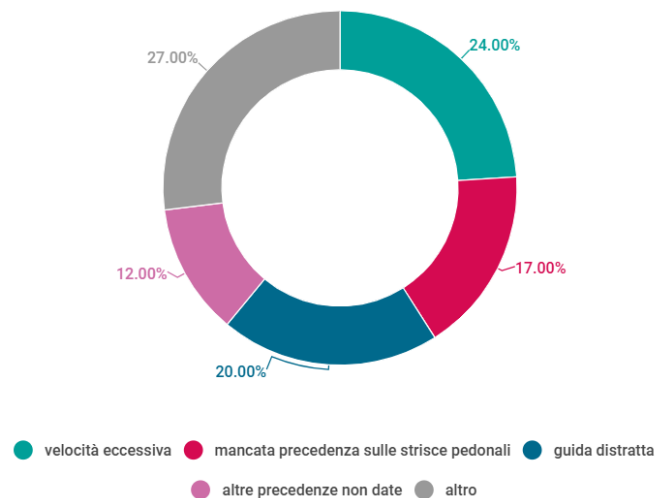


Fig. 9: Major causes of road accidents in Italy [32]

Speed reduction is effective because it decreases a vehicle's braking distance, thereby lowering the likelihood of death or serious injury by reducing the force of impact. The risk of dying when hit by a vehicle traveling at 30 km/h is around 10%, whereas at 50 km/h, that risk increases to over 80% [34]. Lower speeds also result in shorter stopping distances and provide drivers with a wider and safer field of vision.

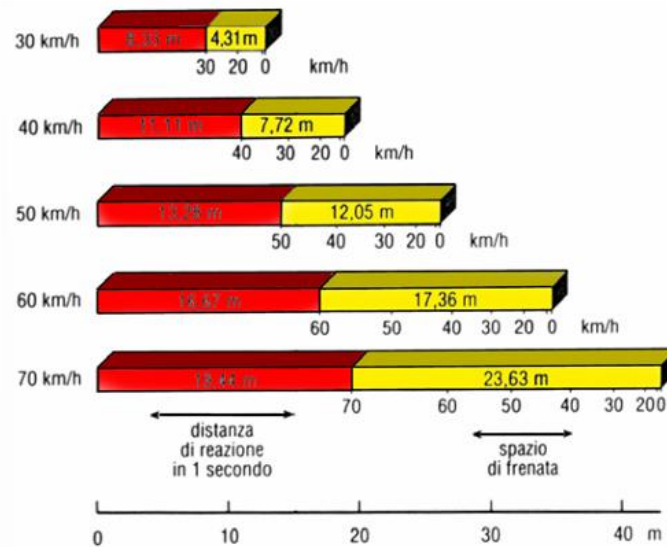


Fig. 10: Reaction and braking distances as a function of vehicle speed [31]

As illustrated in the image above, the **reaction distance** at a speed of 30 km/h is significantly shorter than at 50 km/h, and this trend continues at all higher speeds. The same is true for the **braking distance**. In the context of road accidents, these two parameters are crucial in determining the severity of an impact. Therefore, for greater safety, it is essential to minimize these distances as much as possible.

Generally, the implementation of the "30 km/h zones" project in major cities aims to reduce crash risk, create safer streets for pedestrians and cyclists, and promote a more sustainable, community-friendly approach to transportation. Evidence from several large European cities indicates that road safety has significantly improved following the adoption of such measures.

In Brussels, Belgium, five months after the introduction of the general 30 km/h speed limit, the total number of road crashes decreased by 10%, from 708 in the last quarter of 2020 to 635 in the first quarter of 2021. Additionally, there was a 37% reduction in serious injuries, dropping from 46 in the first quarter of 2020 to 30 in the same period of 2021 [27].

Similarly, in Paris, France, speed limits were reduced to 30 km/h on 60% of the city's roads starting in August 2021. Several months later, this measure led to a 25% decrease in bodily injuries and a 40% reduction in serious and fatal crashes [28].

In Italy, a leading example is Bologna, where a 30 km/h speed limit was introduced in July 2023. Just three months after implementation, road crashes declined by 14.5% compared to the same period the previous year. This included a 13.4% reduction in crashes involving injuries and a 17% decrease in crashes without injuries. Notably, the number of fatal accidents dropped from 3 to 1 [29].

These examples illustrate a clear downward trend in the number of road crashes, fatalities, and injuries, highlighting the positive safety impact of reduced vehicle speeds. Furthermore, these improvements are often closely linked to urban redesign efforts that allocate more space to pedestrians and cyclists.

2.3.2 Health and Livability

Driving at lower speeds promotes healthier and more livable communities. Safer streets encourage children to walk and engage with their neighbors more confidently, while also increasing opportunities for social interaction [30]. Urban roads are not just spaces for mobility; they are also vital components of the public realm where people meet and interact [31].

Lower speed limits also encourage more people to walk or cycle, which in turn helps reduce air pollution. In Graz, Austria, one of the main objectives of reducing the speed limit from 50 to 30 km/h was to decrease car dependency and promote cycling. After the introduction of the 30 km/h limit, over 16% of trips were made by bicycle.

This shift is supported by a **redesign of public space**: reducing the area allocated to vehicles, eliminating architectural barriers, widening sidewalks, and adding urban furniture [34]. These changes help foster the coexistence of mobility and quality of life.

At the same time, noise pollution is significantly reduced, by 3 to 5 decibels in urban areas [35], thanks to lower engine noise and reduced tire-road interaction at slower speeds [36].

2.3.3 Traffic Volume

It might seem intuitive to assume that reducing speed limits would lead to longer travel times and increased congestion on main roads. However, it is important to clarify that lower speed limits can influence road users to choose alternative routes or modes of transportation, significantly impacting overall traffic volumes [30]. This has been observed in Amsterdam, where a notable shift from car use to cycling has taken place following such measures.

According to Ramboll [35], travel time is more influenced by factors like **traffic congestion, road design, and geometric layout than by speed limits themselves**. Moreover, the average speed also varies depending on the type of road intervention: roads with only informational measures showed a smaller reduction compared to those with more 'suggestive' measures. [39].

In Bilbao, a survey revealed that groups initially most resistant to the changes, such as business owners, delivery drivers, and taxi drivers, later reported improvements in traffic flow and noted that the lower speed limit did not negatively affect their operations. Additionally, following the citywide implementation of the 30 km/h limit, a 2% decrease in traffic volume was observed [30].

In Brussels, journey times were analyzed over a four-week period before Christmas 2020 and again before Christmas 2021. The results showed only a minimal increase of 10–15 seconds for trips between 5 and 10 km, suggesting that traffic flow became more consistent, effectively compensating for the reduced speed limit [37].

A study by *Nightingale et al.* (2021) in the city of Edinburgh found a 2.4% decrease in traffic volume on both main and residential roads. The reduction in average speeds remained consistent throughout the week and across different times of day, except during nighttime hours (01:00–06:00), when lighter traffic led to slightly higher average speeds [38].

Similarly, the introduction of 30 km/h speed limits in the Netherlands contributed to a 5–30% reduction in traffic volumes, depending on the area [39].

In conclusion, based on the various studies, it can be said that there is no significant change in travel times with an increase in the number of 30 km/h zones in urban areas. One possible reason for this is that at lower speeds, and with appropriate road design that reduces start-and-stop situations, vehicles can flow more smoothly with fewer interruptions, making traffic more fluid.

2.3.4 Environmental Effects

The impact of speed on vehicle emissions is subject to **varying perspectives**. In general, it is highly dependent on factors such as the type of pollutant, engine or vehicle technology, as well as vehicle age and weight [40]. Numerous studies have investigated this relationship, yielding heterogeneous results. These variations often stem from differences in the spatial scale of analysis, whether at a local/site-specific level or a broader city-wide scale, as well as the emission modeling approaches, and traffic simulation methods employed [40]. This analysis refers to the study '*Review of City-Wide 30 km/h Speed Limit Benefits in Europe*', which examined 40 European cities that have implemented 30 km/h zone policies, as it's possible to visualize from the image below:

A/A	City	Implementation Started	A/A	City	Implementation Started
40	Amsterdam	December 2023	20	Lille	August 2019
39	Wales	September 2023	19	Helsinki	May 2019
38	Bologna	July 2023	18	Madrid	September 2018
37	Florence	November 2022	17	Bilbao	June 2018
36	Copenhagen	June 2022	16	Strasbourg	February 2017
35	Lyon	March 2022	15	Dublin	January 2017
34	Den Haag	December 2021	14	Berlin	January 2017
33	Zurich	December 2021	13	Edinburgh	July 2016
32	Toulouse	November 2021	12	London	June 2016
31	Vienna	September 2021	11	Grenoble	January 2016
30	Paris	August 2021	10	Ljubljana	September 2015
29	Montpellier	August 2021	9	Luxembourg	August 2015
28	Münster	July 2021	8	Ghent	April 2015
27	Valencia	May 2021	7	Bristol	2015
26	Leuven	April 2021	6	Munich	2011
25	Brussels	January 2021	5	Brighton	2010
24	Nantes	August 2020	4	Hove	2010
23	Glasgow	January 2020	3	Warrington	July 2005
22	Antwerp	January 2020	2	Stockholm	2004
21	Barcelona	December 2019	1	Graz	September 1992

Fig. 11: List of 40 European cities that have implemented the 30 Zone model [40]

Among these cities, 8 are in France, 7 in the United Kingdom, 4 in both Belgium and Spain, 3 in Germany, 2 each in Austria, Italy, and the Netherlands, and finally, 1 city each in Denmark, Finland, Ireland, Luxembourg, Scotland, Slovenia, Sweden, and Switzerland. The following chart summarizes the main target goals achieved by these cities:

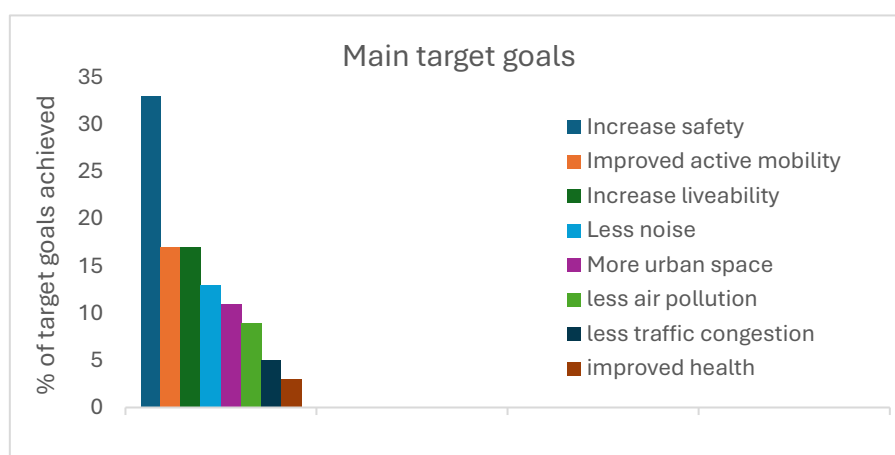


Fig. 12: Main target goals achieved by these cities after the “30 Zone” model implementation

As observed, most of these cities identified increased **traffic safety** as the primary objective behind reducing speed limits. A significant proportion, 35% of the cities (14 out of 40), also cited noise reduction as a key motivation. In contrast, only 11 out of 40 cities adopted this measure specifically to address air pollution. Moreover, promoting the use of active or alternative modes of transport was mentioned by 18 cities, while improving the quality of public space was a goal in 10 cases. Eighteen cities also highlighted objectives such as enhancing livability, improving urban friendliness, or increasing overall quality of life.

Notably, improved public health was only referenced by Barcelona, Bilbao, and Wales, and primarily as a secondary benefit linked to noise reduction and increased active mobility.

Only five cities, Amsterdam, Berlin, Copenhagen, Florence, and Lille, mentioned reducing car use and alleviating traffic congestion as a motivation, though not as a primary one but rather as a desirable side effect. It is also noteworthy that objectives such as improving child play opportunities or independence, and enhancing social interaction, social cohesion, or perceived safety were not cited as immediate reasons for implementation.

There is a lack of precise, city-wide data on air pollution reduction as a direct result of speed limit reductions. However, in general terms, cities that explicitly monitored this parameter reported a downward trend, as exemplified by Münster. Bilbao recorded a 19% reduction in atmospheric levels of CO₂, NO_x, and PM, while Berlin reported a 29% decrease, London 10%, Edinburgh 8%, and Graz 25% [40]. These outcomes are heavily influenced by city-specific factors such as the structure of the urban road network, the composition of the vehicle fleet, and local driving behavior.

Indeed, each of the 40 European cities analyzed varied in size and characteristics, with differences in the extent of the 30 km/h zones (e.g., 75% of the road network, 65% of urban streets, or only the city center), population size, and implementation timelines.

For example, Berlin converted five major roads into 30 km/h zones and recorded the highest reduction in emissions among the studied cities, whereas Graz, despite applying the policy to 80% of the road network excluding major roads, reported lower reductions.

It is also possible for pollutant levels to increase following a reduction in speed limits, depending on local conditions. In Budapest, for instance, a simulation study suggested that levels of CO₂, NO_x, and hydrocarbons (HC) could rise due to longer idling times at traffic signals caused by lower average speeds. This results in increased stop-and-go conditions, which in turn lead to more frequent acceleration events and higher emissions [42].

However, these latter findings did not account for road redesign strategies specifically aimed at minimizing unnecessary braking and acceleration. When roads are properly reconfigured to support smoother traffic flow and constant speeds, **drivers are encouraged to adopt a more sustainable driving style**, mitigating potential increases in emissions.

The following table summarizes the benefits in terms of safety, environmental and traffic of the cited-above study, considering all the 40 cities analyzed.

No	City	Safety			Environment		Traffic
		Crashes	Fatalities	Injuries	CO ₂ , NO _x , PM	Noise	Congestion
40	Amsterdam						
39	Wales						
38	Bologna	–14.5%					
37	Florence						
36	Copenhagen						
35	Lyon	–22%		–40%			
34	Den Haag						
33	Zurich	–16%	–25%	–20%		–1.7 dB	
32	Toulouse						
31	Vienna						
30	Paris	–40%		–25%		–3 dB	
29	Montpellier						
28	Münster			–72%	↓	↓	
27	Valencia						
26	Leuven						
25	Brussels	–10%	–55%	–37%		–2.5 dB	
24	Nantes						
23	Glasgow		–31%				
22	Antwerp						
21	Barcelona						
20	Lille						
19	Helsinki	–9%		–42%			
18	Madrid						
17	Bilbao	–28%			–19%		–2%

No	City	Safety			Environment		Traffic
		Crashes	Fatalities	Injuries	CO ₂ , NO _x , PM	Noise	Congestion
16	Strasbourg						
15	Dublin						
14	Berlin	–10%			–29%	–3 dB	
13	London	–46%	–25%	–25%	–10%		
12	Grenoble	–30%	–20%	–50%			–9%
11	Ljubljana						
10	Luxembourg	↓					
9	Ghent						
8	Edinburgh	–38%	–23%	–33%	–8%		–2.4%
7	Bristol		–63%				
6	Munich						
5	Brighton			–45%			
4	Hove			–45%			
3	Warrington			–43%			
2	Stockholm						
1	Graz	–12%		–20%	–25%	–2.5 dB	

Fig. 13: Registered benefits in terms of safety, environmental and traffic for the 40 European cities analyzed [40]

2.4 Expanded Cycling Networks

Another useful strategy to overcome urban environment pollution problems, it's represented by the **promoting mode shift to cycling transport**, which is a completely non-emitted mode of transport that provides also positive effects on human health. Well-designed increased cycling lanes and paths make cycling more attractive to non-cyclists, even if there is no any rigorous statistical studies that demonstrated their impact on cycling. For example, Lansing et al. [55] examined bicycle use by school children in new communities with varying levels of bicycle paths and found that as paths increased so did school children's use of them, from a 22% of children to 29% and 49% with one and two paths more, respectively.

Nelson et al. [56] published a study examining the link between the availability of cycling infrastructure and the adoption of cycling as a daily mode of transport in U.S. cities. The authors conducted a cross-sectional analysis using data from 18 U.S. cities, controlling for various factors such as climate, topography, and the presence of university students. They investigated the correlation between kilometers of cycling infrastructure per 100,000 inhabitants and the percentage of commuters who cycle. The results revealed a significant positive correlation, suggesting that **a greater availability of cycling infrastructure is associated with a higher percentage of cycling commuters**. However, the authors emphasized that while the provision of cycling infrastructure is an important factor, other elements such as perceived safety, the continuity of cycling networks, and cycling culture in different cities play a crucial role in the effectiveness of such interventions. Nevertheless, they conclude that it serves as a good starting point for promoting a sustainable transport strategy.

Subsequently, a further study [50] is analyzed, which aims to examine various European cities that possess significant potential to increase their cycling mode share. The cities with the largest standardized cycling network lengths are Örebro and Antwerp, followed by urban centers such as Vienna, Zurich, London, Barcelona, and Rome.

Demographic and transport data				Mode share data															
				Car				Public transport				Bicycle				Walking			
City	Population	Trips/day	Trips/ person/day	%	Persons/day	Mean distance (km)	Mean time(h)	%	Persons/day	Mean distance (km)	Mean time (h)	%	Persons/day	Mean distance (km)	Mean time (h)	%	Persons/day	Mean distance (km)	Mean time (h)
Antwerp ^a	493,517	1,362,107	2.8	41	202,342	11.81	0.30	16	78,963	9.81	0.57	23	113,509	3.84	0.24	20	98,703	1.31	0.35
Barcelona ^b	1,620,943	4,908,402	3.7	26	344,915	8.77	0.43	40	530,638	6.71	0.55	2	26,532	3.50	0.27	32	424,510	1.35	0.27
London ^c	8,673,713	19,740,640	2.5	38	2,980,311	7.00	0.38	29	2,274,448	7.00	0.75	3	235,288	3.00	0.38	30	2,352,877	1.00	0.27
Örebro ^d	138,952	276,000	2.6	55	58,385	7.90	0.30	9	9,554	10.00	0.62	25	26,538	3.30	0.27	11	11,677	1.20	0.25
Rome ^e	2,869,461	4,900,000	2.6	54	1,017,692	13.00	0.73	29	546,538	11.50	0.82	1	18,846	7.70	0.40	16	301,538	1.35	0.27
Vienna ^f	1,797,337	4,251,000	3.4	27	340,585	12.00	0.40	39	491,955	8.20	0.47	6	75,685	3.30	0.31	28	353,199	1.00	0.25
Zurich ^g	410,404	1,559,535	3.8	30	123,121	5.27	0.31	39	160,058	7.84	0.52	4	16,416	2.77	0.24	27	110,809	1.13	0.27

Fig. 14: Demographic, transport and mode share data of the cities with the largest standardized cycling network lengths [50]

The table above shows the current situation of the cities taken as case-studies in terms of demographic, transport and mode share data.

In Figure 15, the possible situation is represented due to the implementation of four different scenarios based on different proportional increases of the cycling networks, until a S4 scenario which considers the involvement of all streets.

It's possible to observe that **an increasing number of cycling km is translated into a decrease in car and public transport mode share**. Since cycling is a zero net source of emissions in terms of transport modality, the reduction in car and public transport use brings a decrease in terms of traffic emissions.

In addition, the same study talked about the net health benefits resulted due to this strategy with over 10,000 premature deaths due to traffic incidents avoidable in all 167 cities [50], because of the increased number of networks exclusively dedicated to cyclist and the reduction in car dependence.

City	Mode share				Cycling network	
	Car (%)	Public transport (%)	Cycling (%)	Walking (%)	Cycling km	Cycling km/100,000 persons
Antwerp (baseline)	41.00	16.00	23.00	20.00	469.17	95.07
S1 10%	41.67	18.02	20.31	20.00	516.09	104.57
S2 50%	41.02	16.05	22.93	20.00	703.76	142.60
S3 100%	40.71	15.12	24.18	20.00	938.34	190.13
S4 all-streets	40.57	14.70	24.74	20.00	1,651.74	334.69
Barcelona (baseline)	26.00	40.00	2.00	32.00	159.54	9.84
S1 10%	25.73	39.18	3.09	32.00	175.49	10.83
S2 50%	25.56	38.68	3.76	32.00	239.31	14.76
S3 100%	25.33	37.99	4.68	32.00	319.08	19.68
S4 all-streets	21.68	27.03	19.30	32.00	1,554.56	95.90
London (baseline)	38.00	29.00	3.00	30.00	969.17	11.17
S1 10%	37.92	28.76	3.32	30.00	1,066.09	12.29
S2 50%	37.72	28.16	4.12	30.00	1,453.76	16.76
S3 100%	37.45	27.34	5.21	30.00	1,938.34	22.35
S4 all-streets	32.70	13.09	24.21	30.00	1,6439.74	189.54
Örebro (baseline)	55.00	9.00	25.00	11.00	361.35	260.05
S1 10%	55.08	9.23	24.69	11.00	397.49	286.06
S2 50%	55.07	9.20	24.74	11.00	542.03	390.08
S3 100%	55.07	9.20	24.74	11.00	722.70	520.11
S4 all-streets	55.07	9.20	24.74	11.00	3,045.27	2,191.60
Rome (baseline)	54.00	29.00	1.00	16.00	120.64	4.20
S1 10%	53.71	28.12	2.17	16.00	132.70	4.62
S2 50%	53.65	27.95	2.40	16.00	180.96	6.31
S3 100%	53.57	27.72	2.71	16.00	241.28	8.41
S4 all-streets	48.07	11.22	24.71	16.00	8,281.36	288.60
Vienna (baseline)	27.00	39.00	6.00	28.00	715.63	39.82
S1 10%	26.01	36.02	9.97	28.00	787.19	43.80
S2 50%	25.14	33.41	13.46	28.00	1,073.45	59.72
S3 100%	24.23	30.68	17.10	28.00	1,431.26	79.63
S4 all-streets	22.38	25.13	24.49	28.00	3,946.11	219.55
Zurich (baseline)	30.00	39.00	4.00	27.00	118.36	28.84
S1 10%	29.19	36.58	7.23	27.00	130.20	31.72
S2 50%	28.54	34.61	9.85	27.00	177.54	43.26
S3 100%	27.75	32.24	13.01	27.00	236.72	57.68
S4 all-streets	24.82	23.47	24.71	27.00	1,193.59	290.83

S = Scenario.

Fig. 15: Changing in the mode share after the implementation of different scenarios (S1, S2, S3, S4) based on different proportional increases of the cycling networks [50]

From another perspective, the study by Keall *et al.* [57] analyzed the effectiveness of an intervention aimed at promoting cycling and walking as active transport modes in two New Zealand cities: New Plymouth and Hastings. The primary objective of the study was to evaluate whether the implementation

of dedicated active mobility infrastructure, such as cycle lanes and pedestrian pathways, combined with awareness programs, could reduce carbon dioxide emissions from motorized transport. The results demonstrated a 1.6% decrease in the average distance traveled by passenger vehicles, consequently leading to a 1% reduction in associated CO₂ emissions from transport.

Despite this modest reduction, the 2018 study still highlights how investing in active and sustainable mobility is an effective strategy, predicting that more extensive interventions would yield greater environmental benefits [57].

2.4.1 Bike Sharing System (BSS)

According to the expansion of cycling networks, also the bike-sharing system (BSS) usage is a significant factor to be considered, and which will probably increase with the coupling decrease of the other mode-shift transport. BSS can reduce fuel consumption by considering **how many car trips are substituted by bicycles**. BSS has a positive environmental impact, effects such as reduction of traffic and energy consumption, emissions decrease, public health improvements as well as promoting the economic growth of the city. Based on the result of a study conducted in China, by using bike-sharing 8,358 tons of fuel are saved, and 25,240 and 64 tons of CO₂ and NO_x emissions are reduced respectively by BSS in Shanghai [51].

Another study, has analyzed the bike share trip data from a program located in eight American cities to quantifying the environmental benefits of BSS. In terms of GHG emission reduction, using a Bike Share Emission Reduction Estimation Model (BS-EREM). This model considers the trip distance, trip purpose, trip start time, public transit accessibility around each bike share station, as well as the historical distributions of transportation mode choices in different cities. The main assumption is that these trips have the same emission reduction per trip.

With this implemented model, New York city has the largest amount of total GHG emissions reduction: with 10,262,649 bike share trips taken in 2016, New York's BSS contributed to 5417 tons of GHG emission reduction (in CO₂-eq). In contrast, Seattle's BSS only reduced 41 tons of GHG emissions [52].

City	Seattle	Los Angeles	Bay Area	Philadelphia	Boston	Washington D.C.	Chicago	New York
Total trips in 2016	102,606	184,345	193,506	499,306	1,236,199	2,562,718	3,595,383	10,262,649
Total stations	59	64	74	119	327	407	581	687
Total docks ^a	1,038	1,352	1,357	2,280	5,729	6,720	9,987	20,390
Docks per station ^a	17.59	21.12	18.34	19.16	17.52	16.51	17.19	29.68
Percentage of stations with public transit access	57.63%	67.19%	93.24%	100.00%	96.94%	71.01%	98.28%	57.79%
Percentage of trips used for simulation ^b	91.64%	89.40%	97.58%	91.90%	96.87%	95.36%	95.73%	97.94%
NHTS trips used for simulation ^c	1,619	49,427	29,284	3,350	3,293	14,199	6,096	40,631
Total number of bikes ^d	463	763	421	1,023	1,797	4,305	5,746	10,486
System diameter (miles) ^e	4.71	2.85	2.33	5.06	8.57	14.28	23.29	11.17
Average number of trips per station	1,739	2,880	2,615	4,196	3,780	6,297	6,188	14,938
Average number of trips per dock	99	136	143	219	216	381	360	503
Average number of trips per bike	222	242	460	488	688	595	626	979
Median of trip distance (miles)	1.16	1.2	1.39	1.46	1.43	0.91	1.39	1.31
Average trip distance (miles)	1.27	1.23	1.56	1.7	1.72	1.02	1.71	1.68
Average speed of bike share trips (miles/hour)	6.87	6.24	7.97	7.28	8.21	7.55	7.71	7.92
Percentage of commuting trips	51.92%	48.45%	52.30%	54.37%	52.57%	52.85%	52.88%	46.95%
Total GHG emission reduction (without round trips, ton CO ₂ -eq)	37.21	46.56	67.43	234.83	668.11	1,275.88	2,000.89	5305.13
Total GHG emission reduction (including round trips, ton CO ₂ -eq) ^f	40.60	52.08	69.10	255.51	689.66	1,338.00	2,090.05	5,416.68
Percentage of GHG emission reduction from commuting trips (without round trips)	57.70%	53.93%	60.89%	60.50%	60.14%	61.49%	60.93%	57.16%
Average emission reduction (g CO ₂ -eq) per mile travelled	324.57	286.59	298.75	340.89	345.02	329.69	352.66	329.48
Average emission reduction (g CO ₂ -eq) per trip	395.73	282.50	357.12	511.73	557.89	522.10	581.32	527.81
Average emission reduction (ton CO ₂ -eq) per station	0.69	0.81	0.93	2.15	2.11	3.29	3.60	7.88
Average emission reduction (ton CO ₂ -eq) per dock	0.04	0.04	0.05	0.11	0.12	0.20	0.21	0.27
Average GHG emission reduction (ton CO ₂ -eq) per bike	0.09	0.07	0.17	0.26	0.35	0.28	0.37	0.49

Fig. 16: Analysis on environmental benefits after BBS implementation in eight American cities [52]

Even if this approach has been used for quantifying GHG emission reduction, using an appropriate emission factor can lead to quantify other environmental pollutants (NO_x, PM, ...).

However, there is an annual GHG reduction in all the analyzed systems, the largest is the bike share program, the largest will be the reduction. So, expanding the BSS system size (e.g., building more stations and docks, launching more bikes) can help increase the GHG emission reduction by generating more bike share trips [52].

Further confirmation emerged from a study conducted in Shanghai [58]. In 2015, Shanghai's transport sector consumed 20% of gasoline, 36% of diesel oil, and 96% of fuel oil, resulting in 42 Mt of CO₂ emissions, which accounted for 24% of the city's total emissions. By 2016, bike sharing in Shanghai had saved 8,358 tonnes of petrol and reduced CO₂ and NO_x emissions by 25,240 and 64 tonnes, respectively. The environmental benefits were notably higher in more developed districts, typically characterized by higher population density.

In Shanghai, the highest density of environmental benefits was observed in the Hongkou district. For each square kilometer (km²) within this district, bike sharing led to a reduction of 33 tonnes of petrol, 100 tonnes of CO₂, and 254 kg of NO_x in 2016 (Table 1). Hongkou indeed boasts the highest population density in Shanghai, at 35,000 people per km². Consequently, bike sharing in this district resulted in a decrease of 2.9 kg of CO₂ emissions per person [58]. The study highlights that environmental benefits are more pronounced in Shanghai's more developed, densely populated districts, and that these benefits are concentrated during the evening peak hours, when bicycle usage is most intense and vehicular traffic is high.

It's necessary to clarify that the environmental impact of using bicycles is strongly dependent on the transportation mode choice preferences, because environmental benefit is heavily contingent on the urban context, the availability of cycling infrastructure, and the alternative choices of non-cyclists (who might opt for more or less impactful vehicles).

3. An Integrated Approach to Urban Sustainability

The main strategies adopted by major cities (both within and outside of Europe) against vehicular traffic pollution were individually analyzed.

The results are typically presented in terms of **health, traffic, social and/or environmental benefits**. Focusing on the last point, the situation can be summarized as shown in the following table, according to the analyzed case studies:

ADOPTED STRATEGIES	ENVIRONMENTAL BENEFITS
30 Zones	<i>Overall CO₂, NO₂ and PM reduction:</i> Bilbao: -19% Berlin: -29% London: -10% Edinburgh: -8% Gratz: -25%
Bike Sharing System and Expansion of Cycling Networks	<i>Overall GHGS reduction:</i> Seattle: -57% Los Angeles: -53.9% Bay: -61% Philadelphia: -60% Boston: -60% D.C: -61% Chicago: -60% New York: -57%
Pedestrian Areas	Chester: - 17% CO₂, -10% NO_x, -13% PM
Low Emission Zones	London: -44% NO₂ Madrid: - 10% NO₂

Table 1: Schematization of environmental benefits according to the adopted strategy

It is important to note, according to the analysis of the previous cities case-studies, that for any of these strategies to yield effective benefits, they must be accompanied by a series of supporting interventions that ensure their effectiveness. For example, implementing a **30 km/h zone** might need to be paired with adequate road redesign and an appropriate driving style. Similarly, with **pedestrian zones**, careful attention must be paid to potential traffic diversions, as explained in previous chapters.

Naturally, the results differ for each case study analyzed, as every city has a unique configuration and has distinct needs to address. But in general, for any single strategy to be considered fully effective in reducing traffic pollution, it must be implemented correctly, addressing every possible problematic consequence and seeking to resolve any resulting issues.

Another interesting finding in the field of low-emission strategies is that there is a higher probability of success if a strategy is accompanied by one or more others, rather than being implemented individually. As the study of Milan in the following paragraph demonstrates, this is because each strategy brings different consequences that could be mitigated, or even directly resolved, by implementing another strategy, which will undoubtedly lead to greater overall benefits.

3.1 Milan Case-Study

Milan is the second-most populated Italian city with 1.35 million people in the city and other 3.2 million in its metropolitan area. Since is a fundamental transport node for the country, during a working day the area is interested by 7.5 million trips [53]. The baseline case of modal split is shifted toward private car (59%), followed by local public transport (LPT) (24%), according to the figure below:

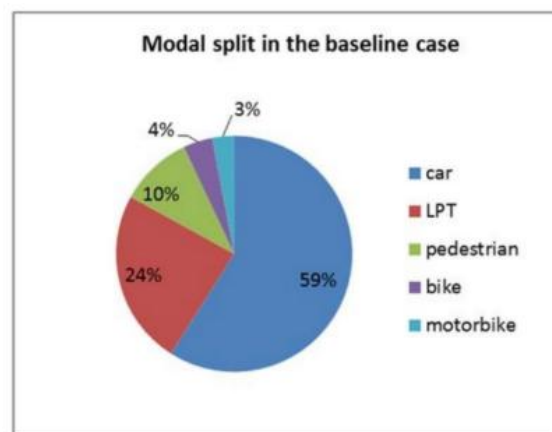


Fig. 17: Modal split in Milan city [53]

All the mobility frameworks in the city of Milan are responsible of 719 toe/y (647 toe/y of them are fossil fuels, the other is a minor consumption of electricity), while through COPERT methodology the main pollutant estimation is 1781 kg/y of CO₂ and 738 t/y of PM_{2.5} [53].

It's possible to use this study to assess how pollutant emissions from the transport sector would change in a large city, helping to understand the importance of low-emission initiatives and strategies.

The study, from 2019, simulates 11 different mobility measures with the aim of improving the overall sustainability of the transport sector. In the table below are reported these strategies:

Mobility measures		Description
A – Transit	A1 – Tram	• 20% speed increase on existing trams and trolleybuses.⁽¹⁾ • Introduction of 5 new tramways lines in areas not adequately covered by public transport.
	A2 – Subway	• Extension of existing subways towards hinterland municipalities. • Introduction of 2 new subways (Metro 4 and Metro 6).
	A3 – Railway	• Introduction of 14 new railway stations on the existing railway track. • 10% frequency increase of the whole railway service.
	A4 – Free ticket	• Free public transport ticket on the urban network.⁽²⁾ • Half-fare ticket on the public transport extra-urban network.
B – e-Move	B1 – LEZ	• Extension of the Low Emission Zone (called Area C) to Euro 0 petrol vehicles and Euro 0-4 diesel vehicles with or without Diesel Particulate Filter (DPF).⁽³⁾ • Paid parking throughout Milan.
	B2 – Bike	• Introduction of new 240 km of cycle paths in the urban area of Milan. • 20% speed increase on cycle paths.⁽⁴⁾
	B3 – Car Pooling	Introduction of a centralized and digital Car Pooling service able to increase to 1.5 the average occupancy ratio of private cars. ⁽⁵⁾
	B4 – Techno	Diffusion of environmentally friendly cars in the circulating fleet: 20% electric cars and 20% LPG/NG/hybrid cars. ⁽⁶⁾
C – All	From A1 to B4	This measure combines all the above-mentioned mobility measures.

(1)In the baseline case the commercial speed of trams and trolleybuses is 15–16 km/h.
(2)In the baseline case (and also currently in Milan) the city ticket costs 1.50 € while the extra-urban ticket varies from 1.60 to 4.20 € depending on the area and the distance from the city centre [21].
(3)In the baseline case (and also currently in Milan) Area C is limited to the historic city centre and access is prohibited to Euro 0 petrol vehicles and Euro 0-4 diesel vehicles without Diesel Particulate Filter (DPF). Access is chargeable to all other vehicle categories.
(4)In the baseline case (and also currently in Milan) the total length of cycle paths amounts to 167 km, while the maximum speed allowed is 9 km/h.
(5)In the baseline case (and also currently in Milan) the average occupancy ratio of private cars is 1.2.
(6)In the baseline case (and also currently in Milan) the circulating fleet is composed by 92% conventional cars (petrol and diesel), 8% LPG/methane/hybrid cars, 0.06% electric cars [30].

Fig. 18: Low-emission strategies tested and analyzed on the Milan area [53]

Strategies from A group, aim at boosting the local public transport, acting on the extension of existing transport lines such as subways or railways, the improvement of the fleet (5 new tramways, 2 new subways or 14 new railway stations) and the free or discounted transport tickets.

Instead, strategies from group B aiming at discouraging private car use, by the extension of LEZ to more Euro standard vehicles, the extension of new cycle paths, the introduction of a Car Pooling service or the improving of the electric vehicle fleet. At least, C-All group considers all these strategies simultaneously.

According to the results of this study, with the increase of public transport, private car use decrease from 58.8% in the baseline case, to 47.7% in B1-ZTL and 49.5% in A4-NoTicket [53]. Analyzing the distances travelled by people, expressed in passenger-km, Local Public Transport (LPT) passengers strongly increase in the single measures A2-Subway (+22%), A4-NoTicket (+31%), A3-Railway (+9%) and B1-LEZ (+18%).

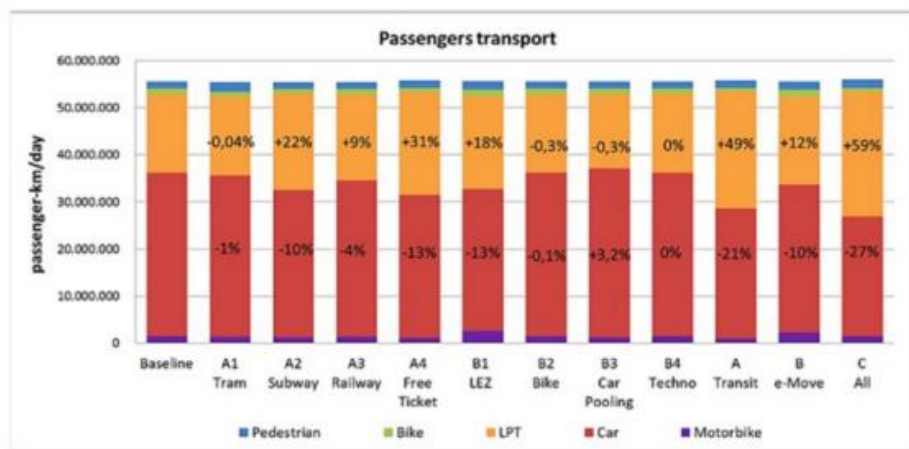


Fig. 19: Distances traveled by people for different mobility measures [53]

The traffic flow, which is the distances travelled by vehicles, decrease significantly in scenarios A2 – subway (-10%), A4 – free tickets (-12 %), B1 – LEZ (-13%) and B3 – Car Pooling (-17%). Greater reduction are observed when these strategies are considered simultaneous, according to the following image:

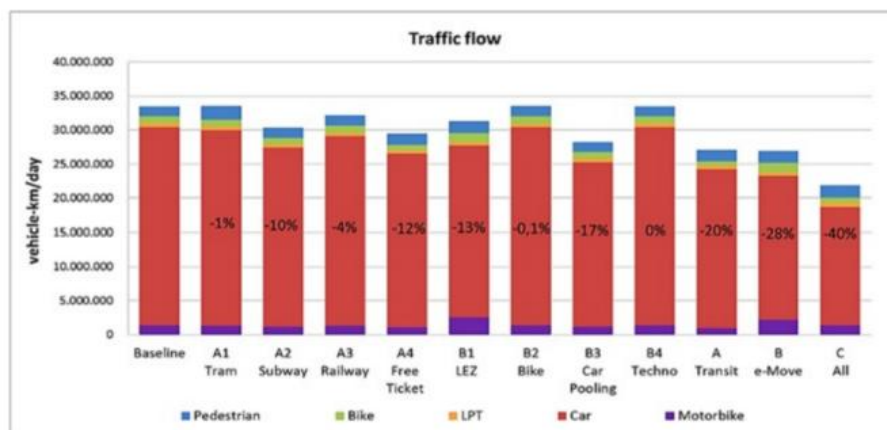


Fig. 20: Distances traveled by vehicles for different mobility measures [53]

When all strategies about public transport (A group) are implemented, the reduction in terms of traffic flow reaches about -20%, for the B-group it's seen a decrease of -28%, while when all strategies are implemented together (C-All) the reduction is the largest recorded (-40%).

The environmental impact of these simulations is shown on Fig. 22: reducing fuel consumption is a direct method to reduce CO₂ emissions:

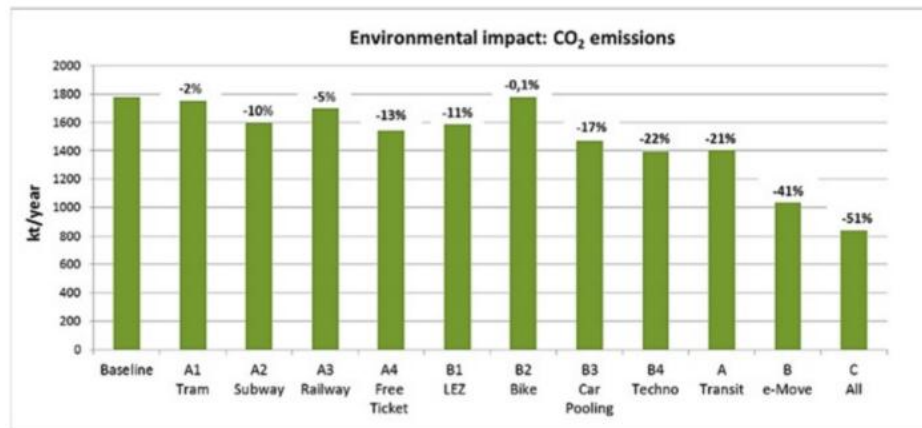


Fig. 21: CO₂ emission reduction for each measure [53]

It is evident that modifying fleet composition (B group strategies) for example moving to a more sustainable car fleet (B1) or by increasing the percentage of electric/hybrid vehicles (B4) can be an interesting method for CO₂ emission reduction, even if these vehicle types do not eliminate non-exhaust PM emissions. Also in this case, more promising results are recorded when several strategies are implemented together, instead of individually.

Overall, from the analysis of this case-study it emerges that **the optimal solution involves implementing these strategies collectively**, or at the very least for CO₂ reduction, prioritizing options and scenarios that discourage private car usage. This approach, however, must be accompanied by an enhancement of public transport or other sustainable mobility options to function as effectively as possible. Therefore, it is preferable to focus on interconnected low-emission strategies rather than implementing a single measure, also to act on the reduction of non-exhaust sources of pollution and obtain a better overall result in terms of air quality.

Indeed, a standalone analysis of the "30 Zones" project applied in Milan, as revealed by another study [54], demonstrates how the results of a single intervention are not always promising or impactful. Using COPERT Methodology, the study is focused on the average 2022 vehicle fleet distribution and considers the appropriate Emission Factors for CO, NO_x, PM exhaust and CO₂ multiplied by traffic volume and the total mileage per vehicle to obtain emission values.

In this analysis, 9 Zone 30 scenarios are evaluated:

Scenario ID	Roads with Zone 30	Circle	Diff. (minutes)	Diff. %
circle_1.allstreets	Residential + tertiary + secondary	Circle 1	0.00	0.01
circle_2.onlyresidential	Only residential	Circle 2	0.02	0.09
circle_2.tertiary	Residential + tertiary	Circle 2	0.06	0.25
circle_3.onlyresidential	Only residential	Circle 3	0.15	0.83
circle_3.tertiary	Residential + tertiary	Circle 3	0.26	1.36
circle_3.secondary	Residential + tertiary + secondary	Circle 3	0.67	2.99
circle_4.onlyresidential	Only residential	Circle 4	0.57	2.86
circle_4.tertiary	Residential + tertiary	Circle 4	0.91	4.77
circle_4.secondary	Residential + tertiary + secondary	Circle 4	1.48	7.24

Fig. 22: Scenarios analyzed as new 30 zones [54]

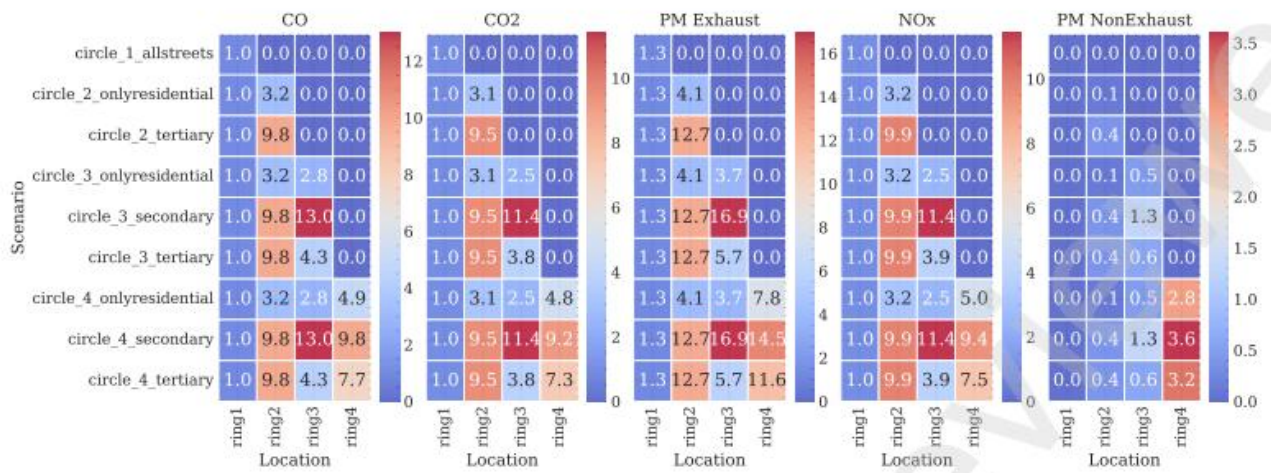


Fig. 23: Pollutant emission reduction for each scenario [54]

The main results indicate a modest overall increase in travel time and emissions, with travel time rising up to 7.24% (1.48 minutes) and emissions increasing between 0.66% to 3.53% across different pollutants, in the most restrictive scenario.

Even if other studies generally found an effective reduction in terms of emission due to Zone 30 implementation, this analysis suggests a slight increase maybe since Zone 30 projects are implemented solely in the city center, where there is most of the existing traffic of the city and the velocity is already slow. As the study suggests, based on the feedback and the outcomes of real-world experiments, a gradual expansion of Zone 30 could be strategically planned. Additionally, as has been highlighted, opting for a **multi-strategic approach is preferable** to secure improved results and environmental benefits.

4. Turin Case-study

This thesis aims to evaluate and analyze a series of **low-emission strategies** for a specific area of Turin, using case studies from previous chapters as a guide. The ultimate goal is to reduce emissions from vehicular traffic.

Considering the **San Salvario district** as a case study, and drawing from the strategic models discussed earlier, the most suitable solutions appear to be the simultaneous implementation of two key strategies: the establishment of a new '**Zone 30**' in a particularly congested street, and the extension of **bicycle lanes** to additional secondary roads. These approaches are chosen based on the understanding that a combination of strategies yields greater success.

4.1 Data and Methods

The quantitative evaluation of emissions reduction under these new scenarios will be conducted using specific models and software, which are detailed in the subsequent sections.

4.1.1 COPERT

For the **Zone 30 scenario**, the **COPERT** program and its methodology, which is based on the use of emission factors for each pollutant, appears to be a suitable starting point. This approach is also supported by the analysis of the case study in Milan.

COPERT (COmputer Programme to calculate Emissions from Road Transport) is a software tool that implements a methodology which creates air emission scenarios and inventories based on the emission factor approach. According to this approach, emissions of a given pollutant for a specific sector are the product of individual activities that generate emissions and their respective emission factors. The main pollutants of interest are CO₂, NO_x, CH₄, N₂O, NH₃, SO_x, and PM.

Based on data availability, there are three calculation methodologies to choose from:

- **TIER 1:** is the most simplified method. It uses fuel consumption as an activity indicator and associates it with average emission factors. It is only suitable when the sole available data are national fuel consumption statistics, as it lacks detail.

- **TIER 2:** is an intermediate method where fuel consumption is broken down by different vehicle categories and emission standards. It requires the number of vehicles and annual mileage by technology, applying emission factors expressed in grams per vehicle-kilometer.
- **TIER 3:** is the most detailed approach, implemented in the COPERT software. The calculated emissions are the sum of hot emissions (when the engine is at operating temperature) and cold emissions (during the thermal transition, or warm-up phase).

For this thesis, the TIER 3 approach will be used. Among the three methods, it's the only one where emission factors consider vehicle speed, and they can therefore be calculated using a general equation that depends on this value.

To summarize, total emissions can be calculated using the following equation:

$$E_{total} = E_{hot} + E_{cold} \quad (Eq.1)$$

where,

ETOTAL = total emissions (g) of any pollutant for the spatial and temporal resolution of the application

EHOT = emissions (g) during established (hot) engine operation

ECOLD = emissions (g) during transient thermal engine operation (cold start).

A primary distinction is made based on the type of road considered (rural, urban, or highway) because COPERT considers different driving conditions and subsequent different engine operation conditions, each attributed to a specific driving situation. In this way, the sum of emissions from these three types of situations will correspond to the total emissions.

For this thesis, it will be assumed that there is **100% urban driving**.

Total emissions are calculated by combining activity data for each vehicle category with appropriate emission factors. The emission factors vary according to the input data (driving situations, climatic conditions). At this point, the input variables are:

- Fuel variables (consumption, specification).
- Activity data (number of vehicles per category, distribution into different EURO classes, mileage per vehicle class).
- Driving conditions (average speed per vehicle type and road).
- Other variables (climatic conditions, mean trip distance)

By inputting these data, COPERT calculates the emission factors for each type of emission, vehicle class, and road class. The final output is the quantity of annual emissions of all pollutants for all road traffic source categories across all defined territorial units and road classes.

Hot exhaust emissions depend on a variety of factors, including the distance each vehicle travels, its speed (or road type), its age, its engine size, and its weight.

$$E_{hot\ i, k, r} = N_k * M_{k, r} * e_{hot\ i, k, r} \quad (Eq. 2)$$

where,

- **$E_{hot\ i, k, r}$** = hot exhaust emissions of the pollutant i [g], produced in the period concerned by vehicles of technology k driven on roads of type r
- **N_k** = number of vehicles [veh] of technology k in operation in the period concerned
- **$M_{k, r}$** = mileage per vehicle [km/veh] driven on roads of type r by vehicles of technology k
- **$e_{HOT; i, k, r}$** = emission factor in [g/km] for pollutant i , relevant for the vehicle technology k , operated on roads of type r .

In COPERT, cold starts lead to additional exhaust emissions. These occur because:

- The catalytic converter, which reduces pollutants in the exhaust, isn't yet at its optimal operating temperature.
- The engine runs on a richer fuel mixture to compensate for the colder temperature.
- The friction within the engine is higher before the oil has properly warmed up.

These factors result in a temporary increase in emissions until the engine and its components reach their ideal operating temperature.

$$E_{cold\ i, j} = \beta_{i, k} * N_k * M_k * e_{hot\ i, k} * \left(\frac{e_{cold}}{e_{hot\ i, k-1}} \right) \quad (Eq. 3)$$

where,

- **$E_{cold\ i, k}$** = cold-start emissions of pollutant i (for the reference year), produced by vehicle technology k
- **$\beta_{i, k}$** = fraction of mileage driven with a cold engine or the catalyst operated below the light-off temperature for pollutant i and vehicle technology k
- **N_k** = number of vehicles [veh] of technology k in circulation
- **M_k** = total mileage per vehicle [km/veh] in vehicle technology k
- **$e_{hot\ i, k}$** = hot emission factor for pollutant i and vehicles of k technology
- **$e_{cold}/e_{hot\ i, k}$** = cold/hot emission quotient for pollutant i and vehicles of k technology.

For the Tier 3 methodology, emission factors are determined by vehicle type (including emission standard, fuel, and capacity or weight) and traveling speed. These factors are based on extensive experimental data from individual vehicles tested in various European labs, with their emission performance compiled into a database.

Because **COPERT** does not account for specific street configurations, it cannot precisely model braking and acceleration events caused by traffic lights, crosswalks, or signs within the specific context of the case study. For this reason, the **SUMO** program was also chosen, and its results will be used to validate or supplement COPERT analysis.

4.1.2 SUMO

SUMO (Simulation of Urban MObility) is an open-source software that enables microscopic and continuous traffic simulation. It can be used for a variety of analyses, including traffic forecasting, traffic light evaluation, route selection, and the assessment of vehicle pollutant emissions [81].

The program functions based on a model where each vehicle is an autonomous entity that interacts with the surrounding environment and traffic according to specific behavioral patterns. Vehicle movement is determined by a model that calculates speed and acceleration at various points along a route, based on factors like the distance to the vehicle ahead, the set speed, and the vehicle's capabilities [82]. A key strength of SUMO is its detailed simulation of vehicle behavior at intersections, including complex actions like a **left-turning vehicle stopping to wait for a gap in oncoming traffic** [83]. Another core component is the simulation of **lane-changing behavior**, which can occur for various reasons in a real-world scenario. The software also accounts for a safe following distance between vehicles, which is crucial as it often necessitates changes in speed [83].

The main difference between SUMO and COPERT is that SUMO's model is fundamentally driven by the **precise road dynamics of a given case study**. The program takes the street network as input, allowing it to interpret and account for the presence of traffic lights, intersections, lane changes, and any other urban element that could affect the movement of a single vehicle or an entire fleet [82].

For the calculation of emissions such as CO₂, NO_x, and PM, SUMO relies on **HBEFA (Handbook Emission Factors for Road Transport)** models [82]. This results in outputs that are a combination of simulated vehicle speeds and accelerations.

To run a simulation with **SUMO**, you must first define the road network. This network, which serves as the base scenario, needs to include all essential elements for realistic representation, such as lanes, signs, traffic lights, and intersections. The network is made up of **edges** (road segments with specific data) and **nodes** (the intersections between the edges), both of which are modeled and edited using the **NETEDIT** function.

The road network can be created from an **OpenStreetMap (OSM)** file. After selecting the area of interest, the file must be converted to a SUMO-readable format (*.net.xml*) using the **NETCONVERTER** tool.

Next, you need to generate the "mobility demand" for the simulation. This is essentially a list of the vehicles that will participate and their characteristics. This data is managed through XML files (*.rou.xml*), which are edited with a text editor and contain specific information about the vehicular traffic.

To make the simulation more accurate, several parameters can be added to each vehicle [84]. Some of the most important include:

- **departLane**: The lane where the vehicle enters the network.
- **departPos**: The exact starting position within the entry lane.
- **depart**: The simulation time when the vehicle appears on the road network.
- **departSpeed**: The initial speed of the vehicle.
- **arrivalSpeed**: The speed at which the vehicle exits the network.
- **personNumber**: The number of passengers in the vehicle.

It is also possible to specify the vehicle's fuel type and Euro class (e.g., Euro 3 gasoline or Euro 4 diesel) using the **vType** element [82]. This allows for the behavior of individual vehicles to be distinguished by their type, like **COPERT**.

4.2 Context and Current Strategies

Turin is the capital of the Piedmont region, located in northwestern Italy. As of 2023, its population stands at approximately **848,748 inhabitants**, making it the fourth-largest city in Italy by resident count. The municipal area spans **130.17 km²**, resulting in a population density of about **6,520 inhabitants per km²** [43]. Approximately **21.37 km²** [43] of the total area of the city are dedicated to green spaces, especially numerous parks, including the famous *Parco del Valentino*.

Despite this, the city of Turin is located in a natural basin, surrounded by the Alps and morainic hills, making it one of the most polluted cities in Italy attributable to inadequate natural ventilation, with very low wind speed and the thermal inversion in wintertime [44] leading to the accumulation of air pollutants.

Turin consistently ranks among the top Italian cities for air pollution. Legambiente's report [70], in its 2025 edition, reveals a concerning 55 exceedances at the *Rebaudengo* and *Lingotto* monitoring stations. This is significantly higher than the allowed limit of 35 days where the average daily concentration of pollutants exceeds 50 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$):



Fig. 24: Mean annual concentration of PM10 and NO2 ($\mu\text{g}/\text{m}^3$) registered by Rebaudengo and Lingotto monitoring station in 2024 [70]

Turin also has a very high motorization rate, topping the national rankings with 69 cars per 100 inhabitants, as the following image shows. The 2030 objective for Turin city is highlighted in green and as visualized, the city is still very far from that:

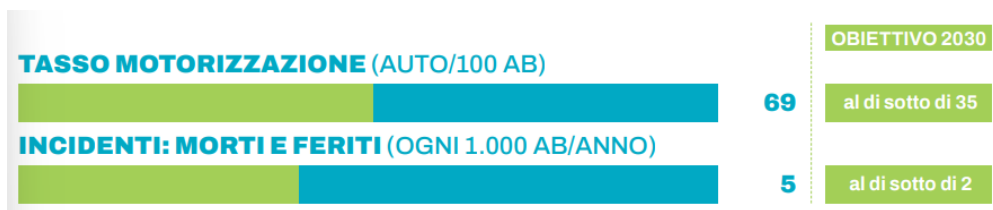


Fig. 25: Motorization rate (car/100 inh) and number of incidents (every 1000 inh/y) registered in Turin in 2024 [70]

Regarding the motorization rate, the objective for 2030 is to have fewer than **35 cars per 100 inhabitants**, which represents a **50% reduction** from the current number. A similar objective applies to

the number of road incidents. Currently, there are **5 incidents with fatalities and injuries** per 1,000 inhabitants. This number is targeted to decrease to **2 per 1,000 inhabitants by 2030**.

In *Figure 26* are still highlighted the city's 2030 objective and the current situation concerning the extension and improving of cycle paths, 20 or 30 km/h zones, and public transport:

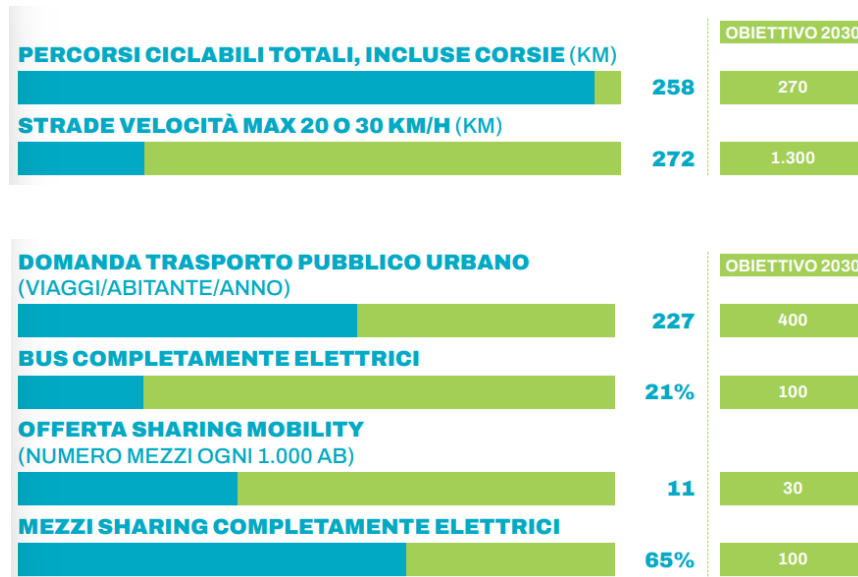


Fig. 26: Current situation compared to 2030 objective in terms of low-emission strategies (cycle paths, 20/30 km/h zones, public transport demand, electric buses, sharing mobility offer, sharing vehicles fully electric) [70]

Also in this case, the blue bars show the current state of low-emission strategies, while the green bars represent the 2030 goal for Turin. There's still a lot of work ahead to make public transport a more sustainable option. Most importantly, it needs to make these transport options as green as possible, for instance by switching to fully electric buses.

It's therefore confirmed that in the city of Turin, one of the most impactful sources of pollution is traffic. Specifically, nitrogen dioxide comes 12% from diesel cars, 27% from heavy vehicles (exclusively diesel), and a 16% share from light vehicles [46]. Furthermore, of the city's 583,424 passenger cars, 25% are diesel-powered [70].

According to Figure 27, the transport sector is responsible for 85% of PM's emissions and 61% of NOx's emissions [45].

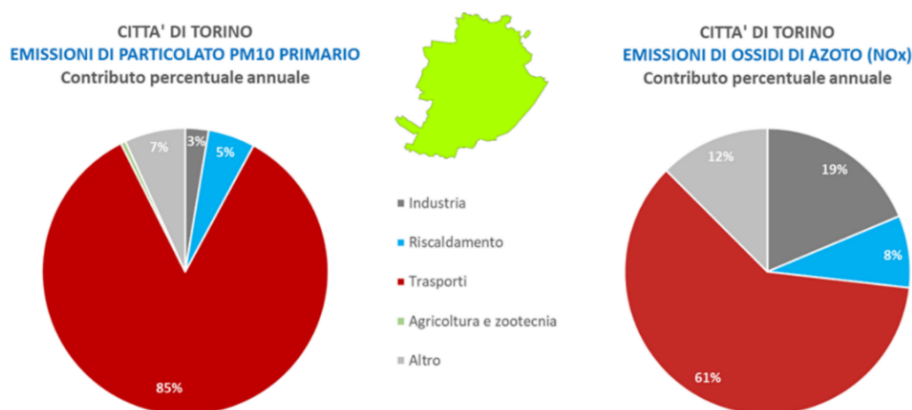


Fig. 27: Most impactful sources for PM10 and NOx in Turin city [45]

The ARPA Piemonte website features a well-detailed report on the emission sources for each type of pollutant, their limit values, and how many days a year these values were exceeded. Considering this data and focusing on road transport, it can be highlighted that this sector is responsible for **32% of PM generation, 56% of NOx, 36.36% of CO, and 24.6% of CO2** [64].

Indeed, several initiatives and policies have already been implemented or are underway, also falling within broader municipal and regional plans, activated based on pollution levels detected by ARPA Piemonte.

Among these, it's possible to find as a permanent measure the limitation on the circulation of more polluting vehicles, varying based on the day of the week and time slots, as established by Ordinance 2537 of 30/04/2025. This ordinance is based on European directives and national regulations, citing European Court of Justice rulings that have condemned Italy for the systematic exceeding of PM10 and NO2 limit values, including the Piedmont region and the Turin area. It specifies the categories of vehicles exempt from restrictions and the alert thresholds for the activation of more stringent temporary measures. Generally, the measures are valid from September 15th to April 15th of each year, with some specific limitations active year-round. In the case of the latter, the circulation within the municipality of Turin is prohibited for all vehicles used for the transport of goods and people with a homologation equal to or lower than Euro 2 if petrol or diesel-powered, and lower than Euro 1 if LPG or methane-powered. Less stringent limitations are adopted for Euro 3 and 4 diesel vehicles and Euro 1 mopeds. The following table provides a summary of the current vehicular circulation situation within the municipality of Turin:

LIMITAZIONI STRUTTURALI VALIDE TUTTO L'ANNO		
	Diesel Euro 0, 1 e 2 Benzina Euro 0, 1 e 2 GPL e Metano Euro 0 e 1	Tutti i giorni dalle 0 alle 24 ⁽ⁱ⁾
LIMITAZIONI STRUTTURALI VALIDE DAL 15/9 al 15/4		
	Diesel Euro 3 e 4	Nei giorni feriali dal lunedì al venerdì dalle 8 alle 19 ⁽ⁱⁱ⁾
	Euro 0 e 1	Tutti i giorni dalle 0 alle 24 ⁽ⁱⁱⁱ⁾
	Obbligo di utilizzare pellets certificato A1 ^(iv)	
	Divieto di abbruciamento di materiale vegetale ^(v)	
LIMITAZIONI TEMPORANEE VALIDE DAL 15/9 al 15/4 – LIVELLO ARANCIO		
LIMITAZIONI TEMPORANEE VALIDE DAL 15/9 al 15/4 – LIVELLO ROSSO		
	Diesel Euro 3, 4 e 5	Tutti i giorni, sabato e festivi compresi, con semaforo arancione acceso dalle 8 alle 19 ^(vi)

Fig. 28: Main limitations on the circulation of vehicles adopted by the city of Turin [65]

In cases of prolonged exceedance of PM10 or NO2 limits, emergency measures are activated (often indicated as "orange" or "red" levels). These measures involve more stringent restrictions, extending even to newer vehicles (e.g., Euro 5 diesel) and for wider time slots. Additionally, there are numerous ZTLs (Limited Traffic Zones) primarily in the city center, with specific hours and permits that restrict access to unauthorized vehicles and significantly reduce traffic. At the same time, the city is moving towards a greater enhancement of public transport by strengthening the GTT (Gruppo Trasporti Torinese) network, increasing the number of buses and trams, and aiming for a greater number of electric vehicles, thanks to resources from the **PNRR (National Recovery and Resilience Plan)**.

Another strategic component of Turin's approach to greater urban sustainability is a series of shared mobility initiatives, including bike sharing, car sharing, and electric scooters. As of 2024, this type of service included **3,000 electric scooters, 2,300 bikes, 650 scooters, and 3,600 cars** [69]. The bike-sharing service is complemented by a series of cycling infrastructures, which currently extend for **290 km** [66] as shown on the map provided by the *Muoversi a Torino* website:

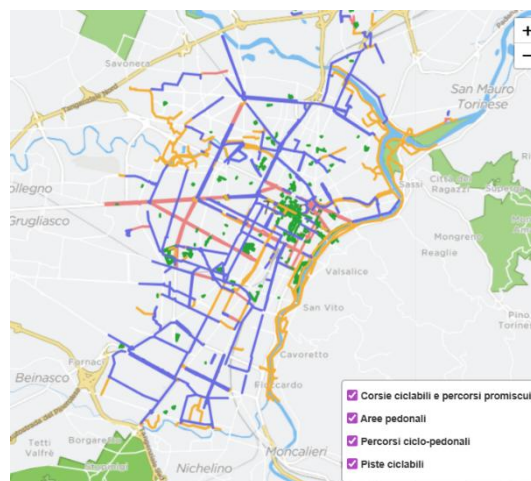


Fig. 29: Map of the already existing cycle paths in Turin [66]

Car-sharing with Enjoy (by Eni) is also gaining increasing importance, partly because the car can be used and then parked within a defined area without the need for fixed stations. Fuel/recharge, insurance, and parking costs (within the designated area) are included in the hourly or per-minute rate, eliminating the burdens of ownership. Finally, among all shared transport modes, the use of shared electric scooters stands out for their greater versatility and practical use.

Despite this series of interventions, many strategies are still to be implemented and are under development. As discussed in previous chapters and analyzed in various case studies, **an integrated approach among various low-emission strategies appears to be the best option**. This means implementing diverse and effective strategies that together allow for the achievement of full sustainable mobility within the city of Turin. This involves considering a greater extension or eventual creation of pedestrian areas and cycling paths, which would discourage private car use and favor movement on foot or by bicycle with the aim of reducing traffic (and consequently emissions) and increasing safety. It also includes approving the "city 30" model for most urban roads, while promoting better traffic optimization and management systems, and finally, consistently detecting and monitoring air quality data to address growing atmospheric pollution.

4.2.1 San Salvario Neighborhood

With the aim of simulating a series of new low-emission strategies in the city of Turin, a precise zone of the city, namely the San Salvario district, was taken into consideration. This area is delimited by the Turin Porta Nuova railway line, Corso Vittorio Emanuele II, Corso Bramante and the Po River, and it is one of the most trafficked and populated areas of the city, with a surface area of **2.46 km²** and **38,110 inhabitants**.



Fig. 30: San Salvario district (Turin) [68]

One of the most significant initiatives implemented in the district was the **Torino Mobility Lab**, launched in 2017. This national experimental program for sustainable home-to-school and home-to-work mobility aimed to reduce polluting emissions and test a new mobility system [68].

Fig. 31: Initiatives proposed by Torino Mobility Lab (pedestrianized areas, shared mobility roads, cycle paths) [68]



Fig. 32: Interventions currently carried out in San Salvario district [68]

In the image below, modeled using the QGIS program, it's possible to visualize how the San Salvario area (outlined in yellow) features a cycle path along the entire length of *Via Nizza* and part of *Corso Marconi* (blue, indicating a dedicated cycle path), a mixed-use cycle and vehicle path along *Via Ormea*, *Via Principe Tommaso*, and *Corso Marconi* (in red), and a green-space cycle path within the Parco del Valentino (in yellow).

Additionally, there are two pedestrian zones: a small area in *Piazzetta Primo Levi* and a pedestrian path along most of the *Valentino Park*, the city's largest and most famous public park.

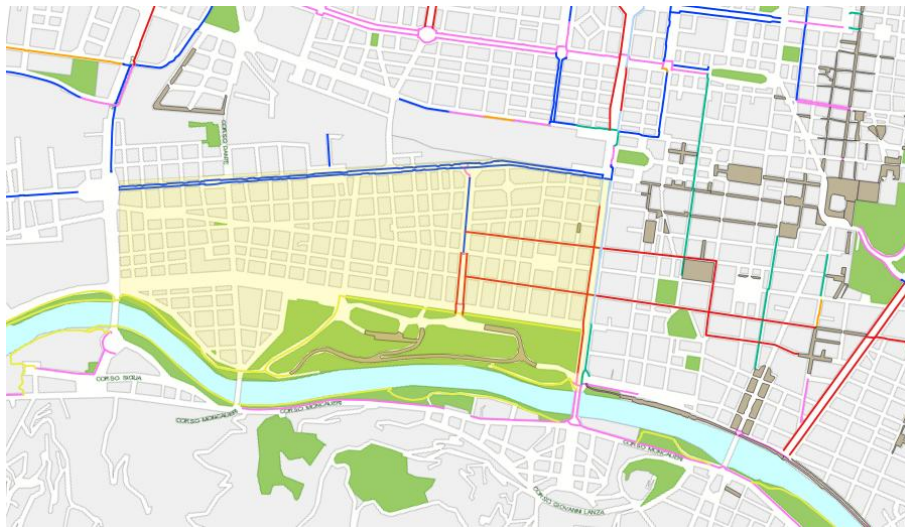


Fig. 33: Current bike lanes (red and blue lines) and pedestrian zones (grey areas) in San Salvario district

However, this information dates to 2018. In fact, with the *Torino Cambia* project, an environmental redevelopment was completed in 2025 that enhanced the historic avenue of *Corso Marconi*, from the Church of San Salvario to the *Castello del Valentino*. The works included new paving in the central avenue from *Via Madama Cristina* to *Corso Massimo D'Azeglio*, featuring a large pedestrian area and two one-way cycle paths in the center.

The tree-lined verges were improved by removing the damaged or degraded existing road surface and replacing it with draining pavements. In the section from *Largo Marconi* to *Corso Massimo D'Azeglio*, traffic calming measures were implemented on the service roads (*controviali*), along with safety improvements for pedestrian crossings, removal of architectural barriers, and the placement of new traffic lights for cycling crossings on *Corso D'Azeglio* from *Corso Marconi* towards the *Valentino*. The road surface on the service roads was also redone [67].

This intervention, already planned by the City of Turin's Cycling Mobility Plan, was funded by **PON Metro – REACT EU** and has resulted in annual savings of **23.36 tons of CO2** and **4.6 kg of PM10** [67].

Also, thanks to the *Torino Cambia* interventions, the Green To Share project was implemented in the city of Turin, including the San Salvario district, with the intention of replacing internal combustion vehicles with **87 electric vehicles** [67]. This involved implementing a new telematics management platform and creating a new network with 18 charging areas, saving **12 kg/year of PM10** and **63.3 tons of CO2** annually [67].

Through two monitoring stations located on *Via Nizza*, data is available on the number of cyclists generally passing through the district and on the cycle path of the same street. One of these stations is situated in the central area of the street, while the other collects information on the more peripheral area. In any case, the two stations have respectively collected an average daily cyclist count of **794** and **962**, with data updated from May 10, 2019, to July 8, 2025.

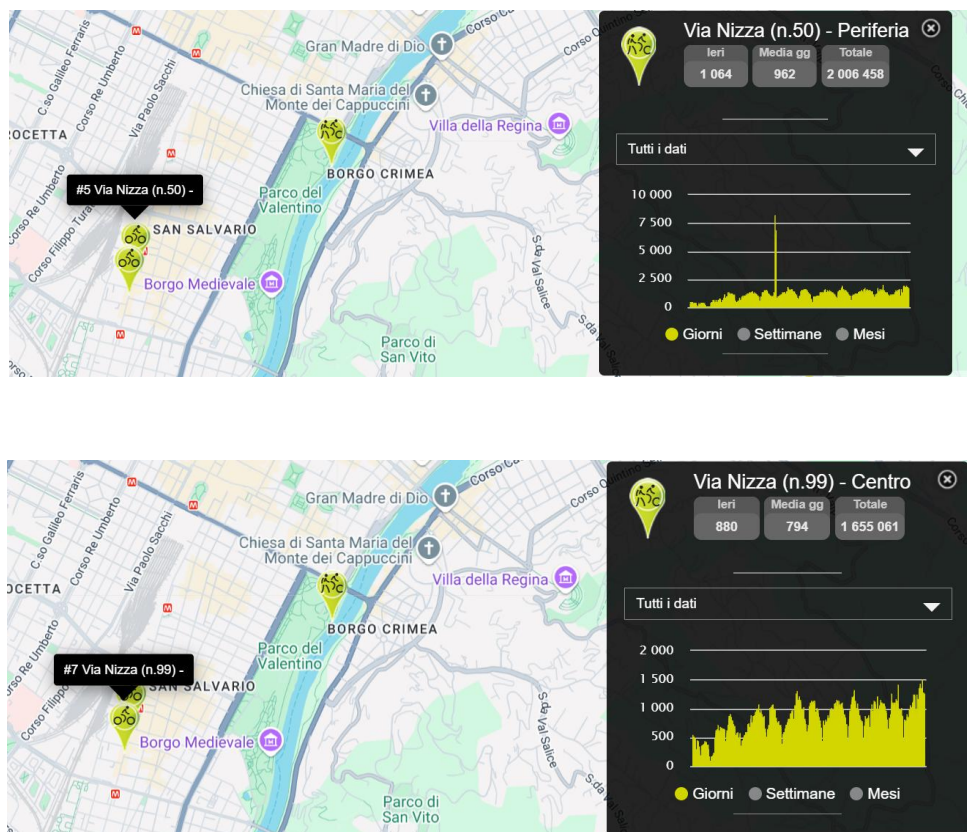


Fig. 34: Average daily cyclists registered in Via Nizza n. 50 and n. 99 stations [69]

Despite the city of Turin placing significant emphasis on environmental sustainability, especially within the San Salvario district, **further low-emission strategies could still be considered for implementation** in this neighborhood. Given its size, central location, and considerable traffic, such

strategies could further reduce atmospheric emissions from vehicular traffic across the entire city, while simultaneously enhancing road safety in such a large and populous urban area.

4. 3 Low-Emission Strategies for San Salvario

Considering the various strategies previously mentioned and analyzed, an implementation of a **new 30 km/h zone** on *Via Madama Cristina* (2.2 km) could be proposed for the case-study of this thesis.

While it is a busy street, it is not a main thoroughfare, which would make implementing this strategy more difficult. This change would also make it safer for cyclists and pedestrians, thus improving overall road safety throughout the neighborhood.



Fig. 35: Streets (green) for which are known data about fleet compositions

Figure 35 shows the specific road segments within the district for which data on vehicular fleet composition is available. This data, which includes the number and fuel type of the main vehicles, is crucial for modeling the new scenario using the **COPERT** and **SUMO** software mentioned in the preceding sections.

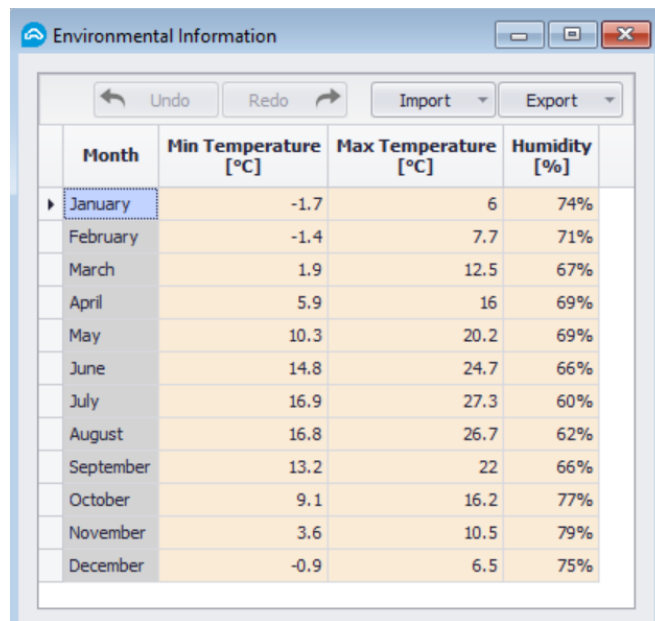
4.3.1 COPERT

To begin compiling data for COPERT, the inputs can be organized into main categories: **Year**, **Properties**, **Fuel**, **Vehicles**, and **Factors**. The **Year** chosen for this analysis is 2024.

The **Properties** category is further divided into Environmental information and Trip characteristics. For the first category, it is necessary to know the climatic conditions, specifically the minimum and maximum temperatures and humidity.

The monthly average values for Turin in 2024, as processed by *IlMeteo* [72], were selected. These data are required to calculate the load of air conditioning and fuel evaporation [73].

For the second category, it's necessary to specify the trip length in kilometers as the typical length traveled by a vehicle in Turin and the trip duration in hours. From the literature, this typical length is equal to 20.3 km [77], but this value is approximated to 20 km for the purpose of software application.



Month	Min Temperature [°C]	Max Temperature [°C]	Humidity [%]
January	-1.7	6	74%
February	-1.4	7.7	71%
March	1.9	12.5	67%
April	5.9	16	69%
May	10.3	20.2	69%
June	14.8	24.7	66%
July	16.9	27.3	60%
August	16.8	26.7	62%
September	13.2	22	66%
October	9.1	16.2	77%
November	3.6	10.5	79%
December	-0.9	6.5	75%

Fig. 36: Monthly temperature and humidity average values implemented in COPERT

The **Fuel** section provides all the tools to describe the characteristics of the fuel [73]. The fuel specification is provided, allowing the user to access information about energy content, fuel density, and the content of various species, as shown in the image below:

The **Vehicles** item provides all the tools needed to describe the fleet composition and behavior for the current analysis. Within the Vehicles menu, you can find commands like Stock Configuration, Stock & Activity Data, Circulation Data, Fuel Evaporation Data, Driving Conditions, Axles Number, SCR, A/C usage, Technology Share, Blend Share, and Bifuel Share and CO2 Correction [73].

Therefore, data on the number of vehicles registered in Turin, categorized by type, is required and can be easily obtained from **ACI (Automobile Club D'Italia)**. Due to the difficulty of handling a large volume of data, and to simplify the work while still getting a representative result of how the COPERT program functions, we used the highlighted values in the following tables.

These values represent the entire vehicle fleet of Turin, including cars, buses, trucks, and motorcycles. As explained at the beginning of Chapter 4, there is a ban on the circulation of Euro 0, 1, and 2 diesel and petrol vehicles, so these were not included in the calculation.

Legenda

NC NON CONTEMPLATO
ND NON DEFINITO

Categorie

AB AUTOBUS
AM AUTOCARRI TRASPORTO MERCI
AS AUTOVEICOLI SPECIALI / SPECIFICI
AV AUTOVETTURE
MC MOTOCICLI
MM MOTOCARRI E QUADRICICLI TRASPORTO MERCI
MS MOTOVEICOLI E QUADRICICLI SPECIALI / SPECIFICI
RM RIMORCHI E SEMIRIMORCHI TRASPORTO MERCI
RS RIMORCHI E SEMIRIMORCHI SPECIALI / SPECIFICI
TS TRATTORI STRADALI O MOTRICI

Alimentazione

AL ALTRE
BE BENZINA
BG BENZINA E GAS LIQUIDO
BM BENZINA E METANO
EL ELETTRICITA
GA GASOLIO
GG GASOLIO E GAS
IB IBRIDO BENZINA
IG IBRIDO GASOLIO
IM IBRIDO METANO
IBG IBRIDO BENZINA GAS LIQUIDO
IBM IBRIDO BENZINA METANO
IGG IBRIDO GASOLIO GPL
IGM IBRIDO GASOLIO METANO
ME METANO

Fig. 37: Legend of the following tables

AUTOVEICOLI																		
Anno	Comune	Euro	AL	BE	BG	BM	EL	GA	GG	IB	IBG	IBM	IG	ME	ND	Totale		
2024	TORINO	EURO 0	11	37132	2242	80	0	6905	0	53	0	0	0	4	8	46435		
2024	TORINO	EURO 1	0	6044	522	15	0	1376	0	0	0	0	0	2	0	7959		
2024	TORINO	EURO 2	0	16545	1519	46	0	4259	0	0	0	0	0	1	0	22370		
2024	TORINO	EURO 3	0	21077	1354	187	0	11678	0	0	0	0	0	5	0	34301		
2024	TORINO	EURO 4	0	53472	15322	3635	0	22924	0	94	0	0	0	85	0	95532		
2024	TORINO	EURO 5	0	29122	10520	1372	0	26198	0	604	2	0	21	138	0	67977		
2024	TORINO	EURO 6	2	119674	39994	1574	0	84799	0	106410	3	0	4637	511	3	357607		
2024	TORINO	NC	0	0	0	0	7895	0	0	0	0	0	0	0	0	7895		
2024	TORINO	ND	0	371	1	1	0	2	0	0	0	0	0	0	3	378		
2024	Totale Comuni		13	283437	71474	6910	7895	158141	0	107161	5	0	4658	746	14	640454		

AUTOBUS																		
Anno	Comune	Euro	AL	BE	BG	BM	EL	GA	GG	IB	IG	IM	ME	ND	Totale			
2024	TORINO	EURO 0	0	8	0	0	0	84	0	0	0	0	0	0	0	92		
2024	TORINO	EURO 1	0	0	0	0	0	15	0	0	0	0	0	0	0	15		
2024	TORINO	EURO 2	0	0	0	0	1	46	0	0	0	0	0	0	0	47		
2024	TORINO	EURO 3	0	0	0	0	0	195	0	0	0	0	0	0	0	195		
2024	TORINO	EURO 4	0	0	0	0	1	51	0	0	0	0	0	0	0	52		
2024	TORINO	EURO 5	0	1	0	2	0	560	0	0	0	0	0	40	0	603		
2024	TORINO	EURO 6	0	0	0	1	0	567	0	0	10	0	244	0	822			
2024	TORINO	NC	0	0	0	0	263	0	0	0	0	0	0	0	263			
2024	TORINO	ND	0	1	0	0	0	1	0	0	0	0	0	0	2			
2024	Totale Comuni		0	10	0	5	263	1519	0	0	10	0	284	0	2091			

AUTOCARRI TRASPORTO MERCI																		
Anno	Comune	Euro	AL	BE	BG	BM	EL	GA	GG	IB	IBG	IG	ME	ND	Totale			
2024	TORINO	EURO 0	0	898	76	3	0	4758	0	0	0	0	0	2	5738			
2024	TORINO	EURO 1	0	334	31	0	0	1733	0	0	0	0	0	1	2099			
2024	TORINO	EURO 2	0	299	32	15	0	3521	0	0	0	0	0	0	3867			
2024	TORINO	EURO 3	0	291	26	27	0	5228	1	0	0	0	0	2	5575			
2024	TORINO	EURO 4	0	258	184	200	0	5814	0	0	0	0	0	24	6480			
2024	TORINO	EURO 5	0	129	110	209	0	5617	0	0	0	0	0	42	6107			
2024	TORINO	EURO 6	0	815	682	1890	0	34654	0	2543	0	598	245	0	41427			
2024	TORINO	NC	0	0	0	0	1191	0	0	0	0	0	0	0	1191			
2024	TORINO	ND	0	29	0	0	0	30	0	0	0	0	0	0	59			
2024	Totale Comuni		0	3053	1141	2344	1191	61355	1	2543	0	598	316	1	72543			

MOTOCICLI												
Anno	Comune	Euro	AL	BE	BG	BM	EL	GA	IB	ME	ND	Totale
2024	TORINO	EURO 0	4185	16754	0	5	0	0	0	0	0	20949
2024	TORINO	EURO 1	415	8901	0	0	0	0	0	0	0	9316
2024	TORINO	EURO 2	21	8615	0	0	0	5	1	0	0	8642
2024	TORINO	EURO 3	52	21558	0	0	0	0	3	0	0	21613
2024	TORINO	EURO 4	22	8072	0	0	0	0	0	0	0	8094
2024	TORINO	EURO 5	21	10609	0	0	0	0	2	0	0	10632
2024	TORINO	EURO 6	8	143	0	0	0	0	0	0	2	153
2024	TORINO	NC	0	0	0	0	551	0	0	0	0	551
2024	TORINO	ND	0	99	0	0	0	0	0	0	1	100
2024	Totale Comuni		4724	74751	0	5	551	5	6	0	8	80050

Table 2: Number of cars, buses, trucks, and motorcycles divided by category and fuel type to be implemented in the software [76]

The "Zone 30" project was designed to be applied to the entire length of **Via Madama Cristina**, which is approximately **2.2 km** long. Daily traffic flow data for this specific street is available, categorized into light and heavy vehicles.

For the purpose of this thesis, heavy vehicles can be classified as buses and trucks, while light vehicles can be classified as motorcycles and cars. Using this breakdown, we were able to proportionally determine the vehicle flow on this street.

Heavy vehicles Via Madama Cristina*	Light vehicles Via Madama Cristina*	Heavy vehicles Torino (ACI)	Light vehicles Torino (ACI)
295	7053	55633 - 1636 buses - 53997 trucks	417772 - 40933 motorcycles - 376839 cars

With this data, it was possible to calculate the number of buses and trucks (as heavy vehicles) that travel on *Via Madama Cristina*. We used a proportion, assuming that the 1,636 buses in Turin's total heavy vehicle fleet are proportional to the number of buses on *Via Madama Cristina* relative to the street's total heavy vehicle traffic.

$$1636 : 55633 = x : 295$$

x: buses Via Madama Cristina

$$53997 : 55633 = y : 295$$

y: trucks Via Madama Cristina

Following the same logic for light vehicles, we were able to obtain the precise values for cars and motorcycles. In summary, the calculated vehicle flow for the street is:

BUSES	TRUCKS	CARS	MOTORCYCLES
9	286	6392	691

Using a proportional calculation once again, we were able to assign each vehicle category to a specific Euro standard and fuel type (*GA: Diesel, El: Electric, BE: petrol*) based on the known classification of the Turin fleet.

BUSES

EURO	GA	EL
Euro 3	1	0
Euro 4	0	0
Euro 5	3	0
Euro 6	3	0
NC	0	2

TRUCKS

EURO	GA	BE	EL
Euro 3	28	2	0
Euro 4	31	1	0
Euro 5	30	1	0
Euro 6	183	4	0
NC	0	0	6

MOTORCYCLES

EURO	BE	EL
Euro 3	364	0
Euro 4	136	0
Euro 5	179	0
Euro 6	3	0
NC	0	9

CARS

EURO	GA	BE	EL
Euro 3	198	358	0
Euro 4	389	907	0
Euro 5	444	494	0
Euro 6	1438	2030	0
NC	0	0	134

Once the number of vehicles for each category has been determined, it's possible to fill in the parameters for each one: **Mean Activity (km/year)** and **Lifetime Cumulative Activity (km)**.

The **Lifetime** value represents the average distance traveled by each vehicle of a specific technological level since it was introduced. This value is then used to provide an emission degradation factor that depends on the vehicle's age (or total mileage driven).

According to a report from the Piedmont region, this graph can be analyzed to get an idea of the age of the circulating vehicle fleet in the province of Turin:

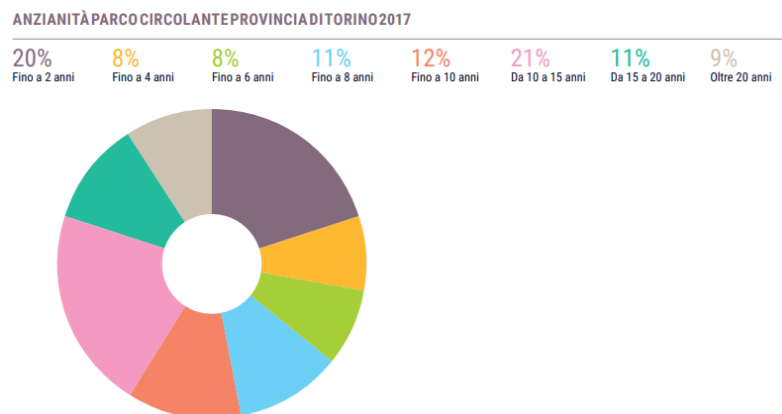


Fig. 38: Age of the circulating vehicle fleet in the province of Turin [77]

Although the provided analysis was conducted in 2017, the idea that most vehicles are between 10 and 15 years old can be a starting point for determining a plausible **Lifetime Activity** value (a value of 120.000 km will be considered).

Furthermore, according to UNRAE [74], a car in Italy travels 10,712 km annually. This is a good approximate figure to use for the city of Turin as the **Mean Activity** value. This parameter acts as a scaling factor, linking emissions per kilometer to overall emissions. It represents the total distance

traveled by a specific vehicle category in a defined area over a given period, which in this case is the average annual kilometers driven in Turin (a value of 10.000 km/y will be considered).

COPERT does not treat a vehicle's start-and-stop events as a separate input. Instead, it uses average speed and road type to estimate emission factors for a given situation. A scenario with urban roads will have different emission factors because COPERT assumes urban parameters are characterized by higher traffic density, frequent start-and-stop situations, and lower speeds compared to rural or highway driving [75].

The program also accounts for the increased emissions during cold starts, which are more common in urban areas due to shorter trips and frequent stopping and starting. The low speeds often found in cities are associated with a lot of stop-and-go driving, which leads to higher emissions due to frequent acceleration and deceleration [75].

In an ideal "**Zone 30**" scenario, lower speeds would be paired with appropriate road redesigns to avoid frequent stop-and-go situations as the main source of pollution. However, this cannot be predicted or calculated with the COPERT program because road characteristics are not input parameters; they are already implemented within the software.

Regardless, the model proposed by COPERT can be a good indicator of traffic emissions in the San Salvario neighborhood. It can be useful to see how the changing of input parameters influences the final emission values. The simulations conducted are based on a representative annual fleet of vehicles typical of the analyzed neighborhood, categorized by Euro standard and fuel type. The results represent the annual emissions produced by this equivalent fleet, depending on the scenario considered. Among all pollutants, CO₂, NO_x, and PM₁₀ are considered the most representative, as they are both the most emitted and the most easily comparable

4.3.1.1. Results and Discussion

SCENARIO 1

Mean activity = 10.000 km/y

Lifetime activity = 120.000 km

Trip length = 20 km

In this scenario, a basic situation is analyzed. The mean and lifetime activity values correspond to typical values for a vehicle in Italy. The used trip length corresponds to the typical distance traveled by a vehicle in Turin [77].

50 km/h									
Category1	Fuel1	Segment	Euro Standard1	CO2 [t]	TOTAL	PM10 [t]	TOTAL	NOx [t]	TOTAL2
Passenger Cars	Petrol	Small	Euro 3	CO2	530.26	PM10	0.1041	NOx	0.254
Passenger Cars	Petrol	Small	Euro 4	CO2	1370.67	PM10	0.2637	NOx	0.409
Passenger Cars	Petrol	Small	Euro 5	CO2	746.54	PM10	0.1447	NOx	0.122
Passenger Cars	Petrol	Small	Euro 6 a/b/c	CO2	3067.76	PM10	0.5737	NOx	0.499
Passenger Cars	Diesel	Small	Euro 3	CO2	296.84	PM10	0.1164	NOx	1.370
Passenger Cars	Diesel	Small	Euro 4	CO2	583.19	PM10	0.2241	NOx	1.860
Passenger Cars	Diesel	Small	Euro 5	CO2	665.65	PM10	0.1243	NOx	2.200
Passenger Cars	Diesel	Small	Euro 6 a/b/c	CO2	2155.87	PM10	0.4025	NOx	6.350
Passenger Cars	Battery el	Small	Electric	CO2	0.00	PM10	0.0261	NOx	0.000
Light Commercial	Petrol	N1-I	Euro 3	CO2	3.52	PM10	0.0007	NOx	0.001
Light Commercial	Petrol	N1-I	Euro 4	CO2	1.85	PM10	0.0003	NOx	0.000
Light Commercial	Petrol	N1-I	Euro 5	CO2	1.85	PM10	0.0003	NOx	0.000
Light Commercial	Petrol	N1-I	Euro 6 a/b/c	CO2	7.40	PM10	0.0013	NOx	0.001
Light Commercial	Diesel	N1-I	Euro 3	CO2	41.97	PM10	0.0178	NOx	0.194
Light Commercial	Diesel	N1-I	Euro 4	CO2	46.47	PM10	0.0193	NOx	0.149
Light Commercial	Diesel	N1-I	Euro 5	CO2	44.97	PM10	0.0098	NOx	0.149
Light Commercial	Diesel	N1-I	Euro 6 a/b/c	CO2	274.35	PM10	0.0599	NOx	0.809
Light Commercial	Battery el	N1-I	Electric	CO2	0.00	PM10	0.0012	NOx	0.000
Buses	Diesel	Urban Buses S	Euro III	CO2	7.46	PM10	0.0023	NOx	0.060
Buses	Diesel	Urban Buses S	Euro IV	CO2	0.00	PM10	0.0000	NOx	0.000
Buses	Diesel	Urban Buses S	Euro V	CO2	20.27	PM10	0.0049	NOx	0.089
Buses	Diesel	Urban Buses S	Euro VI A/B/C	CO2	25.05	PM10	0.0032	NOx	0.031
Buses	Battery el	-	Electric	CO2	0.00	PM10	0.0020	NOx	0.000
L-Category	Petrol	Mopeds 2-stro	Euro 3	CO2	194.64	PM10	0.0730	NOx	1.430
L-Category	Petrol	Mopeds 2-stro	Euro 4	CO2	70.19	PM10	0.0182	NOx	0.060
L-Category	Petrol	Mopeds 2-stro	Euro 5	CO2	92.38	PM10	0.0240	NOx	0.079

Table 3: CO2, PM10 and NOx values at 50 km/h in Scenario 1

30 km/h									
Category	Fuel	Segment	Euro Standard	CO2 [t]	TOTAL	PM10 [t]	TOTAL	NOx [t]	TOTAL
Passenger Cars	Petrol	Small	Euro 3	CO2	625.11	PM10	0.1157	NOx	0.346
Passenger Cars	Petrol	Small	Euro 4	CO2	1659.10	PM10	0.2932	NOx	0.674
Passenger Cars	Petrol	Small	Euro 5	CO2	903.63	PM10	0.1608	NOx	0.207
Passenger Cars	Petrol	Small	Euro 6 a/b/c	CO2	3713.31	PM10	0.6398	NOx	0.710
Passenger Cars	Diesel	Small	Euro 3	CO2	340.06	PM10	0.1330	NOx	1.560
Passenger Cars	Diesel	Small	Euro 4	CO2	668.10	PM10	0.2594	NOx	2.520
Passenger Cars	Diesel	Small	Euro 5	CO2	762.56	PM10	0.1387	NOx	2.770
Passenger Cars	Diesel	Small	Euro 6 a/b/c	CO2	2469.75	PM10	0.4494	NOx	8.060
Passenger Cars	Battery el	Small	Electric	CO2	0.00	PM10	0.0280	NOx	0.000
Light Commercial	Petrol	N1-I	Euro 3	CO2	4.21	PM10	0.0008	NOx	0.002
Light Commercial	Petrol	N1-I	Euro 4	CO2	2.14	PM10	0.0004	NOx	0.001
Light Commercial	Petrol	N1-I	Euro 5	CO2	2.14	PM10	0.0004	NOx	0.000
Light Commercial	Petrol	N1-I	Euro 6 a/b/c	CO2	8.59	PM10	0.0015	NOx	0.001
Light Commercial	Diesel	N1-I	Euro 3	CO2	48.08	PM10	0.0203	NOx	0.222
Light Commercial	Diesel	N1-I	Euro 4	CO2	53.24	PM10	0.0223	NOx	0.201
Light Commercial	Diesel	N1-I	Euro 5	CO2	51.52	PM10	0.0110	NOx	0.187
Light Commercial	Diesel	N1-I	Euro 6 a/b/c	CO2	314.30	PM10	0.0670	NOx	1.020
Light Commercial	Battery el	N1-I	Electric	CO2	0.00	PM10	0.0013	NOx	0.000
Buses	Diesel	Urban Buses Stand	Euro III	CO2	9.30	PM10	0.0029	NOx	0.084
Buses	Diesel	Urban Buses Stand	Euro IV	CO2	0.00	PM10	0.0000	NOx	0.000
Buses	Diesel	Urban Buses Stand	Euro V	CO2	25.40	PM10	0.0057	NOx	0.171
Buses	Diesel	Urban Buses Stand	Euro VI A/B/C	CO2	26.64	PM10	0.0036	NOx	0.044
Buses	Battery el	-	Electric	CO2	0.00	PM10	0.0022	NOx	0.000
L-Category	Petrol	Mopeds 2-stroke <=	Euro 3	CO2	194.64	PM10	0.0776	NOx	1.430
L-Category	Petrol	Mopeds 2-stroke <=	Euro 4	CO2	70.19	PM10	0.0199	NOx	0.060
L-Category	Petrol	Mopeds 2-stroke <=	Euro 5	CO2	92.38	PM10	0.0262	NOx	0.079

Table 4: CO2, PM10 and NOx values at 30 km/h in Scenario 1

In COPERT, emissions do not increase with a longer travel time because they are a function of the distance traveled (km). Travel time itself is not a direct parameter used for calculating emissions, unless the distance, average speed, and vehicle type change.

There's a clear difference between the emissions produced at 30 km/h and 50 km/h. In almost all vehicle categories, **pollutant emissions are higher at 30 km/h than at 50 km/h**.

Both gasoline and diesel cars show a significant increase in emissions when speed is reduced from 50 km/h to 30 km/h. This is particularly noticeable in newer Euro standard categories (Euro 4, 5, 6). COPERT calculates hot-engine emissions using emission factors that directly depend on the vehicle's average speed [75].

A speed of 30 km/h is more representative of urban driving, which often involves frequent stop-and-go cycles, accelerations, decelerations, and extended idling periods. Even with a warm engine, these less fluid driving conditions lead to less efficient combustion and, consequently, higher emissions per kilometer.

In contrast, a speed of 50 km/h can represent smoother urban driving or initial rural conditions, where traffic flow is more regular. This allows the engine to operate under more optimal and efficient conditions, resulting in lower emissions per kilometer.

Therefore, the observed decrease in emissions when increasing speed from 30 to 50 km/h in the COPERT model is a direct result of its speed-dependent emission factors. These factors reflect that, for

many pollutants, driving at a moderate, smoother pace is more emission-efficient per kilometer than driving at lower speeds with frequent interruptions typical of urban traffic [75]. This model is also found in the literature and confirms that when cold-start emissions are taken into account, the resulting emission curve shows a peak at lower speeds, followed by a stabilization as the engine gradually reaches operating conditions, and then another peak at higher speeds. This is generally called “U-shaped” emission curve [85]. Generally, lower speeds are associated with start and stop driving periods, but when the speed is too high, the engine loads require more fuel, leading to higher emissions [86].

As is shown in the following figures, PM is unaffected by vehicles speed, but NO_x, CO and CO₂ emissions follow the typical U-shape behavior [85][86].

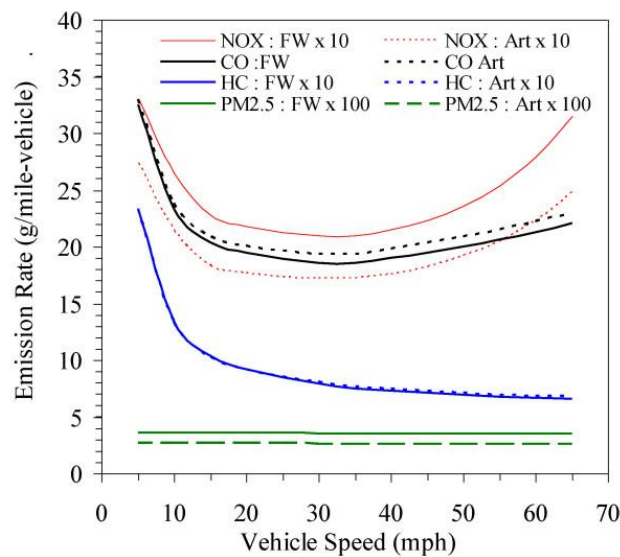


Fig. 39: Vehicle emission as function of speed [85]

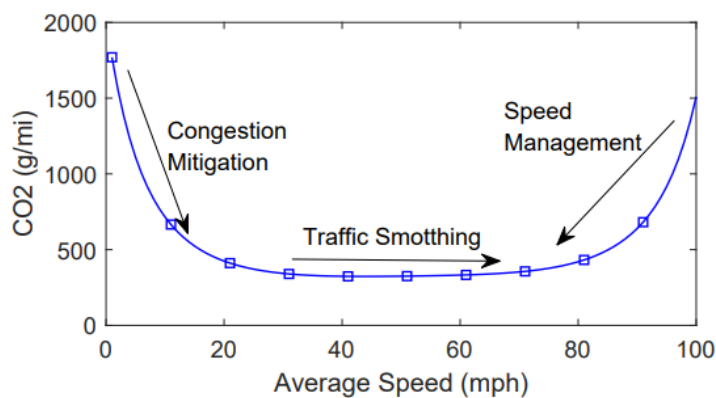


Fig. 40. CO₂ emission as a function of average speed [86]

In the following graphs it is possible to visualize the difference in the CO₂, PM₁₀ and NO_x values emitted by vehicles by comparing them with the two speeds, divided by fuel use and Euro standard:

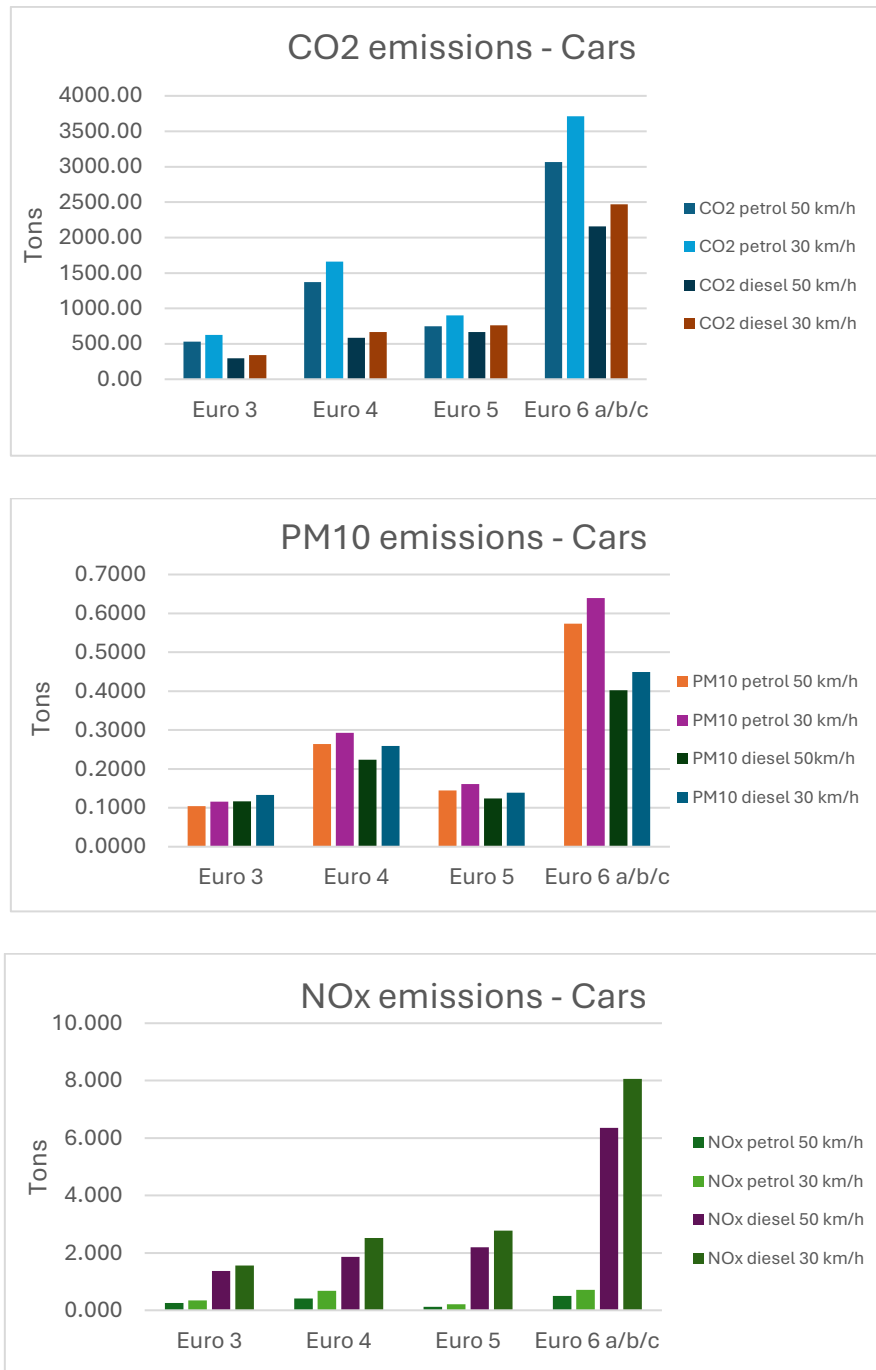


Fig. 41: Comparison of CO₂, PM₁₀ and NO_x emissions at 30 km/h and 50 km/h for cars in Scenario 1

CO₂ and PM₁₀ values are higher in petrol cars, while NO_x is greater for a diesel fuel type car. It's possible also to notice how the tons of CO₂ emitted are higher than the other two pollutants. This is

also valid for the other vehicles analyzed, as the charts below show, except for the opposite situation for diesel and petrol trucks:

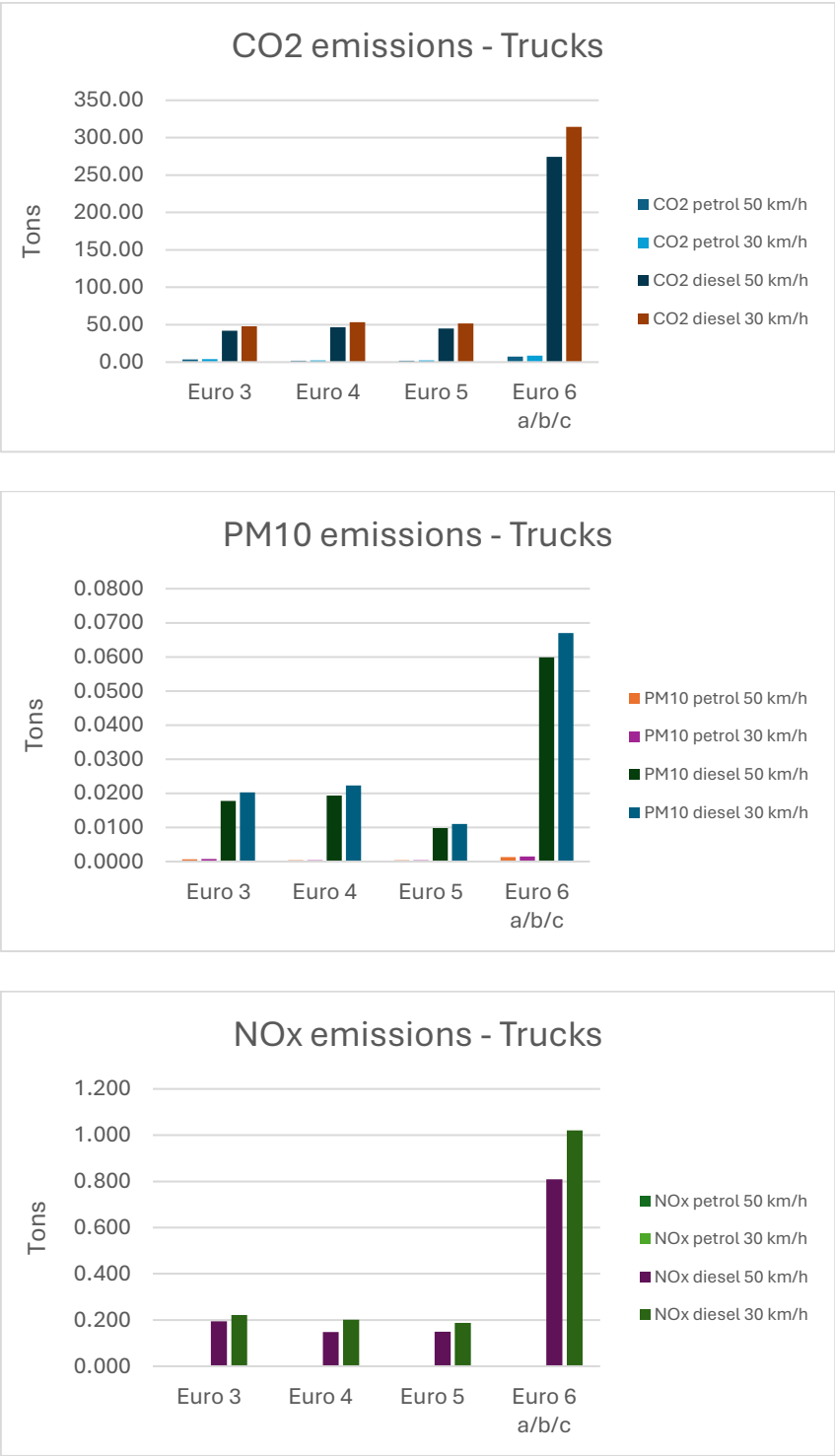


Fig. 42: Comparison of CO2, PM10 and NOx emissions at 30 km/h and 50 km/h for trucks in Scenario 1

For buses, which are only diesel, emissions are still higher at lower speeds, no emissions are registered for Euro 4 vehicles because in the calculation there are no Euro 4 buses:

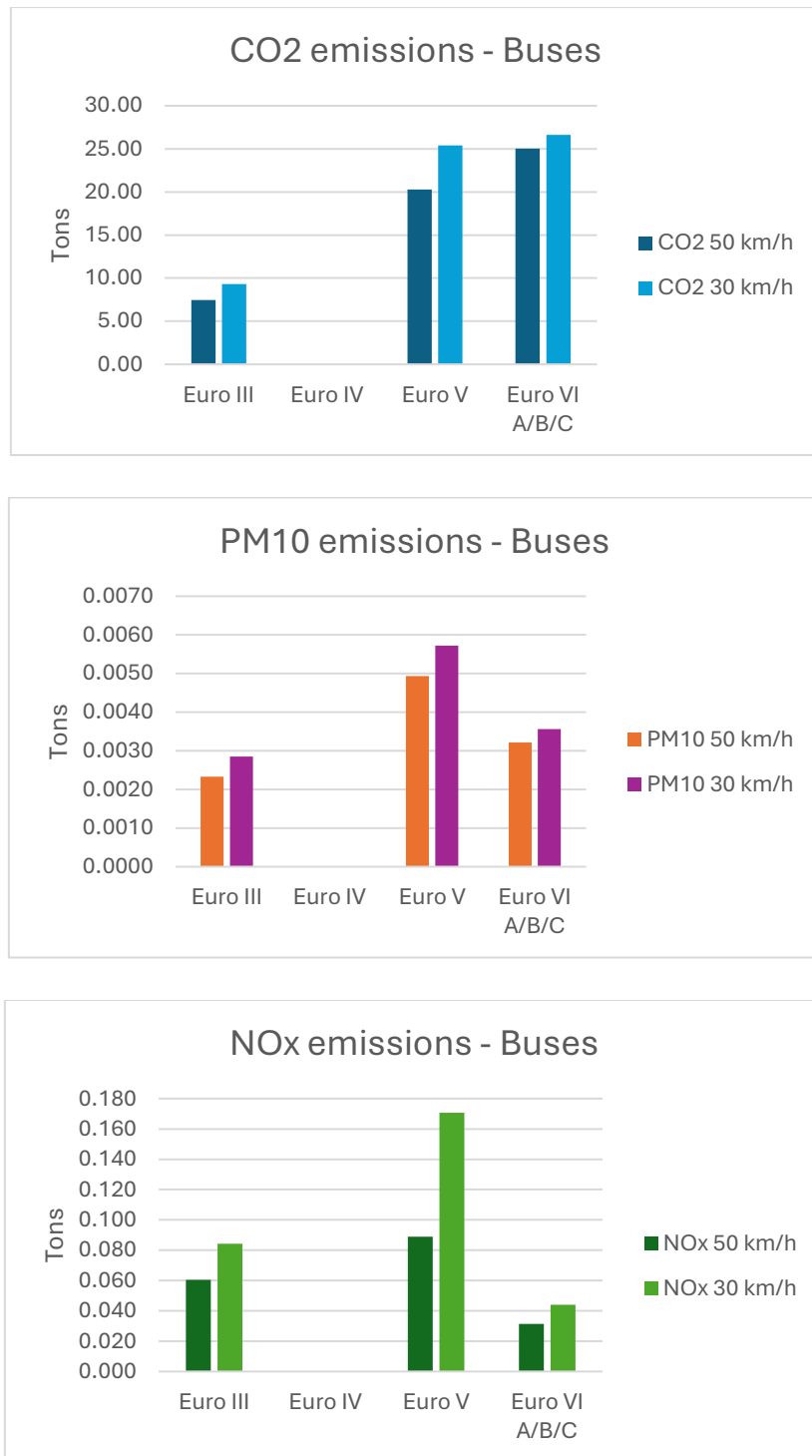


Fig. 43: Comparison of CO2, PM10 and NOx emissions at 30 km/h and 50 km/h for buses (only diesel) in Scenario 1

A further consideration to be made concerns all pollutant values for motorcycles, which do not appear to change with a decrease in speed:

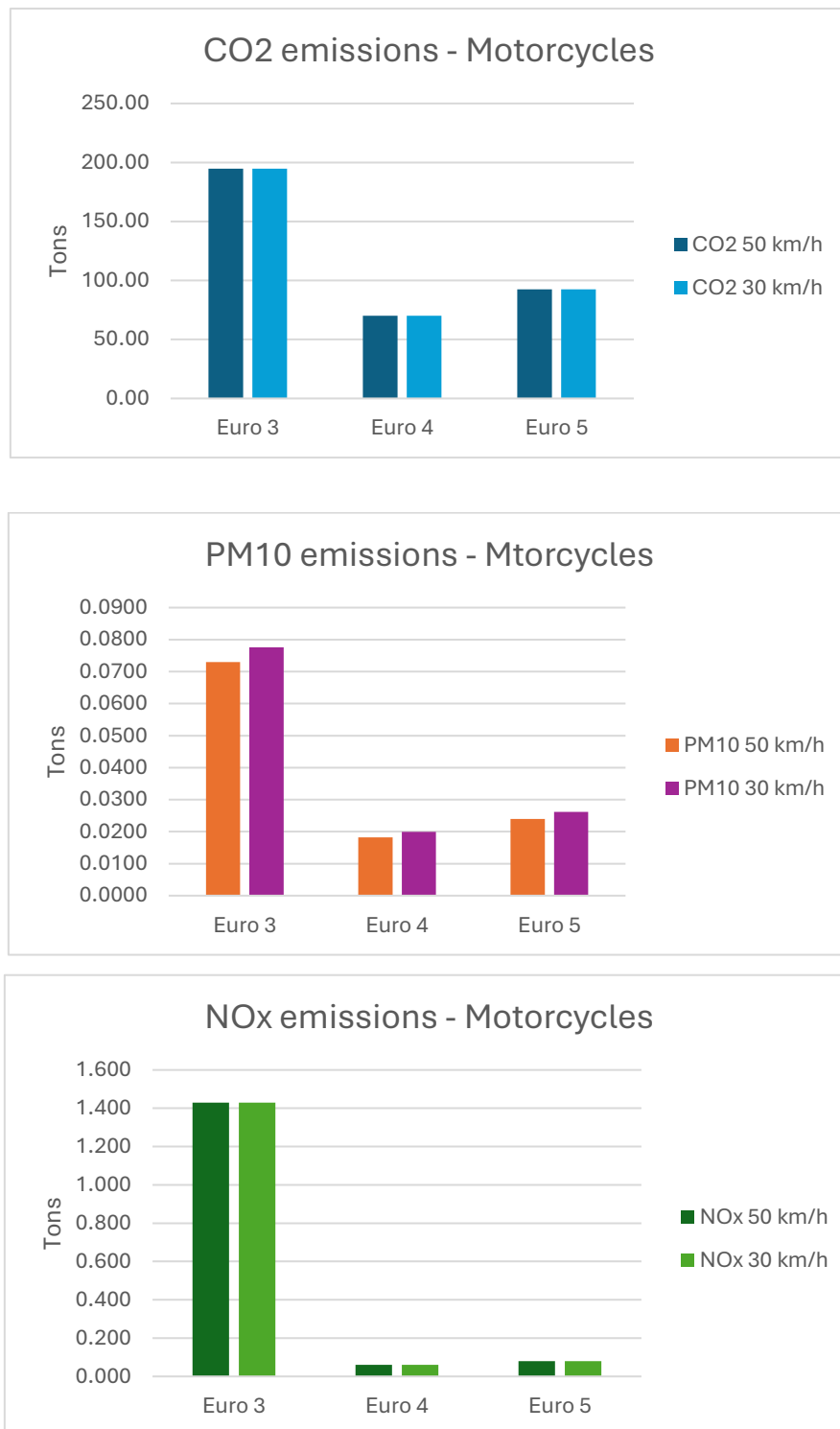


Fig. 44: Comparison of CO2, PM10 and NOx emissions at 30 km/h and 50 km/h for motorcycles (only petrol) in Scenario 1

Similarly, for electric vehicles, pollutant values are higher at lower speeds, just as they are for the other vehicles analyzed, but higher in cars instead of trucks or buses.

It is important to specify that the only pollutant contributing to an electric vehicle's emissions is PM10, as it does not depend on the vehicle's engine but on non-exhaust sources. In the case of COPERT, particulate matter emissions are the contribution of tire wear, brake wear, and road abrasion.

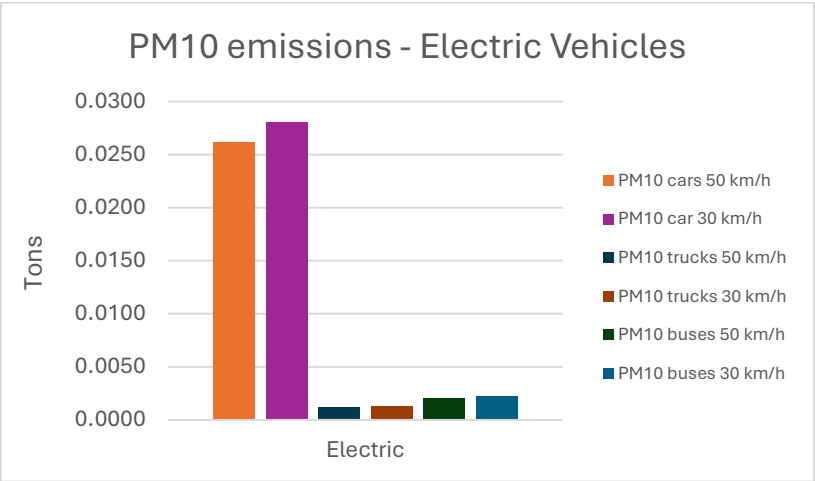


Fig. 45: Comparison of PM10 emissions at 30 km/h and 50 km/h for electric vehicles in Scenario 1

Given that these data are heavily influenced by the number of vehicles in each category, it is useful to analyze the situation from an alternative perspective. **COPERT** shows that emissions increase as speed decreases, a trend whose magnitude varies depending on the specific pollutant. The following graphs present this increase in percentage terms:

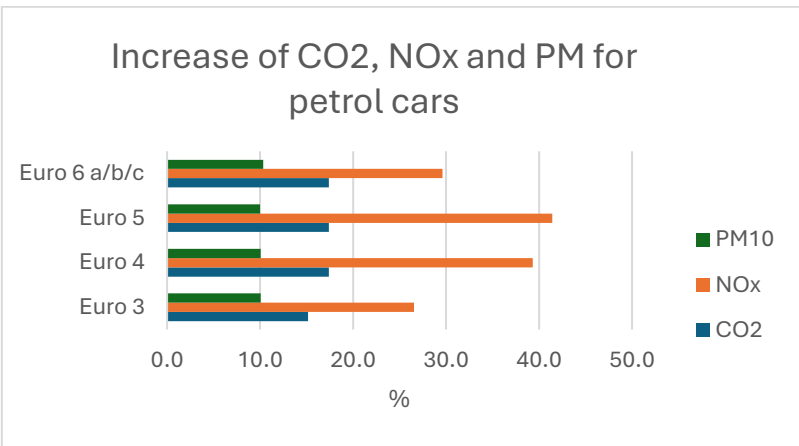


Fig. 46: Percentage increase of pollutants by lowering the speed for petrol cars in Scenario 1

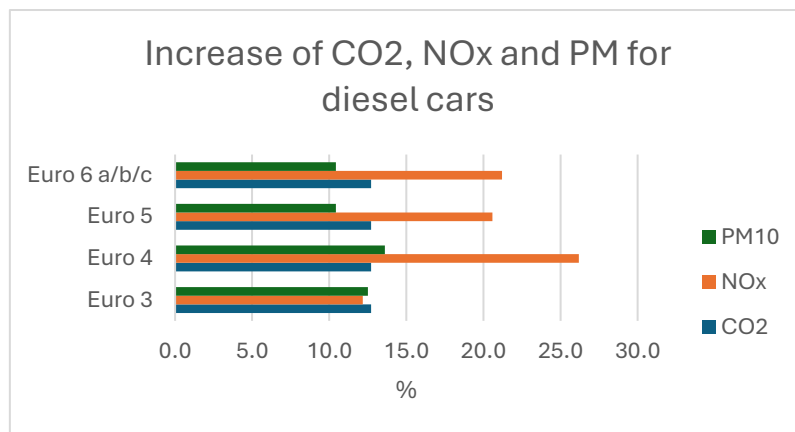


Fig. 47: Percentage increase of pollutants by lowering the speed for diesel cars in Scenario 1

For cars, the pollutant most affected by this increase is **NOx**, which rises significantly more in gasoline-powered vehicles compared to diesel ones. The same trend applies to trucks, as Figure 48 shows.

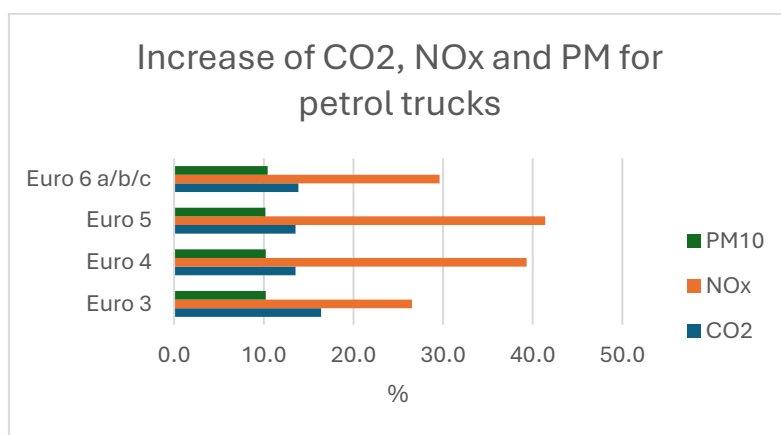


Fig. 48: Percentage increase of pollutants by lowering the speed for petrol trucks in Scenario 1

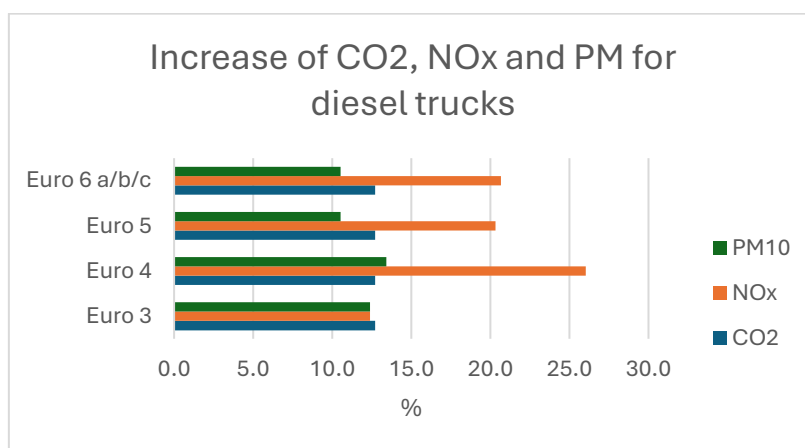


Fig. 49: Percentage increase of pollutants by lowering the speed for diesel trucks in Scenario 1

In the case of buses as well, which are exclusively diesel-powered in this analysis, **NOx** is the pollutant that shows the largest increase. For motorcycles, on the other hand, **COPERT** records constant values for both **CO2** and **NOx**, while **PM10** is the only pollutant that varies with changes in speed, though not by a significant amount:

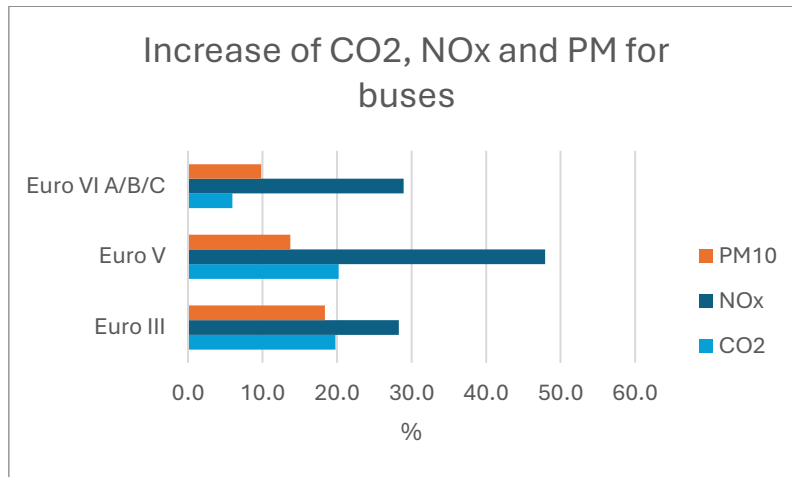


Fig. 50: Percentage increase of pollutants by lowering the speed for buses in Scenario 1

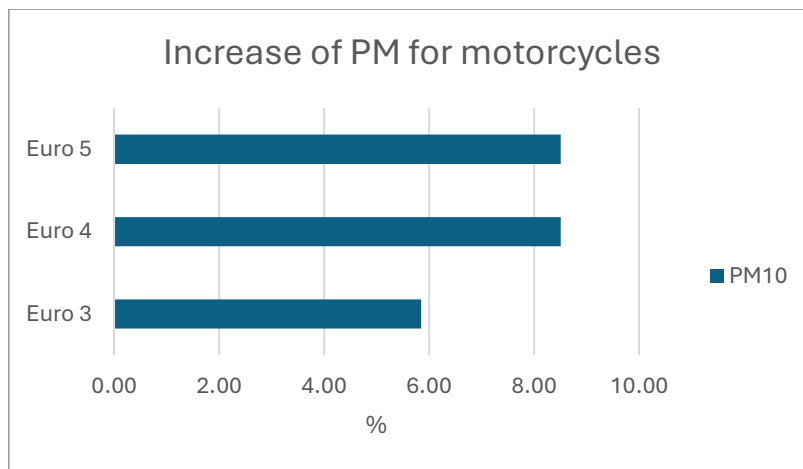


Fig. 51: Percentage increase of PM10 by lowering the speed for motorcycles in Scenario 1

These values for **CO2**, **PM10**, and **NOx** each represent the total emissions for their respective vehicle categories, based on the assumed typical fleet composition of the San Salvador district.

To gain a more precise understanding of individual vehicle emissions in the area, it's possible to calculate the emissions for a single vehicle within each category. This is done by dividing the total emissions obtained from **COPERT** by the number of vehicles for that specific fuel type and Euro standard. This situation is illustrated in *Tables 5 and 6*.

50 km/h					
Category	Fuel	Euro Standard	Tons CO2	Tons PM10	Tons NOx
Car	Petrol	Euro 3	1.481	0.0003	0.0007
Car	Petrol	Euro 4	1.511	0.0003	0.0005
Car	Petrol	Euro 5	1.511	0.0003	0.0002
Car	Petrol	Euro 6 a/b/c	1.511	0.0003	0.0002
Car	Diesel	Euro 3	1.499	0.0006	0.0069
Car	Diesel	Euro 4	1.499	0.0006	0.0048
Car	Diesel	Euro 5	1.499	0.0003	0.0050
Car	Diesel	Euro 6 a/b/c	1.499	0.0003	0.0044
Car	Battery electric	Electric	0.000	0.0002	0.0000
Truck	Petrol	Euro 3	1.760	0.0003	0.0007
Truck	Petrol	Euro 4	1.850	0.0003	0.0005
Truck	Petrol	Euro 5	1.850	0.0003	0.0002
Truck	Petrol	Euro 6 a/b/c	1.850	0.0003	0.0002
Truck	Diesel	Euro 3	1.499	0.0006	0.0069
Truck	Diesel	Euro 4	1.499	0.0006	0.0048
Truck	Diesel	Euro 5	1.499	0.0003	0.0050
Truck	Diesel	Euro 6 a/b/c	1.499	0.0003	0.0044
Truck	Battery electric	Electric	0.000	0.0002	0.0000
Bus	Diesel	Euro III	7.460	0.0023	0.0604
Bus	Diesel	Euro IV	0.000	0.000	0.000
Bus	Diesel	Euro V	6.757	0.0016	0.0296
Bus	Diesel	Euro VI A/B/C	8.350	0.0011	0.0104
Bus	Battery electric	Electric	0.000	0.0010	0.0000
Motorcycle	Petrol	Euro 3	0.535	0.0002	0.0039
Motorcycle	Petrol	Euro 4	0.516	0.0001	0.0004
Motorcycle	Petrol	Euro 5	0.516	0.0001	0.0004

Table 5: Comparison of CO2, PM10 and NOx annual emissions at 50 km/h for each single vehicle in Scenario 1

30 km/h					
Category	Fuel	Euro Standard	Tons CO2	Tons PM10	Tons NOx
Car	Petrol	Euro 3	1.746	0.0003	0.0010
Car	Petrol	Euro 4	1.829	0.0003	0.0007
Car	Petrol	Euro 5	1.829	0.0003	0.0004
Car	Petrol	Euro 6 a/b/c	1.829	0.0003	0.0003
Car	Diesel	Euro 3	1.717	0.0007	0.0079
Car	Diesel	Euro 4	1.717	0.0007	0.0065
Car	Diesel	Euro 5	1.717	0.0003	0.0062
Car	Diesel	Euro 6 a/b/c	1.717	0.0003	0.0056
Car	Battery electric	Electric	0.000	0.0002	0.0000
Truck	Petrol	Euro 3	2.105	0.0004	0.0010
Truck	Petrol	Euro 4	2.140	0.0004	0.0007
Truck	Petrol	Euro 5	2.140	0.0004	0.0004
Truck	Petrol	Euro 6 a/b/c	2.148	0.0004	0.0003
Truck	Diesel	Euro 3	1.717	0.0007	0.0079
Truck	Diesel	Euro 4	1.717	0.0007	0.0065
Truck	Diesel	Euro 5	1.717	0.0004	0.0062
Truck	Diesel	Euro 6 a/b/c	1.717	0.0004	0.0056
Truck	Battery electric	Electric	0.000	0.0002	0.0000
Bus	Diesel	Euro III	9.300	0.0029	0.0843
Bus	Diesel	Euro IV	0.000	0.0000	0.0000
Bus	Diesel	Euro V	8.467	0.0019	0.0569
Bus	Diesel	Euro VI A/B/C	8.880	0.0012	0.0147
Bus	Battery electric	Electric	0.000	0.0011	0.0000
Motorcycle	Petrol	Euro 3	0.535	0.0002	0.0039
Motorcycle	Petrol	Euro 4	0.516	0.0001	0.0004
Motorcycle	Petrol	Euro 5	0.516	0.0001	0.0004

Table 6: Comparison of CO2, PM10 and NOx annual emissions at 30 km/h for each single vehicle in Scenario 1

50 km/h (single vehicle-daily)					
Category	Fuel	Euro Standard	Tons CO2	Tons PM10	Tons NOx
Car	Petrol	Euro 3	0.004058	0.0000008	0.0000019
Car	Petrol	Euro 4	0.004140	0.0000008	0.0000012
Car	Petrol	Euro 5	0.004140	0.0000008	0.0000007
Car	Petrol	Euro 6 a/b/c	0.004140	0.0000008	0.0000007
Car	Diesel	Euro 3	0.004107	0.0000016	0.0000190
Car	Diesel	Euro 4	0.004107	0.0000016	0.0000131
Car	Diesel	Euro 5	0.004107	0.0000008	0.0000136
Car	Diesel	Euro 6 a/b/c	0.004107	0.0000008	0.0000121
Car	Battery electric	Electric	0.000000	0.0000005	0.0000000
Truck	Petrol	Euro 3	0.004822	0.0000009	0.0000019
Truck	Petrol	Euro 4	0.005068	0.0000009	0.0000012
Truck	Petrol	Euro 5	0.005068	0.0000009	0.0000007
Truck	Petrol	Euro 6 a/b/c	0.005068	0.0000009	0.0000007
Truck	Diesel	Euro 3	0.004107	0.0000017	0.0000190
Truck	Diesel	Euro 4	0.004107	0.0000017	0.0000131
Truck	Diesel	Euro 5	0.004107	0.0000009	0.0000136
Truck	Diesel	Euro 6 a/b/c	0.004107	0.0000009	0.0000121
Truck	Battery electric	Electric	0.000000	0.0000005	0.0000000
Bus	Diesel	Euro III	0.020438	0.0000064	0.0001656
Bus	Diesel	Euro IV	0.000000	0.0000000	0.0000000
Bus	Diesel	Euro V	0.018511	0.0000045	0.0000812
Bus	Diesel	Euro VI A/B/C	0.022877	0.0000029	0.0000286
Bus	Battery electric	Electric	0.000000	0.0000028	0.0000000
Motorcycle	Petrol	Euro 3	0.001465	0.0000005	0.0000108
Motorcycle	Petrol	Euro 4	0.001414	0.0000004	0.0000012
Motorcycle	Petrol	Euro 5	0.001414	0.0000004	0.0000012

Table 7: Comparison of CO2, PM10 and NOX daily emissions at 50 km/h for each single vehicle in Scenario 1

30 km/h (single vehicle-daily)					
Category	Fuel	Euro Standard	Tons CO2	Tons PM10	Tons NOx
Car	Petrol	Euro 3	0.00478	0.0000009	0.000003
Car	Petrol	Euro 4	0.00501	0.0000009	0.000002
Car	Petrol	Euro 5	0.00501	0.0000009	0.000001
Car	Petrol	Euro 6 a/b/c	0.00501	0.0000009	0.000001
Car	Diesel	Euro 3	0.00471	0.0000018	0.000022
Car	Diesel	Euro 4	0.00471	0.0000018	0.000018
Car	Diesel	Euro 5	0.00471	0.0000009	0.000017
Car	Diesel	Euro 6 a/b/c	0.00471	0.0000009	0.000015
Car	Battery electric	Electric	0.000000	0.0000006	0.000000
Truck	Petrol	Euro 3	0.00577	0.0000010	0.000003
Truck	Petrol	Euro 4	0.00586	0.0000010	0.000002
Truck	Petrol	Euro 5	0.00586	0.0000010	0.000001
Truck	Petrol	Euro 6 a/b/c	0.00588	0.0000010	0.000001
Truck	Diesel	Euro 3	0.00470	0.0000020	0.000022
Truck	Diesel	Euro 4	0.00471	0.0000020	0.000018
Truck	Diesel	Euro 5	0.00471	0.0000010	0.000017
Truck	Diesel	Euro 6 a/b/c	0.00471	0.0000010	0.000015
Truck	Battery electric	Electric	0.000000	0.0000006	0.000000
Bus	Diesel	Euro III	0.02548	0.0000078	0.000231
Bus	Diesel	Euro IV	0.000000	0.0000000	0.000000
Bus	Diesel	Euro V	0.02320	0.0000052	0.000156
Bus	Diesel	Euro VI A/B/C	0.02433	0.0000033	0.000040
Bus	Battery electric	Electric	0.000000	0.0000030	0.000000
Motorcycle	Petrol	Euro 3	0.00147	0.0000006	0.000011
Motorcycle	Petrol	Euro 4	0.00141	0.0000004	0.000001
Motorcycle	Petrol	Euro 5	0.00141	0.0000004	0.000001

Table 8: Comparison of CO2, PM10 and NOX daily emissions at 50 km/h for each single vehicle in Scenario 1

Based on these tables and the **COPERT** model, it is clear that **Euro 3, Euro 6, and Euro 5 diesel buses** are the primary contributors to **CO₂** emissions. They are followed by petrol trucks and petrol cars, with a less significant distinction between the various Euro standards.

When comparing pollutants, **PM₁₀** and **NO_x** are emitted in smaller quantities overall. However, the same vehicle categories—buses, trucks, and cars—follow the same order of responsibility for these emissions as well.

SCENARIO 2

Mean activity = 10.000 km/y

Lifetime activity = 120.000 km

Trip length = 0.5 – 1 – 1.5 – 2 – 2.5 – 3 – 3.5 – 4 – 4.5 – 5 – 10 – 15 – 20 – 25 – 30 – 35 – 40 – 45 – 100 km

In this scenario, the trip length changes from its base value of 20 km, ranging from 0.5 km to 100 km. The objective is to evaluate what happens in the first kilometers of the journey when the engine is still cold, then to assess a more stable situation from 5 km to 45 km with a 5 km step, and finally to evaluate what happens if the trip length increases to 100 km. In this way, it is possible to account for how emissions vary depending on whether the trip consists of several short segments or a few longer ones.

The focus is to understand how the change of these variables can influence results in terms of CO₂, PM₁₀ and NO_x emissions

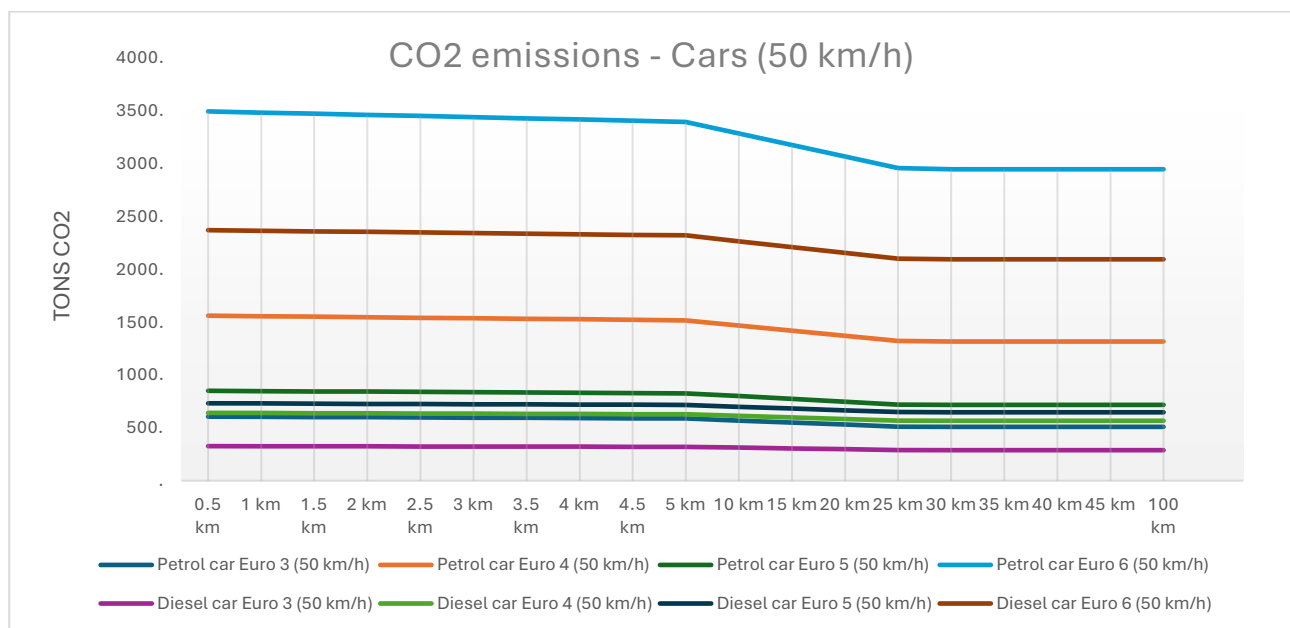


Fig. 52: Comparison of CO₂ emissions at 50 km/h for petrol cars

The trend for 50 km/h cars shows a general decrease in CO₂ emissions as the traveled distance increases, almost reaching an asymptotic state around 25 km until 100 km. This pattern is even more pronounced for vehicles that meet higher Euro standards, especially Euro 6 petrol cars. Below is an illustration of the behavior of Euro 6 petrol and diesel cars as speed changes, which maintain the same trend:

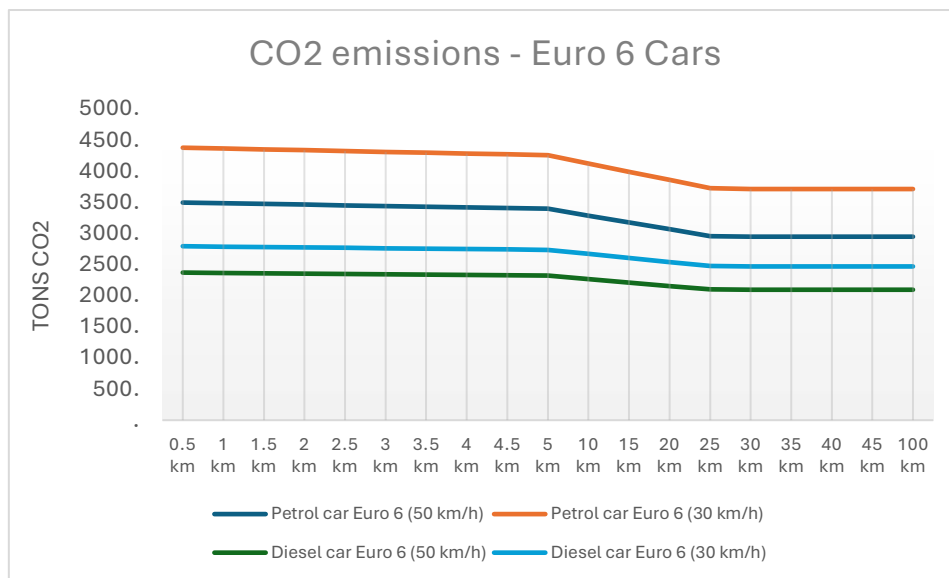


Fig. 53: Comparison of CO2 emissions at 30 km/h and 50 km/h for Euro 6 cars

What's clear is that for both fuel types, **CO2 emissions are higher at lower speeds**, even though the trend of decreasing emissions with increasing distance remains. The situation does not change when comparing cars with different Euro standards under the same conditions.

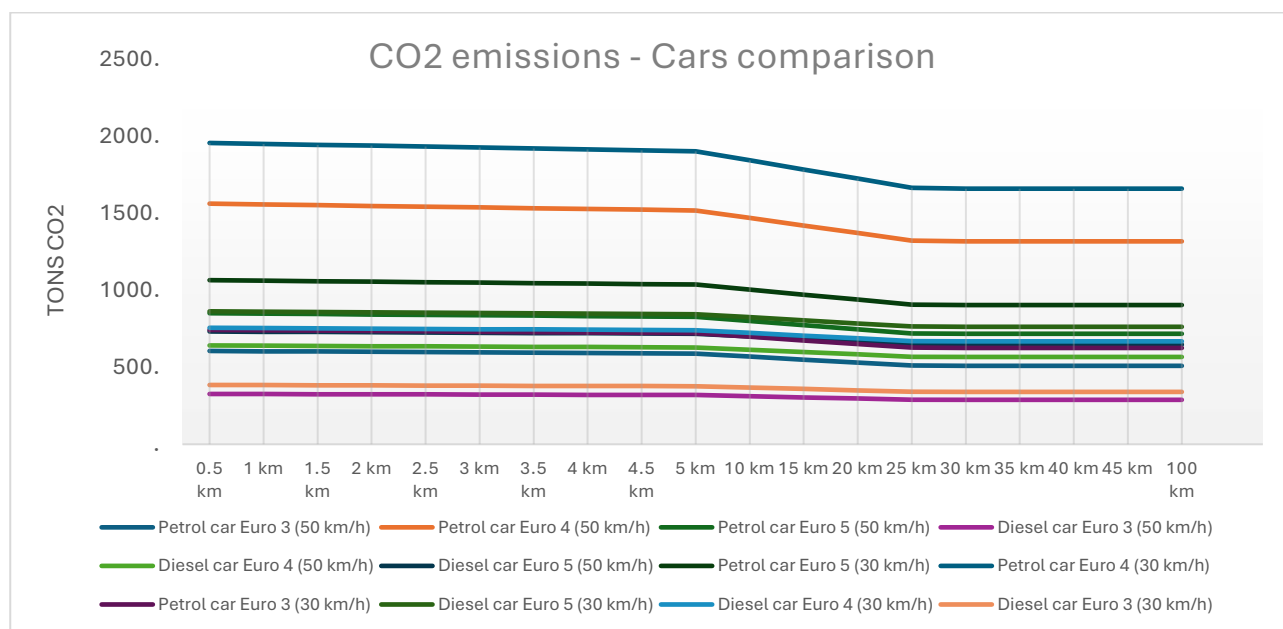


Fig. 54: Comparison of CO2 emissions at 30 km/h and 50 km/h for cars

Comparing both speed scenarios for Euro 6 petrol and diesel cars, which is the one more evident, the trend for PM10 is the same: at lower speeds, pollution levels are higher. Petrol cars emit more PM10, but as the distance traveled increases, there is a slight decrease in emissions, as the tables below show:

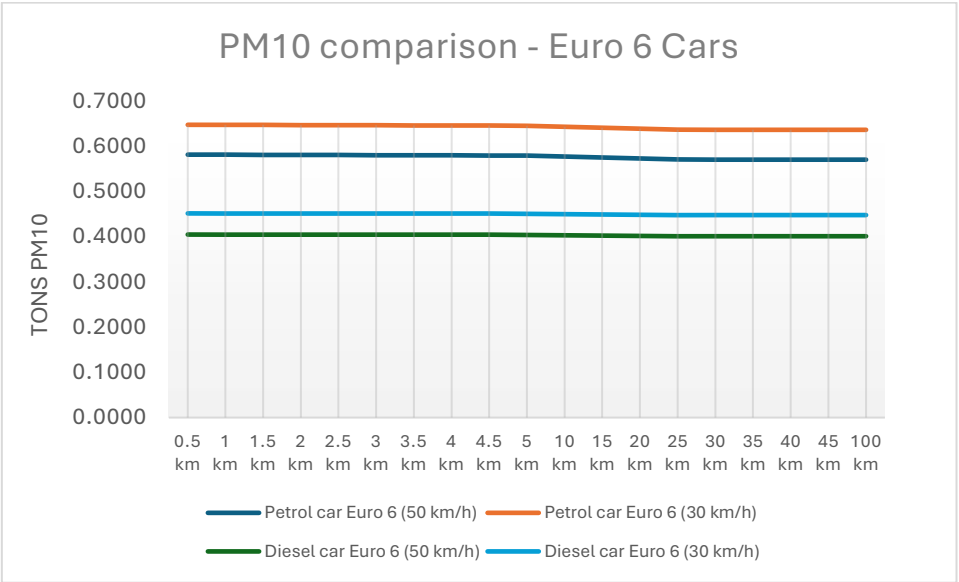


Fig. 55: Comparison of PM10 emissions at 30 km/h and 50 km/h for Euro 6 cars

Concerning NOx, the trend is only clear for Euro 3, 4, and 5 diesel cars and trucks in the 50 km/h speed scenario (the other pollutant values for other vehicles and fuel types don't change). However, at 30 km/h, the values change a little bit also for petrol vehicles:

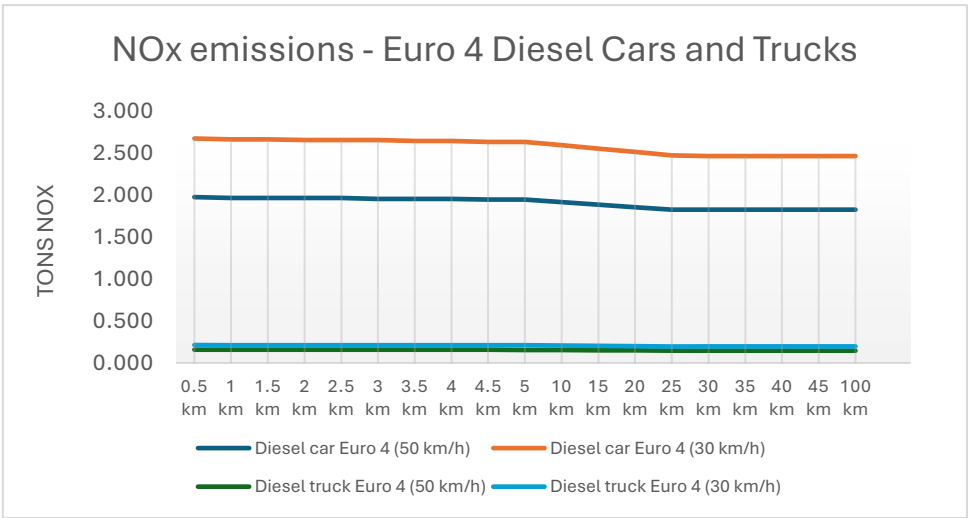


Fig. 56: NOx emissions at 30 km/h and 50 km/h for Diesel cars and trucks

With regard to the other modes of transport analyzed, the situation is quite similar. Trucks exhibit higher emissions at lower speeds and a negative trend in CO₂ emissions as the distance traveled increases, mirroring the behavior of cars. Buses show consistent emission values regardless of the distance covered, with higher emissions at 30 km/h compared to 50 km/h. Motorcycles, by contrast, consistently maintain the same emission value.

The most significant situations for each of the three vehicle types are highlighted in the graph below:

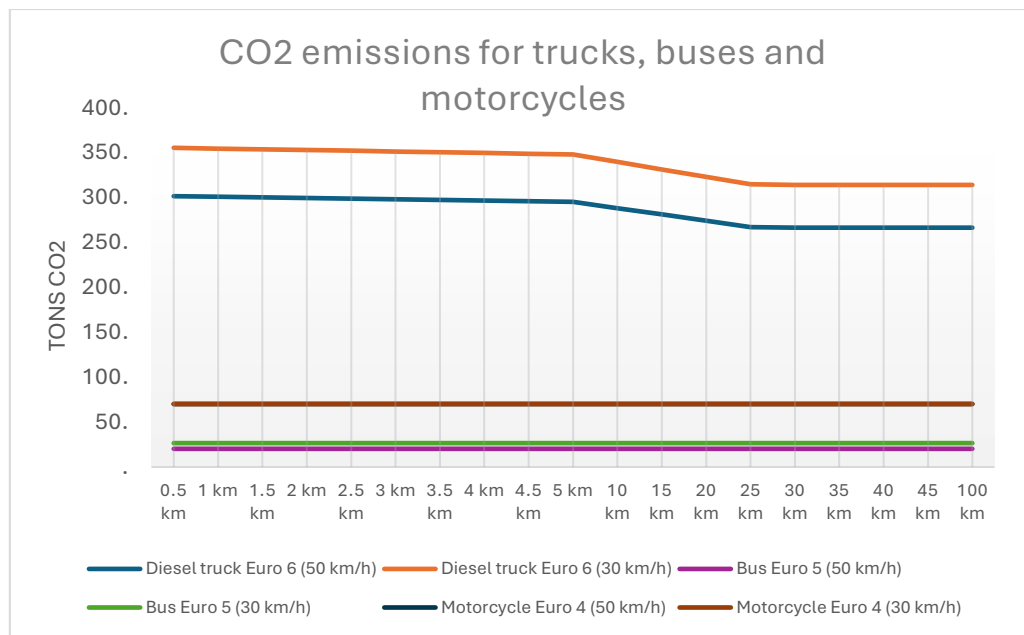


Fig. 57: Comparison of CO₂ emissions at 30 km/h and 50 km/h for trucks, buses and motorcycles

The situation for buses and motorcycles remains unchanged when analyzing the other pollutants (PM₁₀ and NO_x), with a single exception for NO_x emissions from Euro 5 and 6 buses at a speed of 30 km/h. In this specific case, the trend is not constant but shows a decrease, similar to cars and trucks.

A general conclusion from these situations is that when both **trip length** and **trip duration** increase, **emissions decrease** in both scenarios. This is due to the significant impact of "cold start" emissions, which occur when a vehicle is first turned on.

Emissions in COPERT are calculated as the sum of both cold and hot contributions (*Eq. 1*). Emissions during the engine's cold start phase (when the engine is warming up) are significantly higher than emissions from a warm, stabilized engine. The model accounts for these additional emissions using a parameter, **beta** (β), which represents the fraction of mileage driven with a cold engine or with the catalyst below its light-off temperature [75]. The beta parameter depends on several factors, including ambient temperature and, crucially, the average trip length (*l*_{trip}) [75].

According to COPERT guidelines, a shorter average trip length means that a larger proportion of the journey is driven with a cold engine, leading to higher additional emissions. Consequently, as the average trip length increases, the percentage of kilometers driven with a cold engine decreases. This results in a lower beta value. Since cold-start emissions (E_{cold}) are directly proportional to the beta parameter (Eq. 3), a reduction in beta directly translates to lower cold-start emissions.

Furthermore, emissions at **30 km/h** are higher in every case analyzed, which is consistent with the base scenario. As previously explained, this is because COPERT calculates hot-engine emissions using emission factors that are directly dependent on the vehicle's average speed. These factors were derived from experimental data that reflect typical driving conditions.

SCENARIO 3

Mean activity = 4.000 – 6.000 - 8.000 - 10.000 – 12.000 – 14.000 – 16.000 km/y

Lifetime activity = 120.000 km

Trip length = 20 km

Trip duration = 0.4 h

The purpose of this scenario is to simulate how emission values could change by changing the range of the **Mean Activity** parameter for both 30 km/h and 50 km/h. In the COPERT program, these variables are distinct and independent.

- **Lifetime cumulative activity** refers to the total mileage a vehicle travels over its entire lifespan. It's a static value used for specific calculations, such as evaporative emissions or engine degradation.
- **Mean activity** refers to the average annual mileage for each vehicle. It's a dynamic value used to calculate emissions for a given year in reality [73].

The "mean activity" is the primary data used to calculate annual emissions. COPERT multiplies the emission rate per kilometer (g/km) by the average annual mileage to get the total emissions for a year.

For this reason, changing the value of lifetime activity leaves pollutant emissions unchanged. However, changing the mean activity will lead to different results.

It is evident that **CO2 emissions increase with Mean Activity** for every category and fuel type analyzed, at both 50 km/h and 30 km/h. Consistent with the two previous scenarios, emissions are higher at lower speeds, for the reasons already discussed.

50 km/h											
Category	Fuel	Segment	Euro Standard	CO2 [t]	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	CO2	212.10	318.15	424.21	530.26	636.31	742.37	848.42
Passenger Cars	Petrol	Small	Euro 4	CO2	548.26	822.40	1096.53	1370.67	1644.80	1918.94	2193.07
Passenger Cars	Petrol	Small	Euro 5	CO2	298.61	447.92	597.23	746.54	895.84	1045.15	1194.46
Passenger Cars	Petrol	Small	Euro 6 a/b/c	CO2	1227.10	1840.66	2454.21	3067.76	3681.32	4294.87	4908.42
Passenger Cars	Diesel	Small	Euro 3	CO2	118.73	178.10	237.47	296.84	356.21	415.58	474.95
Passenger Cars	Diesel	Small	Euro 4	CO2	233.27	349.91	466.55	583.19	699.83	816.47	933.11
Passenger Cars	Diesel	Small	Euro 5	CO2	266.26	399.39	532.52	665.65	798.78	931.91	1065.04
Passenger Cars	Diesel	Small	Euro 6 a/b/c	CO2	862.35	1293.52	1724.70	2155.87	2587.05	3018.22	3449.40
Passenger Cars	Battery el	Small	Euro 6 a/b/c	CO2	0.00	0.00	0.00	0.0	0.00	0.00	0.00
Light Commercial Vt	Petrol	N1-I	Euro 3	CO2	1.40	2.11	2.81	3.52	4.22	4.93	5.63
Light Commercial Vt	Petrol	N1-I	Euro 4	CO2	0.74	1.11	1.48	1.85	2.22	2.59	2.96
Light Commercial Vt	Petrol	N1-I	Euro 5	CO2	0.74	1.11	1.48	1.85	2.22	2.59	2.96
Light Commercial Vt	Petrol	N1-I	Euro 6 a/b/c	CO2	2.96	4.44	5.92	7.40	8.88	10.36	11.84
Light Commercial Vt	Diesel	N1-I	Euro 3	CO2	16.79	25.18	33.58	41.97	50.37	58.76	67.16
Light Commercial Vt	Diesel	N1-I	Euro 4	CO2	18.59	27.88	37.18	46.47	55.77	65.06	74.36
Light Commercial Vt	Diesel	N1-I	Euro 5	CO2	17.99	26.98	35.98	44.97	53.97	62.96	71.96
Light Commercial Vt	Diesel	N1-I	Euro 6 a/b/c	CO2	109.74	164.61	219.48	274.35	329.22	384.09	438.97
Light Commercial Vt	Battery el	N1-I	Euro 6 a/b/c	CO2	0.00	0.00	0.00	0.0	0.00	0.00	0.00
Buses	Diesel	Urban Bus	Euro III	CO2	2.98	4.47	5.97	7.46	8.95	10.45	11.94
Buses	Diesel	Urban Bus	Euro IV	CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Buses	Diesel	Urban Bus	Euro V	CO2	8.10	12.16	16.21	20.27	24.32	28.37	32.43
Buses	Diesel	Urban Bus	Euro VI A/B/C	CO2	10.02	15.03	20.04	25.05	30.06	35.07	40.08
Buses	Battery el	-	Euro VI A/B/C	CO2	0.00	0.00	0.00	0.0	0.00	0.00	0.00
L-Category	Petrol	Mopeds 2	Euro 3	CO2	77.85	116.78	155.71	194.64	233.56	272.49	311.42
L-Category	Petrol	Mopeds 2	Euro 4	CO2	28.07	42.11	56.15	70.19	84.22	98.26	112.30
L-Category	Petrol	Mopeds 2	Euro 5	CO2	36.95	55.43	73.90	92.38	110.86	129.33	147.81

30 km/h											
Category	Fuel	Segment	Euro Standard	NOx [t]	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	NOx	0.139	0.208	0.277	0.346	0.416	0.485	0.554
Passenger Cars	Petrol	Small	Euro 4	NOx	0.269	0.404	0.539	0.674	0.808	0.943	1.070
Passenger Cars	Petrol	Small	Euro 5	NOx	0.083	0.124	0.166	0.207	0.249	0.290	0.332
Passenger Cars	Petrol	Small	Euro 6 a/b/c	NOx	0.284	0.426	0.568	0.710	0.852	0.993	1.130
Passenger Cars	Diesel	Small	Euro 3	NOx	0.628	0.942	1.250	1.560	1.880	2.190	2.510
Passenger Cars	Diesel	Small	Euro 4	NOx	1.000	1.510	2.010	2.520	3.020	3.530	4.030
Passenger Cars	Diesel	Small	Euro 5	NOx	1.100	1.660	2.210	2.770	3.320	3.870	4.430
Passenger Cars	Diesel	Small	Euro 6 a/b/c	NOx	3.220	4.830	6.450	8.060	9.670	11.280	12.900
Passenger Cars	Battery el	Small	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000
Light Commercial	Petrol	N1-I	Euro 3	NOx	0.001	0.001	0.002	0.002	0.002	0.003	0.003
Light Commercial	Petrol	N1-I	Euro 4	NOx	0.000	0.000	0.001	0.001	0.001	0.001	0.001
Light Commercial	Petrol	N1-I	Euro 5	NOx	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Light Commercial	Petrol	N1-I	Euro 6 a/b/c	NOx	0.001	0.001	0.001	0.001	0.002	0.002	0.002
Light Commercial	Diesel	N1-I	Euro 3	NOx	0.089	0.133	0.178	0.222	0.266	0.311	0.355
Light Commercial	Diesel	N1-I	Euro 4	NOx	0.080	0.121	0.161	0.201	0.241	0.281	0.322
Light Commercial	Diesel	N1-I	Euro 5	NOx	0.075	0.112	0.150	0.187	0.225	0.262	0.300
Light Commercial	Diesel	N1-I	Euro 6 a/b/c	NOx	0.410	0.616	0.821	1.020	1.230	1.430	1.600
Light Commercial	Battery el	N1-I	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000
Buses	Diesel	Urban Bus	Euro III	NOx	0.034	0.051	0.067	0.084	0.101	0.118	0.135
Buses	Diesel	Urban Bus	Euro IV	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buses	Diesel	Urban Bus	Euro V	NOx	0.068	0.102	0.137	0.171	0.205	0.239	0.273
Buses	Diesel	Urban Bus	Euro VI A/B/C	NOx	0.018	0.026	0.035	0.044	0.053	0.062	0.070
Buses	Battery el	-	Euro VI A/B/C	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000
L-Category	Petrol	Mopeds 2	Euro 3	NOx	0.573	0.860	1.140	1.430	1.710	2.000	2.290
L-Category	Petrol	Mopeds 2	Euro 4	NOx	0.024	0.036	0.048	0.060	0.072	0.084	0.097
L-Category	Petrol	Mopeds 2	Euro 5	NOx	0.032	0.048	0.064	0.079	0.095	0.111	0.127

Tables 8, 9: CO2 emissions at 50 km/h and 30 km/h

(The matching results have been highlighted in gray)

The following graph illustrates the trend of emissions as a function of **Mean Activity** for Euro 6 standard vehicles, as the difference is slightly more pronounced than for other fuel types:

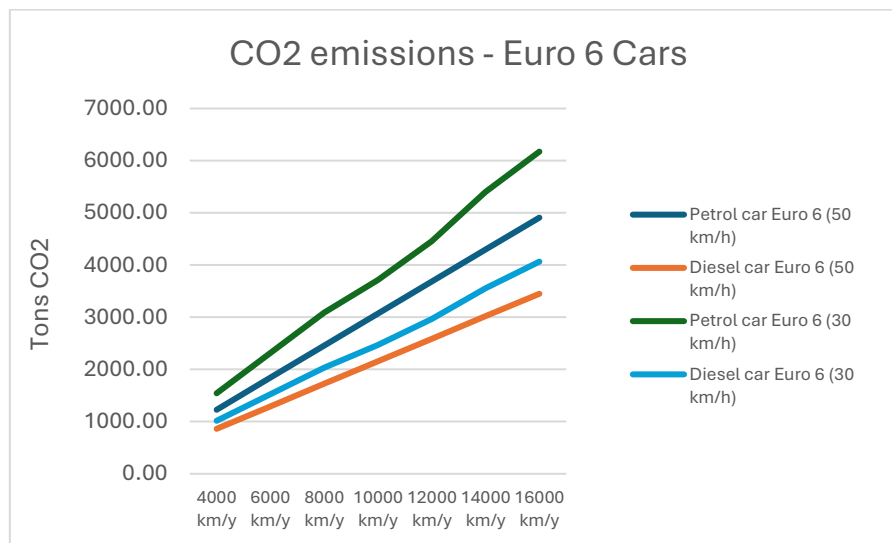


Fig. 58: Comparison of CO2 emissions at 30 km/h and 50 km/h for Euro 6 cars

Not only are emissions higher at lower speeds, but they are also greater in petrol cars than in diesel cars across both speed scenarios.

The situation is different for trucks. While their emissions also increase with both **Mean Activity** and a higher Euro standard, the emissions for diesel trucks are higher than for petrol ones, an opposite trend to that observed in cars.

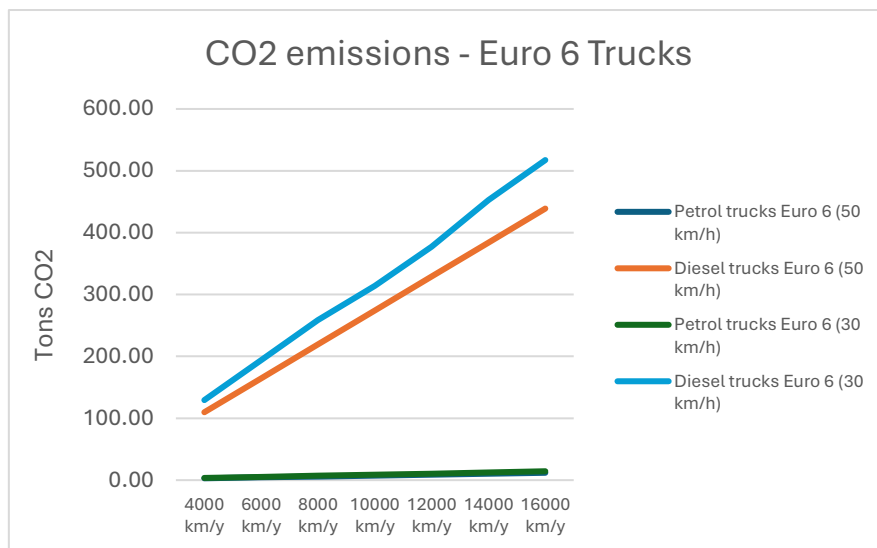


Fig. 59: Comparison of CO2 emissions at 30 km/h and 50 km/h for Euro 6 trucks

Additionally, this is the only scenario where motorcycle emissions change. They increase with increasing **Mean Activity** but remain unchanged as speed varies:

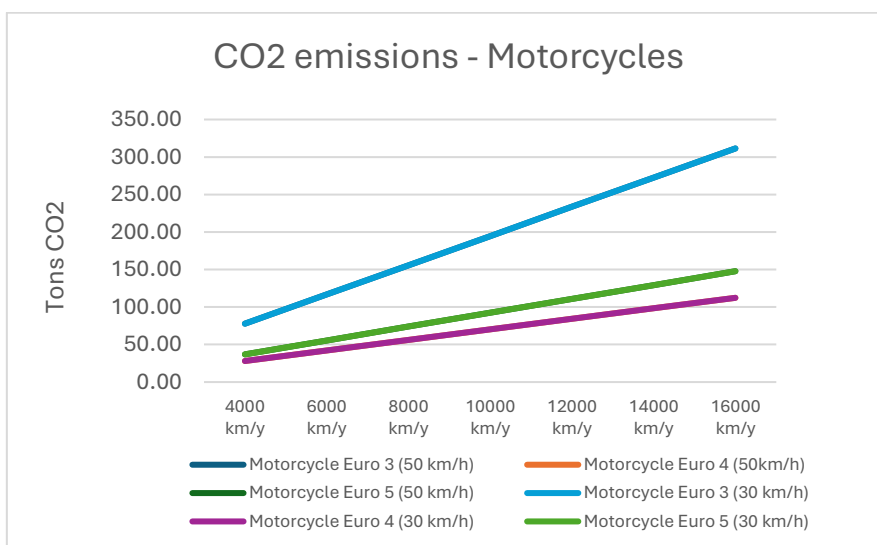


Fig. 60: Comparison of CO2 emissions at 30 km/h and 50 km/h for motorcycles

As for PM10, in this scenario, it not only increases with higher **Mean Activity** for every vehicle, just like CO2, but it also increases for electric vehicles.

50 km/h											
Category	Fuel	Segment	Euro Standard	PM10 [t]	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	PM10	0.0416	0.0624	0.0833	0.1041	0.1249	0.1457	0.167
Passenger Cars	Petrol	Small	Euro 4	PM10	0.1055	0.1582	0.2109	0.2637	0.3164	0.3692	0.422
Passenger Cars	Petrol	Small	Euro 5	PM10	0.0579	0.0868	0.1157	0.1447	0.1736	0.2025	0.231
Passenger Cars	Petrol	Small	Euro 6 a/b/c	PM10	0.2295	0.3442	0.4590	0.5737	0.6885	0.8032	0.918
Passenger Cars	Diesel	Small	Euro 3	PM10	0.0466	0.0698	0.0931	0.1164	0.1397	0.1629	0.186
Passenger Cars	Diesel	Small	Euro 4	PM10	0.0896	0.1345	0.1793	0.2241	0.2689	0.3137	0.359
Passenger Cars	Diesel	Small	Euro 5	PM10	0.0497	0.0746	0.0994	0.1243	0.1491	0.1740	0.199
Passenger Cars	Diesel	Small	Euro 6 a/b/c	PM10	0.1610	0.2415	0.3220	0.4025	0.4830	0.5635	0.644
Passenger Cars	Battery el	Small	Euro 6 a/b/c	PM10	0.0105	0.0157	0.0209	0.0261	0.0314	0.0366	0.042
Light Commercial Vt	Petrol	N1-I	Euro 3	PM10	0.0003	0.0004	0.0142	0.0007	0.0008	0.0009	0.001
Light Commercial Vt	Petrol	N1-I	Euro 4	PM10	0.0001	0.0002	0.0155	0.0003	0.0004	0.0005	0.001
Light Commercial Vt	Petrol	N1-I	Euro 5	PM10	0.0001	0.0002	0.0079	0.0003	0.0004	0.0005	0.001
Light Commercial Vt	Petrol	N1-I	Euro 6 a/b/c	PM10	0.0005	0.0008	0.0479	0.0013	0.0016	0.0018	0.002
Light Commercial Vt	Diesel	N1-I	Euro 3	PM10	0.0071	0.0107	0.0142	0.0178	0.0213	0.0249	0.028
Light Commercial Vt	Diesel	N1-I	Euro 4	PM10	0.0077	0.0116	0.0155	0.0193	0.0232	0.0271	0.031
Light Commercial Vt	Diesel	N1-I	Euro 5	PM10	0.0039	0.0059	0.0079	0.0098	0.0118	0.0137	0.016
Light Commercial Vt	Diesel	N1-I	Euro 6 a/b/c	PM10	0.0240	0.0359	0.0479	0.0599	0.0719	0.0839	0.096
Light Commercial Vt	Battery el	N1-I	Euro 6 a/b/c	PM10	0.0005	0.0007	0.0009	0.0012	0.0014	0.0016	0.002
Buses	Diesel	Urban Bus Euro III	PM10	0.0009	0.0014	0.0019	0.0023	0.0028	0.0033	0.0038	0.004
Buses	Diesel	Urban Bus Euro IV	PM10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000
Buses	Diesel	Urban Bus Euro V	PM10	0.0020	0.0030	0.0039	0.0049	0.0059	0.0069	0.0079	0.008
Buses	Diesel	Urban Bus Euro VI A/B/C	PM10	0.0013	0.0019	0.0026	0.0032	0.0039	0.0045	0.0051	0.005
Buses	Battery el	-	Euro VI A/B/C	PM10	0.0008	0.0012	0.0016	0.0020	0.0024	0.0028	0.003
L-Category	Petrol	Mopeds 2: Euro 3	PM10	0.0292	0.0438	0.0584	0.0730	0.0876	0.1022	0.1168	0.1314
L-Category	Petrol	Mopeds 2: Euro 4	PM10	0.0073	0.0109	0.0146	0.0182	0.0219	0.0255	0.0291	0.0327
L-Category	Petrol	Mopeds 2: Euro 5	PM10	0.0096	0.0144	0.0192	0.0240	0.0288	0.0336	0.0384	0.0432

30 km/h											
Category	Fuel	Segment	Euro Standard	PM10 [t]	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	PM10	0.0463	0.0694	0.0926	0.1157	0.1389	0.1620	0.1852
Passenger Cars	Petrol	Small	Euro 4	PM10	0.1173	0.1759	0.2346	0.2932	0.3519	0.4105	0.4692
Passenger Cars	Petrol	Small	Euro 5	PM10	0.0643	0.0965	0.1286	0.1608	0.1929	0.2251	0.2572
Passenger Cars	Petrol	Small	Euro 6 a/b/c	PM10	0.2559	0.3839	0.5119	0.6398	0.7678	0.8958	1.0200
Passenger Cars	Diesel	Small	Euro 3	PM10	0.0532	0.0798	0.1064	0.1330	0.1596	0.1862	0.2128
Passenger Cars	Diesel	Small	Euro 4	PM10	0.1037	0.1556	0.2075	0.2594	0.3112	0.3631	0.4150
Passenger Cars	Diesel	Small	Euro 5	PM10	0.0555	0.0832	0.1110	0.1387	0.1665	0.1942	0.2220
Passenger Cars	Diesel	Small	Euro 6 a/b/c	PM10	0.1797	0.2696	0.3595	0.4494	0.5392	0.6291	0.7190
Passenger Cars	Battery el	Small	Euro 6 a/b/c	PM10	0.0112	0.0168	0.0224	0.0280	0.0336	0.0392	0.0448
Light Commercial Vt	Petrol	N1-I	Euro 3	PM10	0.0003	0.0005	0.0006	0.0008	0.0009	0.0011	0.0012
Light Commercial Vt	Petrol	N1-I	Euro 4	PM10	0.0002	0.0002	0.0003	0.0004	0.0005	0.0005	0.0006
Light Commercial Vt	Petrol	N1-I	Euro 5	PM10	0.0002	0.0002	0.0003	0.0004	0.0005	0.0005	0.0006
Light Commercial Vt	Petrol	N1-I	Euro 6 a/b/c	PM10	0.0006	0.0009	0.0012	0.0015	0.0018	0.0021	0.0024
Light Commercial Vt	Diesel	N1-I	Euro 3	PM10	0.0081	0.0122	0.0162	0.0203	0.0244	0.0284	0.0325
Light Commercial Vt	Diesel	N1-I	Euro 4	PM10	0.0089	0.0134	0.0179	0.0223	0.0268	0.0313	0.0357
Light Commercial Vt	Diesel	N1-I	Euro 5	PM10	0.0044	0.0066	0.0088	0.0110	0.0132	0.0154	0.0176
Light Commercial Vt	Diesel	N1-I	Euro 6 a/b/c	PM10	0.0268	0.0402	0.0536	0.0670	0.0804	0.0937	0.1071
Light Commercial Vt	Battery el	N1-I	Euro 6 a/b/c	PM10	0.0005	0.0008	0.0010	0.0013	0.0015	0.0018	0.0020
Buses	Diesel	Urban Bus Euro III	PM10	0.0011	0.0017	0.0023	0.0029	0.0034	0.0040	0.0046	0.0052
Buses	Diesel	Urban Bus Euro IV	PM10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Buses	Diesel	Urban Bus Euro V	PM10	0.0023	0.0034	0.0046	0.0057	0.0069	0.0080	0.0092	0.0104
Buses	Diesel	Urban Bus Euro VI A/B/C	PM10	0.0014	0.0021	0.0029	0.0036	0.0043	0.0050	0.0057	0.0064
Buses	Battery el	-	Euro VI A/B/C	PM10	0.0009	0.0013	0.0018	0.0022	0.0027	0.0031	0.0036
L-Category	Petrol	Mopeds 2: Euro 3	PM10	0.0310	0.0465	0.0621	0.0776	0.0931	0.1086	0.1241	0.1396
L-Category	Petrol	Mopeds 2: Euro 4	PM10	0.0080	0.0120	0.0159	0.0199	0.0239	0.0279	0.0319	0.0359
L-Category	Petrol	Mopeds 2: Euro 5	PM10	0.0105	0.0157	0.0210	0.0262	0.0315	0.0367	0.0419	0.0471

Tables 10, 11: PM10 emissions at 50 km/h and 30 km/h
(The matching results have been highlighted in gray)

In previous scenarios, the PM10 value for every electric vehicle remained constant. However, a slight increase is observed in this case according to *Figure 61*:

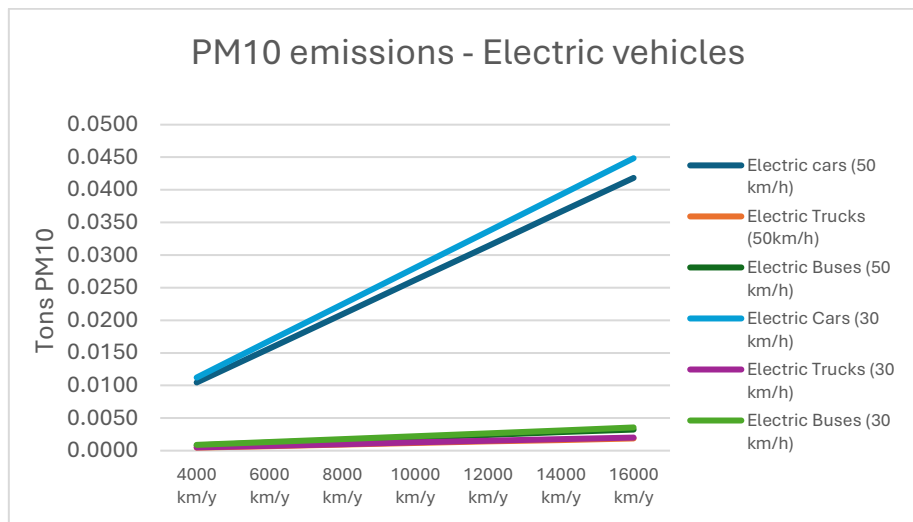


Fig. 61: Comparison of PM10 emissions at 30 km/h and 50 km/h for electric vehicles

Cars consistently exhibit the highest particulate emissions, followed by buses and trucks.

A similar situation to PM10 is observed for NOx, which also shows a positive trend with increasing **Mean Activity**. The main difference is that NOx is primarily produced by diesel-powered vehicles. For this reason, the values are higher for diesel cars and trucks and increase with the Euro standard, as can be seen in the tables below:

50 km/h											
Category	Fuel	Segment	Euro Standard	NOx (t)	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	NOx	0.102	0.153	0.204	0.254	0.305	0.356	0.407
Passenger Cars	Petrol	Small	Euro 4	NOx	0.163	0.245	0.327	0.409	0.490	0.572	0.654
Passenger Cars	Petrol	Small	Euro 5	NOx	0.049	0.073	0.097	0.122	0.146	0.170	0.194
Passenger Cars	Petrol	Small	Euro 6 a/b/c	NOx	0.200	0.300	0.400	0.499	0.599	0.699	0.799
Passenger Cars	Diesel	Small	Euro 3	NOx	0.550	0.825	1.100	1.370	1.650	1.920	2.200
Passenger Cars	Diesel	Small	Euro 4	NOx	0.746	1.110	1.490	1.860	2.230	2.610	2.980
Passenger Cars	Diesel	Small	Euro 5	NOx	0.883	1.320	1.760	2.200	2.640	3.090	3.530
Passenger Cars	Diesel	Small	Euro 6 a/b/c	NOx	2.540	3.810	5.080	6.350	7.620	8.900	10.170
Passenger Cars	Battery el	Small	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Light Commercial Vc	Petrol	N1-I	Euro 3	NOx	0.001	0.001	0.001	0.001	0.002	0.002	0.002
Light Commercial Vc	Petrol	N1-I	Euro 4	NOx	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Light Commercial Vc	Petrol	N1-I	Euro 5	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Light Commercial Vc	Petrol	N1-I	Euro 6 a/b/c	NOx	0.000	0.001	0.001	0.001	0.001	0.001	0.002
Light Commercial Vc	Diesel	N1-I	Euro 3	NOx	0.078	0.117	0.156	0.194	0.233	0.272	0.311
Light Commercial Vc	Diesel	N1-I	Euro 4	NOx	0.059	0.089	0.119	0.149	0.178	0.208	0.238
Light Commercial Vc	Diesel	N1-I	Euro 5	NOx	0.060	0.090	0.119	0.149	0.179	0.209	0.239
Light Commercial Vc	Diesel	N1-I	Euro 6 a/b/c	NOx	0.324	0.485	0.647	0.809	0.971	1.130	1.290
Light Commercial Vc	Battery el	N1-I	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buses	Diesel	Urban Bus	Euro III	NOx	0.024	0.036	0.048	0.060	0.073	0.085	0.097
Buses	Diesel	Urban Bus	Euro IV	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buses	Diesel	Urban Bus	Euro V	NOx	0.036	0.053	0.071	0.089	0.107	0.124	0.142
Buses	Diesel	Urban Bus	Euro VI A/B/C	NOx	0.013	0.019	0.025	0.031	0.038	0.044	0.050
Buses	Battery el	-	Euro VI A/B/C	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L-Category	Petrol	Mopeds 2	Euro 3	NOx	0.573	0.860	1.140	1.430	1.710	2.000	2.290
L-Category	Petrol	Mopeds 2	Euro 4	NOx	0.024	0.036	0.048	0.060	0.072	0.084	0.097
L-Category	Petrol	Mopeds 2	Euro 5	NOx	0.032	0.048	0.064	0.079	0.095	0.111	0.127

					30 km/h						
Category	Fuel	Segment	Euro Standard	NOx [t]	4000 km/y	6000 km/y	8000 km/y	10000 km/y	12000 km/y	14000 km/y	16000 km/y
Passenger Cars	Petrol	Small	Euro 3	NOx	0.139	0.208	0.277	0.346	0.416	0.485	0.554
Passenger Cars	Petrol	Small	Euro 4	NOx	0.269	0.404	0.539	0.674	0.808	0.943	1.070
Passenger Cars	Petrol	Small	Euro 5	NOx	0.083	0.124	0.166	0.207	0.249	0.290	0.332
Passenger Cars	Petrol	Small	Euro 6 a/b/c	NOx	0.284	0.426	0.568	0.710	0.852	0.993	1.130
Passenger Cars	Diesel	Small	Euro 3	NOx	0.628	0.942	1.250	1.560	1.880	2.190	2.510
Passenger Cars	Diesel	Small	Euro 4	NOx	1.000	1.510	2.010	2.520	3.020	3.530	4.030
Passenger Cars	Diesel	Small	Euro 5	NOx	1.100	1.660	2.210	2.770	3.320	3.870	4.430
Passenger Cars	Diesel	Small	Euro 6 a/b/c	NOx	3.220	4.830	6.450	8.060	9.670	11.280	12.900
Passenger Cars	Battery el	Small	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000
Light Commercial	Petrol	N1-I	Euro 3	NOx	0.001	0.001	0.002	0.002	0.002	0.003	0.003
Light Commercial	Petrol	N1-I	Euro 4	NOx	0.000	0.000	0.001	0.001	0.001	0.001	0.001
Light Commercial	Petrol	N1-I	Euro 5	NOx	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Light Commercial	Petrol	N1-I	Euro 6 a/b/c	NOx	0.001	0.001	0.001	0.001	0.002	0.002	0.002
Light Commercial	Diesel	N1-I	Euro 3	NOx	0.089	0.133	0.178	0.222	0.266	0.311	0.355
Light Commercial	Diesel	N1-I	Euro 4	NOx	0.080	0.121	0.161	0.201	0.241	0.281	0.322
Light Commercial	Diesel	N1-I	Euro 5	NOx	0.075	0.112	0.150	0.187	0.225	0.262	0.300
Light Commercial	Diesel	N1-I	Euro 6 a/b/c	NOx	0.410	0.616	0.821	1.020	1.230	1.430	1.600
Light Commercial	Battery el	N1-I	Euro 6 a/b/c	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000
Buses	Diesel	Urban Bus Euro III	NOx	0.034	0.051	0.067	0.084	0.101	0.118	0.135	0.150
Buses	Diesel	Urban Bus Euro IV	NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buses	Diesel	Urban Bus Euro V	NOx	0.068	0.102	0.137	0.171	0.205	0.239	0.273	0.307
Buses	Diesel	Urban Bus Euro VI A/B/C	NOx	0.018	0.026	0.035	0.044	0.053	0.062	0.070	0.079
Buses	Battery el	Euro VI A/B/C	NOx	0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000
L-Category	Petrol	Mopeds 2: Euro 3	NOx	0.573	0.860	1.140	1.430	1.710	2.000	2.290	2.580
L-Category	Petrol	Mopeds 2: Euro 4	NOx	0.024	0.036	0.048	0.060	0.072	0.084	0.097	0.109
L-Category	Petrol	Mopeds 2: Euro 5	NOx	0.032	0.048	0.064	0.079	0.095	0.111	0.127	0.143

Tables 12, 13: NOx emissions at 50 km/h and 30 km/h
(The matching results have been highlighted in gray)

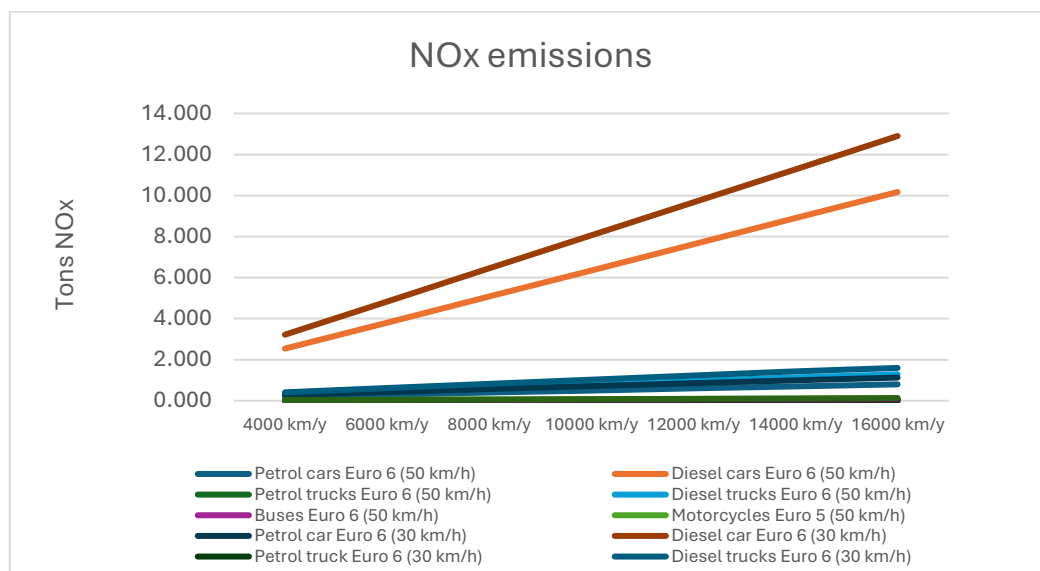


Fig. 62: Comparison of NOx emissions at 30 km/h and 50 km/h for vehicles

In conclusion, **Mean Activity** proves to be a more valuable parameter for **COPERT** than **trip distance**. This is because Mean Activity is not influenced by internal engine dynamics that could otherwise skew emission results, which need to be evaluated within a broader, more realistic context.

4.3.2 SUMO

As mentioned at the beginning of the paragraph, the SUMO software seems to be more suitable for an in-depth analysis of the emission values following the new "Zone 30" scenario. SUMO requires the road network of the area under examination as an input, and it was possible to retrieve the San Salvario network in OSM format via OpenStreetMap, which was then converted into the appropriate format for the software.

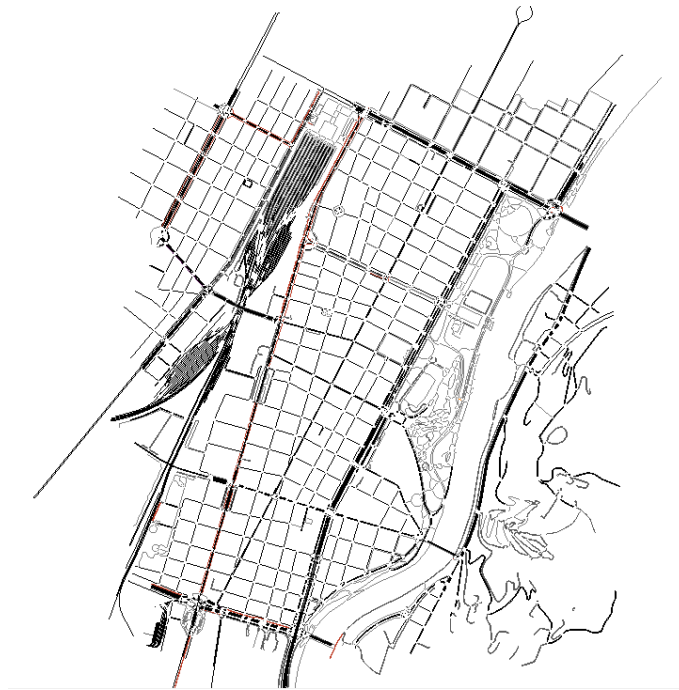


Fig 63: OpenStreetMap Road Network of the San Salvario District

Using **Netedit** to analyze the network, it was possible to identify and record the IDs of the various edges that make up Via Madama Cristina. In general, a network incorporates the realistic urban configuration of the road, including traffic lights, intersections, pedestrian crossings, and other relevant elements. In the analyzed case, the considered road network of San Salvario is focused on a single lane which implements only traffic lights, as shows in figure 66, useless for considering a semi realistic scenario.

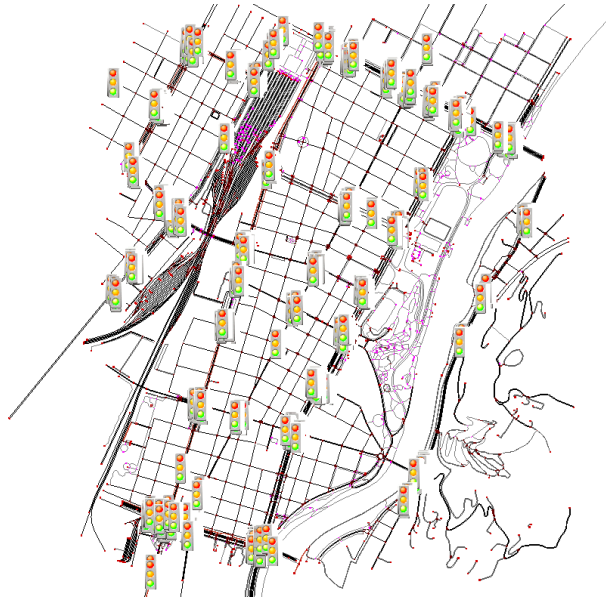


Fig 64: Traffic lights signaled in the road network

To launch the simulation, a text editor was used to write a code that accounted for the traffic flow to be analyzed. In the first simulated scenario, a fleet of only motor vehicles was considered, comparing eight types (with different engines from Euro 3 to Euro 6, gasoline and diesel), which traveled the same stretch of road at a maximum speed of 50 km/h and then 30 km/h, departing one after the other. The program took into account a random urban situation and, most importantly, a certain speed and acceleration corresponded to each moment in time precisely to simulate an urban context that was as realistic as possible.

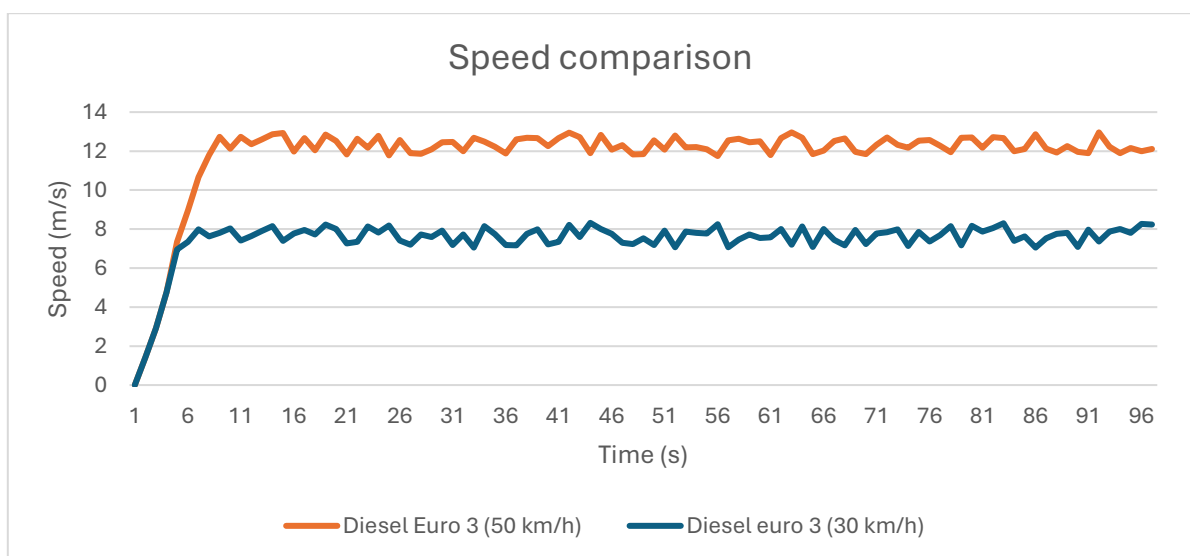


Fig 65: Speed comparison for Diesel Euro 3 cars in Scenario 1

As you can see from the previous figure, when comparing the two speeds for a Euro 3 diesel and gasoline car, the fluctuations represent the moments of acceleration or deceleration considered by the program.

A more specific analysis of what happens to each car with varying standards and fuel types shows that, in the 30 km/h scenario, each vehicle will start at different times and complete the route within the 99-second simulation time. This was a practical choice, as recommended by the program's guide, to prevent all cars from starting at the same moment, a situation that SUMO cannot handle.

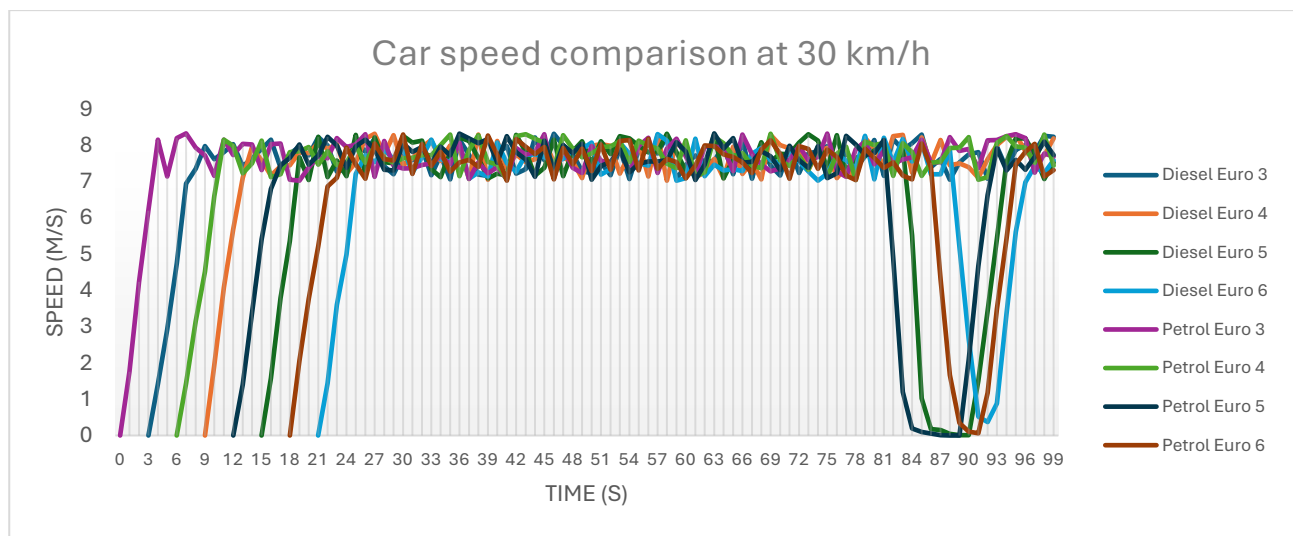


Fig 66: Speed comparison for different standard and fuel cars at 30 km/h in Scenario 1

The goal of the first simulated scenario is to evaluate how vehicle emissions change during the same travel time on the same road and under the same urban conditions. For this reason, the simulation time is set to 99 seconds, making the situations comparable only in terms of emissions. Next, a second scenario will be introduced where we simulate a vehicle fleet under heavy, moderate, and light traffic conditions. This aims to evaluate vehicle behavior in different traffic situations during a one-hour simulation.

4.3.2.1 Results and Discussion

SCENARIO 1

The following graphs show the CO₂ trends with varying speeds over the same simulation time. Unlike the COPERT model, a key observation in this more realistic context is that emissions at 50 km/h demonstrate higher peaks than those at 30 km/h, even when comparing vehicles with the same fuel type and Euro standard. These fluctuations are directly linked to the moments of acceleration and deceleration accounted for by the simulation.

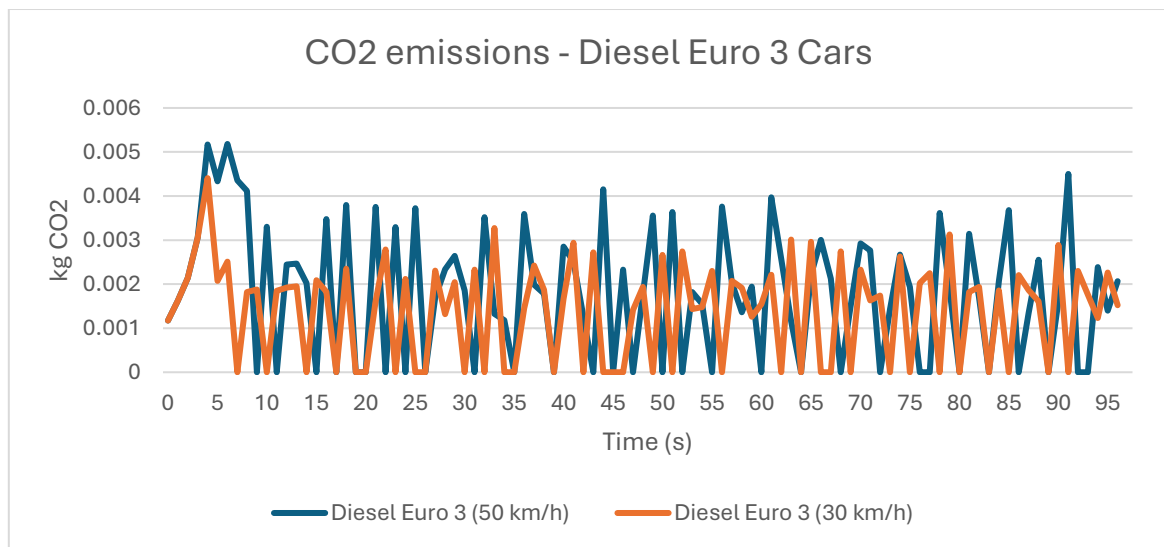


Fig 67: CO₂ emissions comparison for Diesel Euro 3 Cars

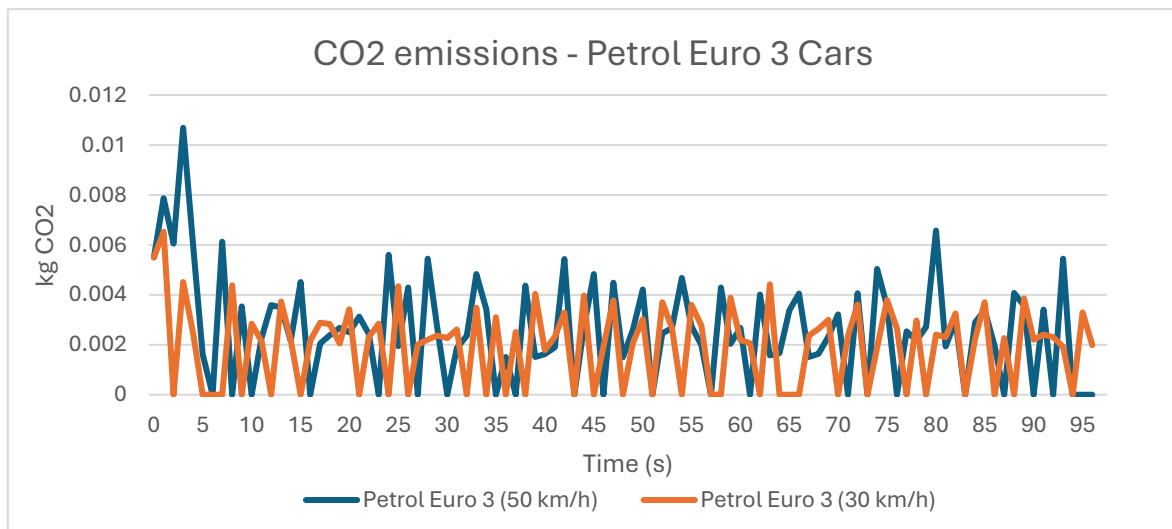


Fig 68: CO₂ emissions comparison for Petrol Euro 3 Cars

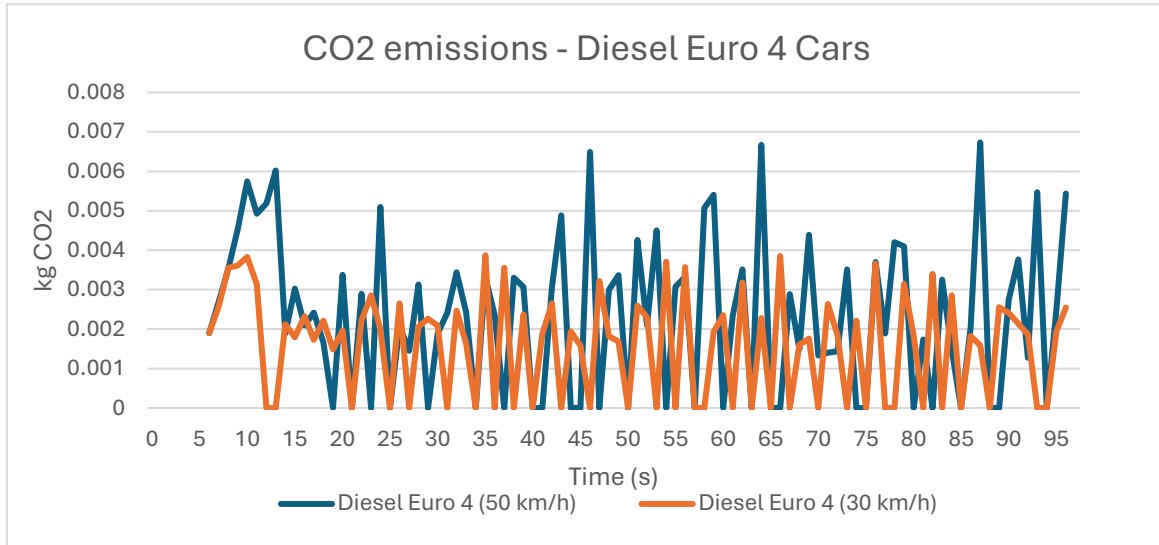


Fig 69: CO2 emissions comparison for Diesel Euro 4 Cars

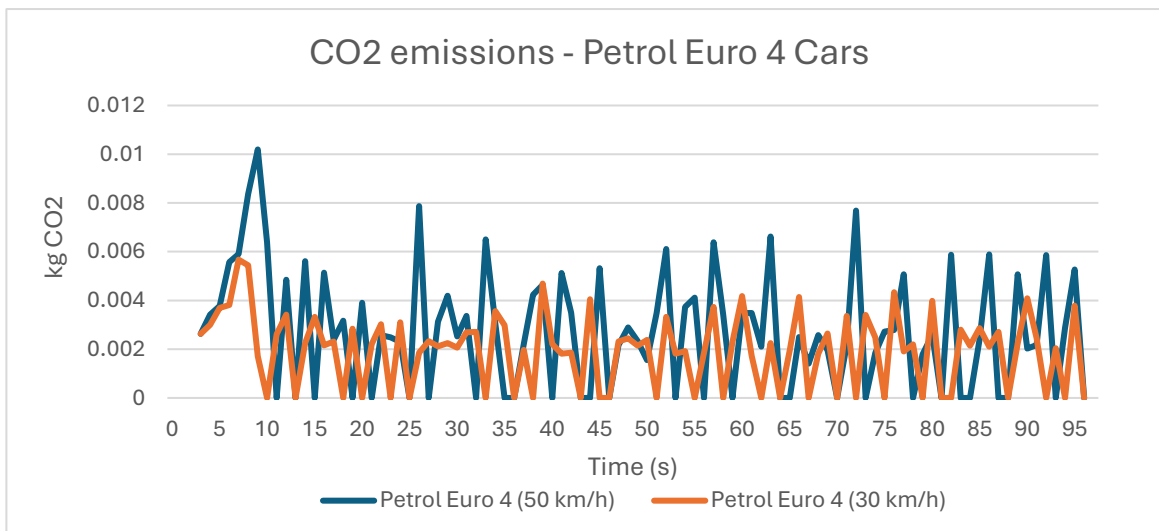


Fig 70: CO2 emissions comparison for Petrol Euro 4 Cars

These figures illustrate the trend of emissions as a function of time, in order to see how they may decrease or increase depending on the relative speed at each time instant. The following graph shows the situation in cumulative terms, displaying how emissions increase over time, comparing the two Euro 3 car power sources. What emerges is that petrol Euro 3 cars are more impactful than diesel Euro 3 cars in both speed scenarios.

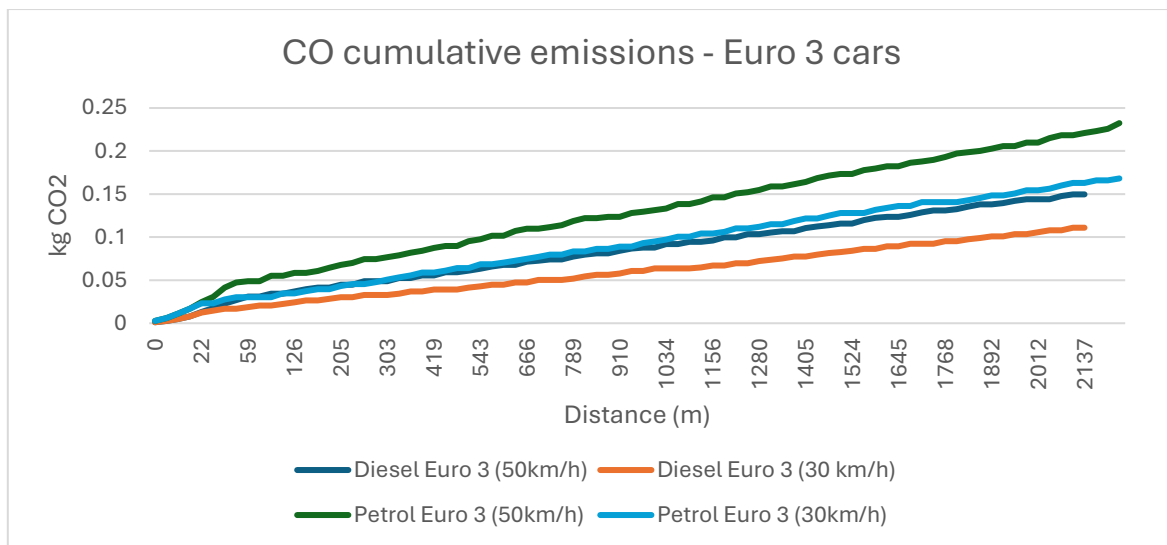


Fig 71: CO2 cumulative emissions for Euro 3 cars

The trend of emissions remains consistent when comparing the remaining car categories, allowing a final overview to be visualized in Figure 72.

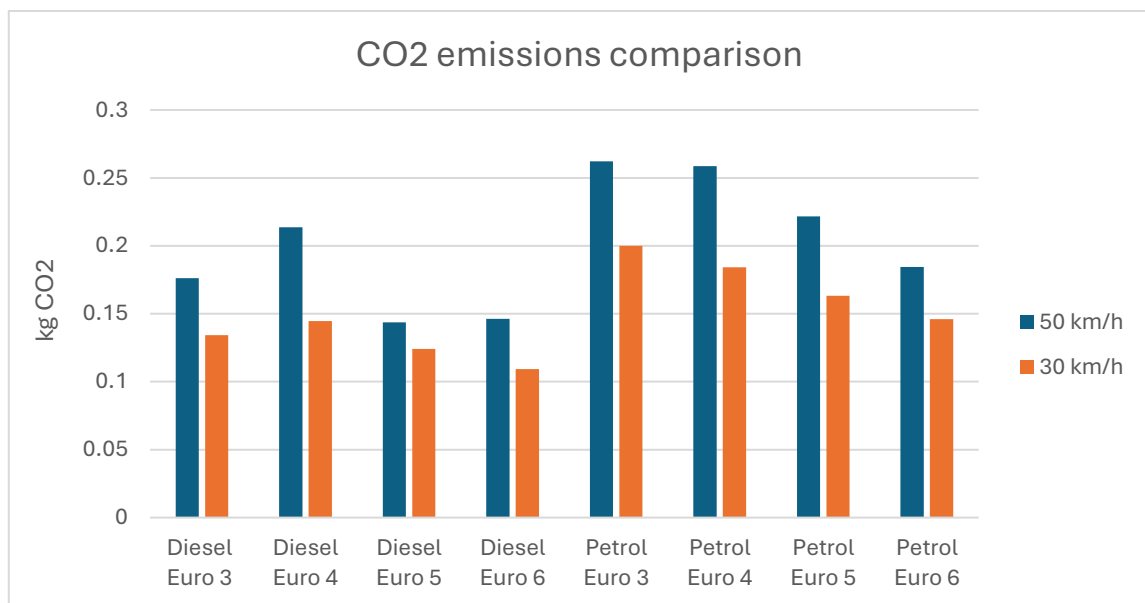


Fig 72: CO2 emissions comparison all cars

Another interesting conclusion regarding the simulation is that gasoline-powered cars emit more than diesel cars of the same Euro standard. Therefore, among the cars analyzed, Euro 3 and Euro 4 gasoline cars emit the most CO₂.

A similar situation, comparing Euro 3 car models, also occurs with NO_x emissions, where higher peaks correspond to higher speeds.

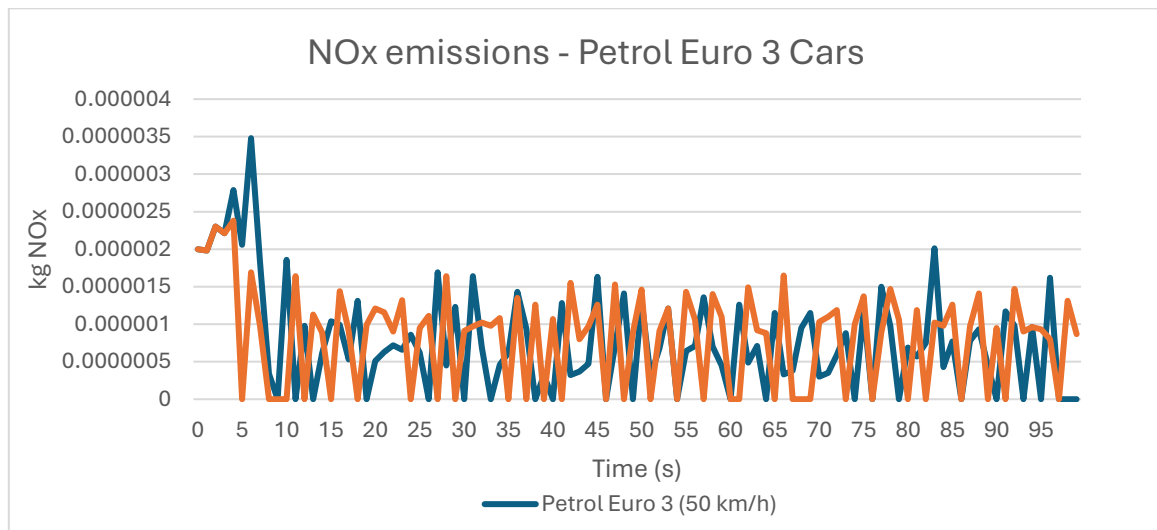


Fig 73: NO_x emissions comparison for Petrol Euro 3 Cars

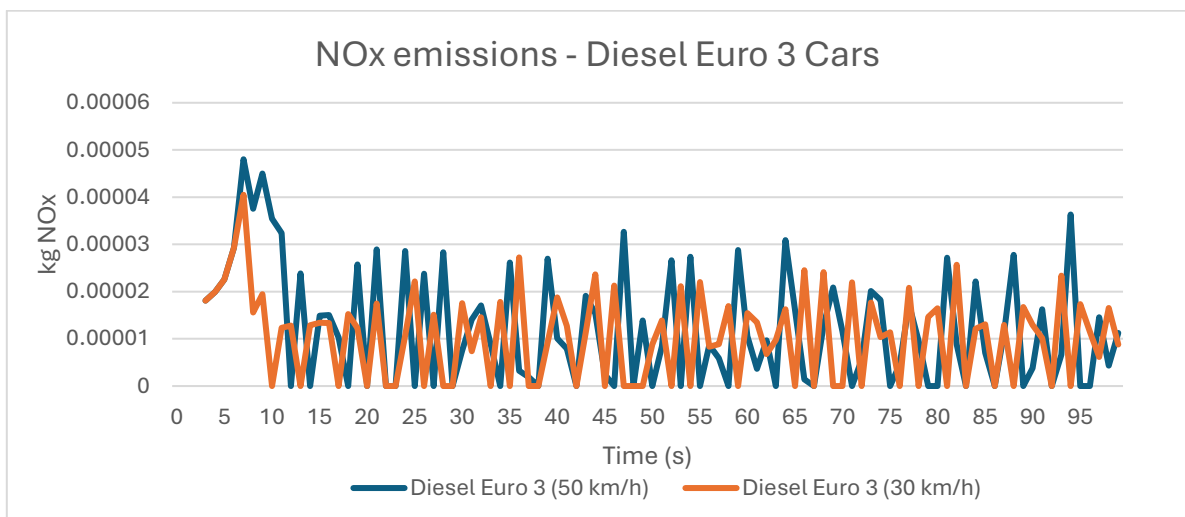


Fig 74: NO_x emissions comparison for Diesel Euro 3 Cars

This point, however, isn't true for all the vehicles analyzed. From Figure 75, you can see that in the case of Euro 5 diesel vehicles, the NO_x emissions are slightly lower at 50 km/h than at 30 km/h. Indeed, Figure 76 shows how some peaks are higher at lower speeds.

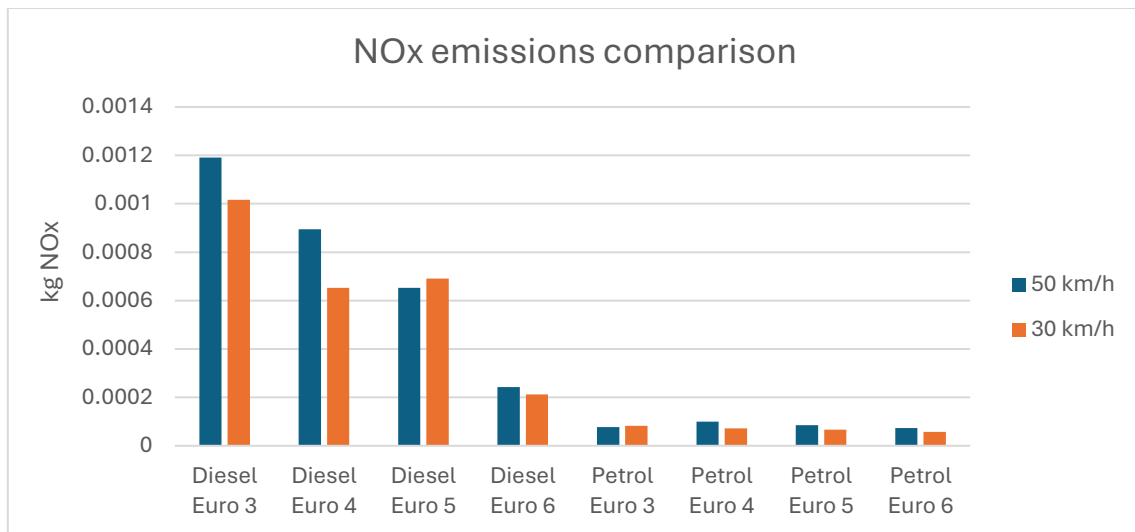


Fig 75: NOx emissions comparison for all cars

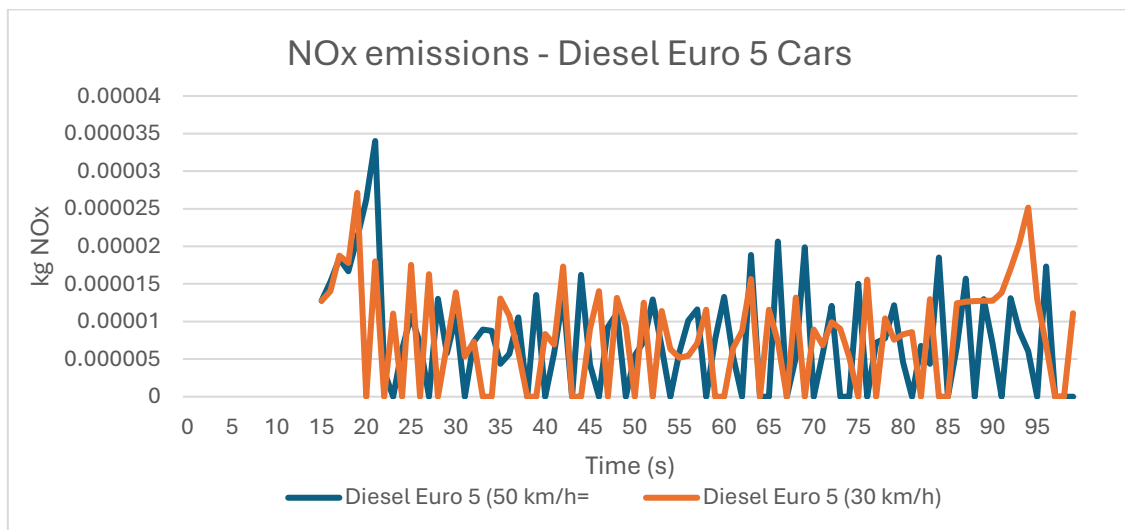


Fig 76: NOx emissions comparison for Diesel Euro 5 Cars

A general observation, also confirmed by COPERT, is that the primary difference with CO₂ is that diesel cars, especially older Euro models, emit more NO_x than gasoline cars, as shown in Figure 75.

The situation with PM is somewhat different. For Euro 3 diesel cars, higher speeds result in more particulate matter emissions. However, the opposite is true for Euro 5 and Euro 6 diesel cars. This is because PM is a unique pollutant; it is not solely emitted from exhaust but also, as noted in COPERT, results from road, brake, and tire abrasion. Consequently, its emission is highly dependent on the specific route and the individual vehicle's driving style.

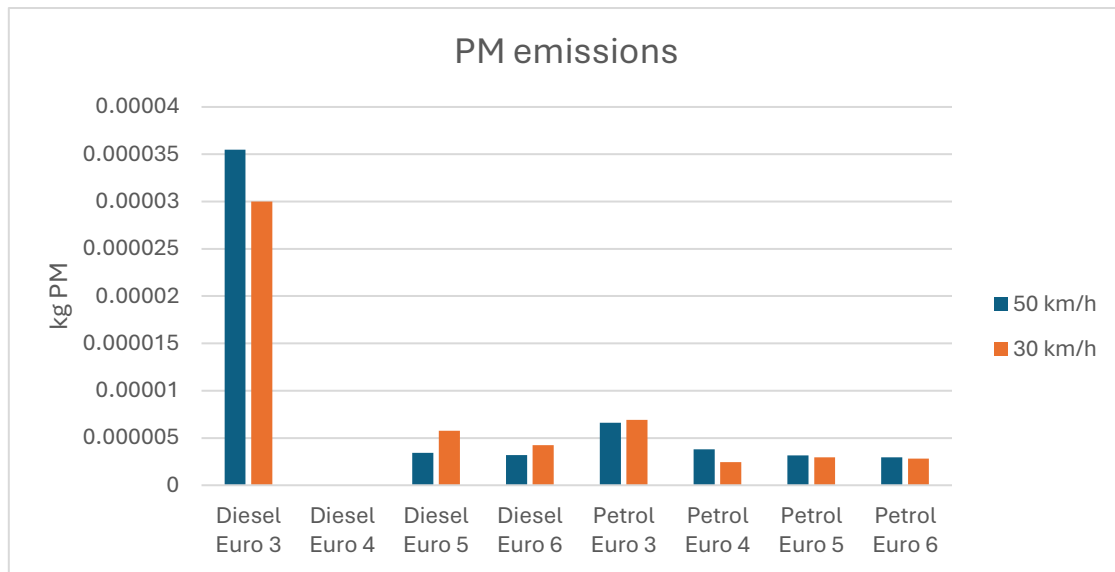


Fig 77: PM emissions comparison for all cars

What happens in this simulation is that vehicles are continuously forced to brake or accelerate to avoid accidents, obstacles, or to adapt to typical urban traffic flows, as shown by the emission and speed peaks over the simulation time. The main difference could reside in the driving profile. At 50 km/h, the driver might brake more sharply or accelerate more aggressively, which would explain the increase in emissions

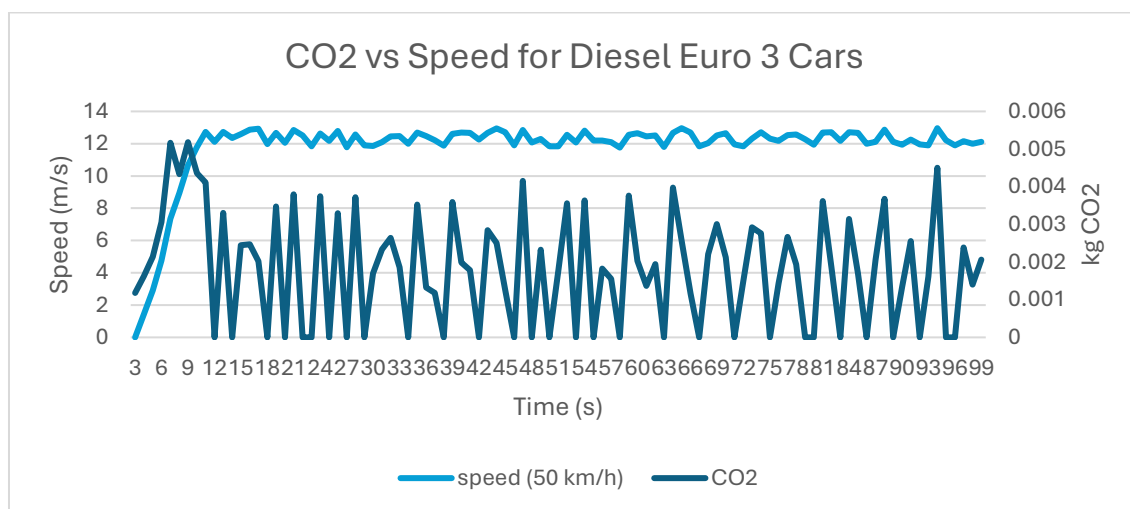


Fig 78: Comparison between CO2 emissions and speed variation for Diesel Euro 3 Cars

In Figure 78, it can be observed how emission peaks correspond precisely to situations of speed peaks—whether from braking or accelerating. In the case of larger speed peaks (e.g., a sudden acceleration), a corresponding increase in emissions occurs.

In contrast, at 30 km/h, the traffic flow is generally slower and more consistent, with less need for sudden acceleration and braking. The engine can operate at a more efficient rate, and emissions per unit of time tend to be lower.

Furthermore, the initial emission peaks are consistently higher because SUMO incorporates the external HBEFA (HandBook Emission Factors for Road Transport) model. This model accounts for the "cold start" parameter, just like in COPERT, where emissions are higher in the short period after the engine is turned on [82].

SCENARIO 2

A second scenario was also analyzed with the goal of simulating a more realistic urban traffic condition.

The analysis considered a fleet of Euro 6 gasoline cars, the typical and most abundant vehicle in the San Salvador area, traveling along Via Madama Cristina for a simulation time of 3600 seconds (1 hour).

Starting from a realistic number of cars that could travel this street in 1 hour (294 cars), this second scenario is further divided into three sub-scenarios based on different traffic simulations, where only the number of cars in the fleet varies, in order to simulate a light and an intense traffic scenario, respectively:

- 294 cars
- 147 cars
- 588 cars

Each of these cases is evaluated at two speeds: 50 km/h and 30 km/h.

Considering the most realistic traffic scenario and running the simulation in SUMO for 3600 seconds, it becomes evident that not all of the 294 vehicles initially considered will actually be involved, as some will not complete the route within the simulation time. The following table summarizes the simulated vehicles, the number of vehicles that enter the simulation (*Actual cars number*), those that complete it (*Ended cars*), and the total pollutant emissions CO₂, NO_x, and PM expressed in tons, both for the entire fleet and on average per single vehicle.

Input cars number	Actual cars number	Ended cars	Average speed (m/s)	Total Co2 (tons)	Average CO2 single vehicle	Total NOx (tons)	Average NOx single vehicle	Total PM (tons)	Average PM single vehicle
294	287	270	7.07	0.143	0.00049	$5.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-7}$	$2.6 \cdot 10^{-6}$	$1.1 \cdot 10^{-8}$
294	287	270	9.72	0.145	0.00050	$5.7 \cdot 10^{-5}$	$2 \cdot 10^{-7}$	$2.7 \cdot 10^{-6}$	$1.2 \cdot 10^{-8}$

Table 14: CO₂, NO_x and PM emissions for actual cars (fleet 294) and for a single vehicle (on average)

At this stage, the analysis focuses on the behavior of a single vehicle from the fleet, in terms of speed and CO₂ emissions as a function of the distance traveled, for both speed scenarios. The distance, expressed in meters, corresponds to the 2.2 km of Via Madama Cristina. The speed profile shows fluctuations, as already observed in Scenario 1, due to frequent braking and acceleration. Consequently, the instantaneous emissions also exhibit an oscillatory pattern. This behavior is common to both speed scenarios, and it is observed that CO₂ emission peaks do not correspond to high speed values, but rather occur shortly after sudden braking events, and are slightly higher in the 50 km/h scenario.

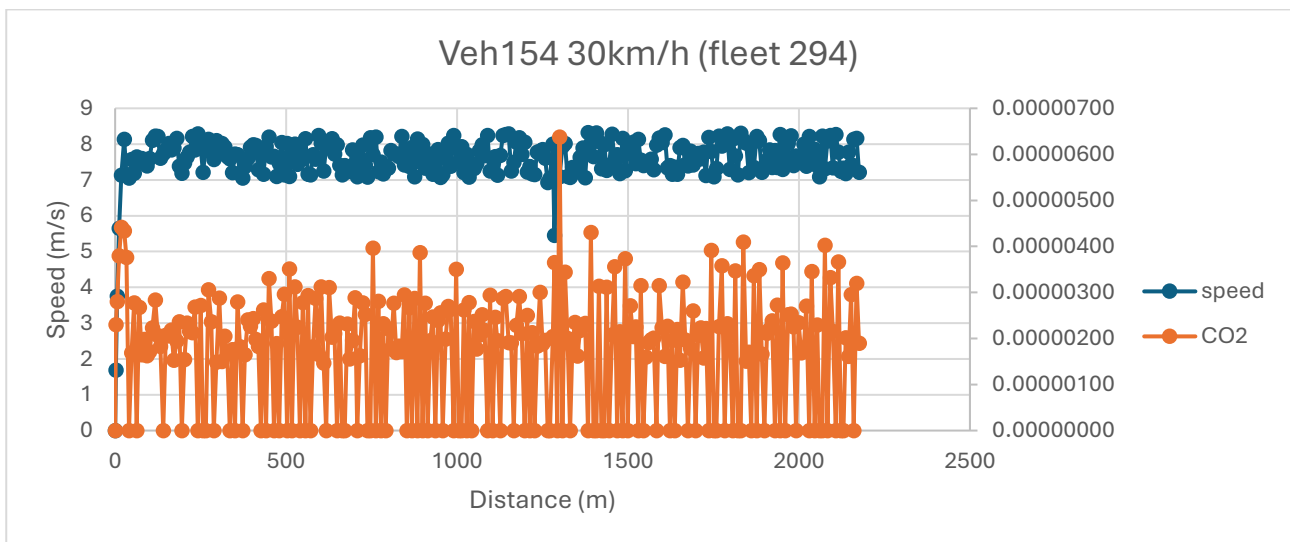


Fig 79: Comparison between CO₂ emissions and speed variation for vehicle 154 at 30km/h (Fleet 294)

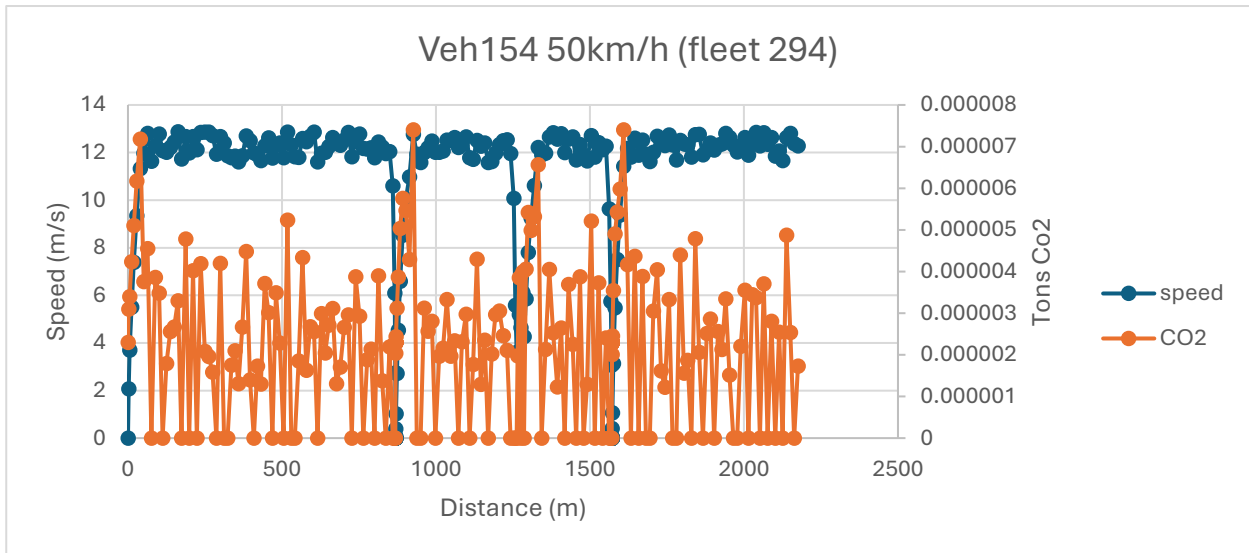


Fig 80: Comparison between CO2 emissions and speed variation for vehicle 154 at 30km/h (Fleet 294)

In the specific case of this vehicle, its behavior differs between the two scenarios due to simulation randomness. At 50 km/h, it experiences more frequent braking as a result of the stochastic behavior of the simulated fleet, which varies with different speeds. In general, however, the overall trend of emissions in relation to speed remains consistent. In the following scatter plot, it can be observed that an emission cloud typically forms around the average speed value of the simulation. However, in the 50 km/h scenario, there is a greater dispersion of points, due to the increased number of braking and acceleration events affecting vehicle 154, as previously mentioned.

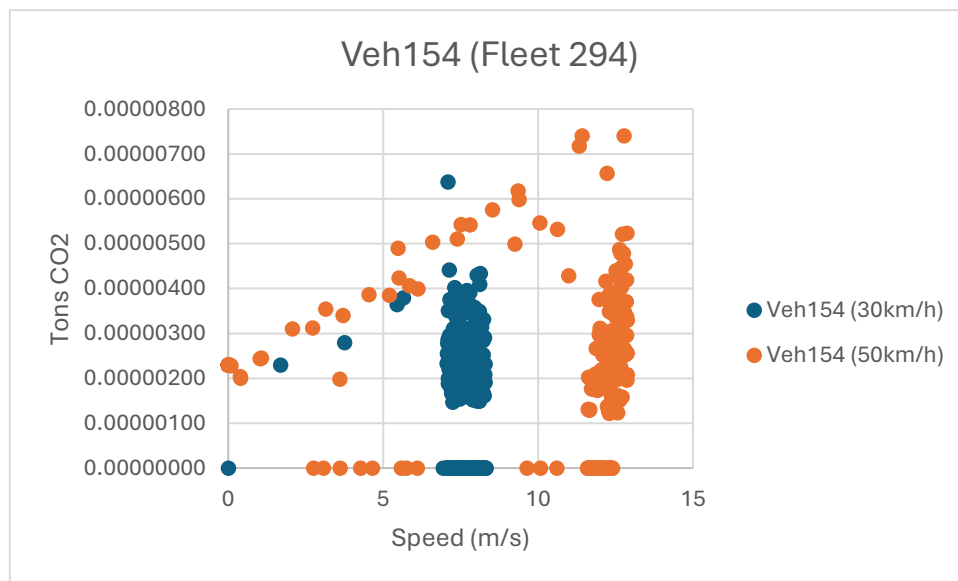


Fig 81: Scatter plot of CO2 emissions and speed variation for vehicle 154

Finally, a scatter plot of the entire fleet is analyzed. For this purpose, only the vehicles that completed the simulation were considered, in order to avoid outliers caused by CO₂ values that deviate significantly from the mean. The results show that the relationship between CO₂ emissions and speed is fairly linear, as suggested by the R² value—more evidently in the 30 km/h scenario. Furthermore, the slope of the regression line is negative in both cases, indicating that higher speeds are associated with lower CO₂ emissions. This trend is more pronounced in the 50 km/h scenario, although the data shows greater dispersion, which could be attributed to various factors such as increased traffic instability, differences in routing, or more heterogeneous vehicle behaviors.

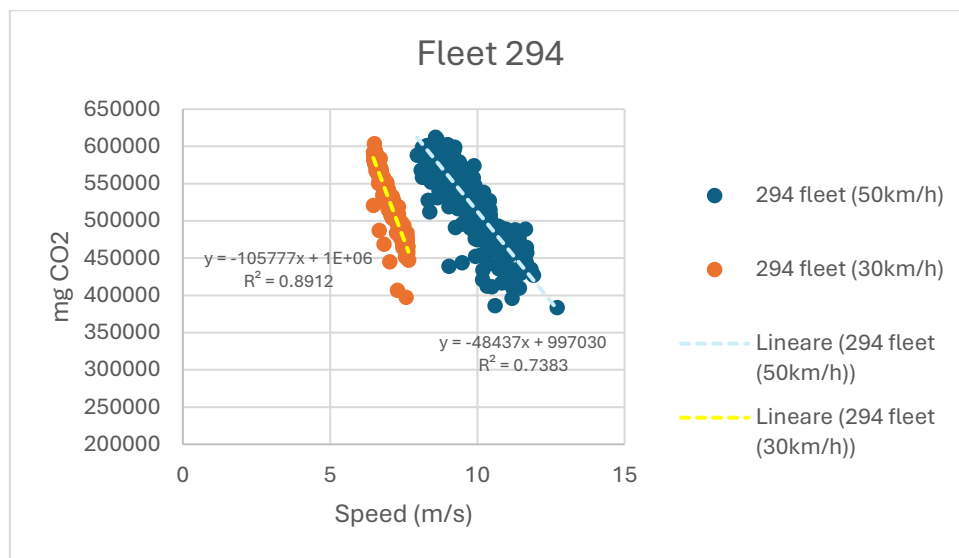


Fig 82: Scatter plot of CO₂ emissions and speed variation for fleet 294

The same analysis is carried out for fleet 588, which represents a scenario with heavier traffic. In this regard, SUMO indicates that the number of vehicles from this fleet that actually pass through within one hour is quite similar to the previous case. This is because the simulation settings are designed to realistically reflect traffic conditions, taking into account vehicle dimensions and the required safety distance between vehicles. As a result, it is not possible for such a dense fleet to pass through within a one-hour period.

Input cars number	Actual cars number	Ended cars	Average speed (m/s)	Total Co2 (tons)	Average CO2 single vehicle	Total NOx (tons)	Average NOx single vehicle	Total PM (tons)	Average PM single vehicle
588	284	270	7.08	0.132	0.00046	0.000045	$1.5 \cdot 10^{-7}$	0.000011	$3.8 \cdot 10^{-8}$
588	284	270	9.79	0.134	0.00047	0.000046	$1.6 \cdot 10^{-7}$	0.000012	$4 \cdot 10^{-8}$

Table 15: CO₂, NO_x and PM emissions for actual cars (fleet 588) and for a single vehicle (on average)

Also in this case, a single random vehicle, car 142, is analyzed, and a trend between CO₂ emissions and speed very similar to the previous case is observed.

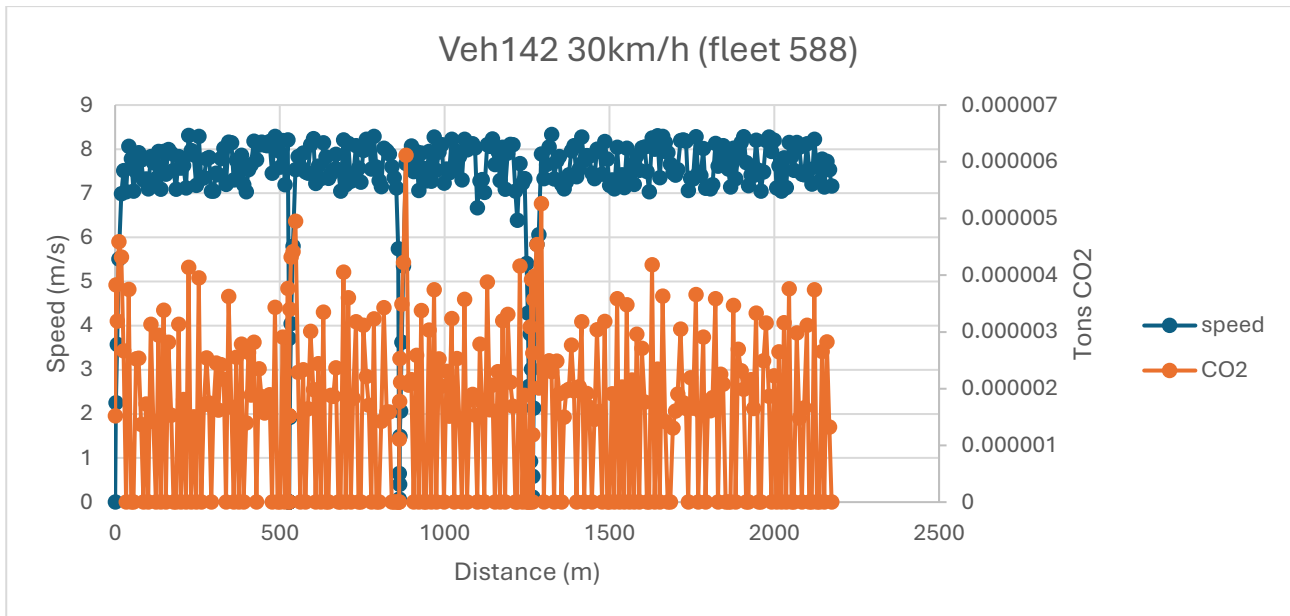


Fig 83: Comparison between CO2 emissions and speed variation for vehicle 142 at 30km/h (Fleet 588)

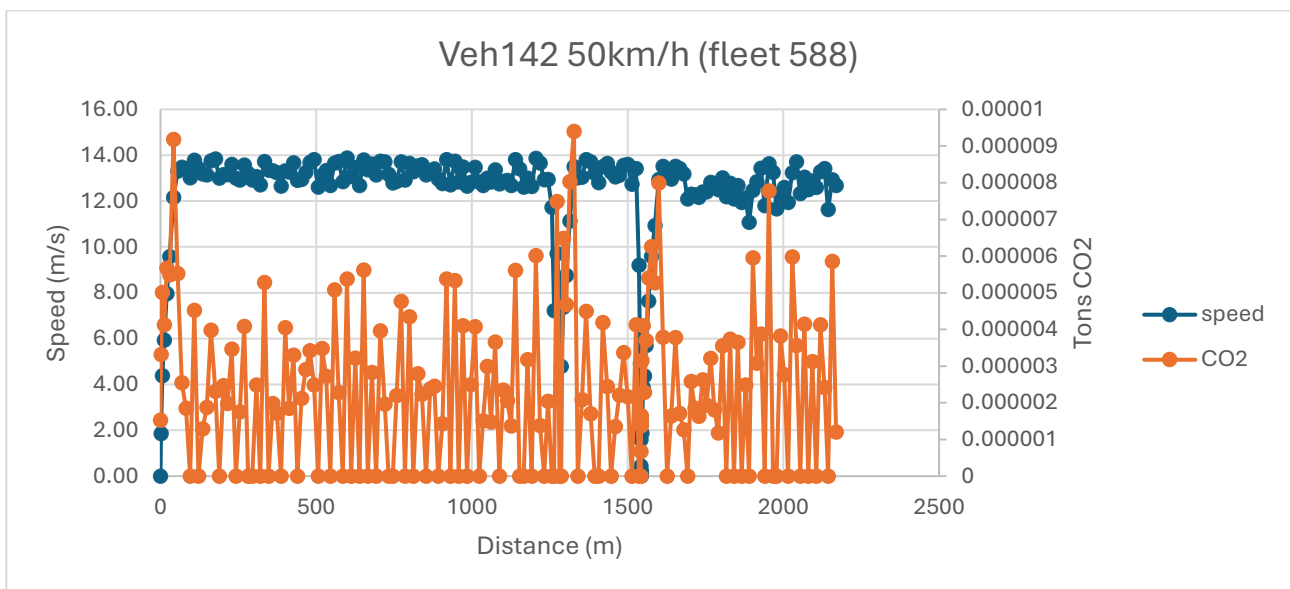


Fig 84: Comparison between CO2 emissions and speed variation for vehicle 142 at 50km/h (Fleet 588)

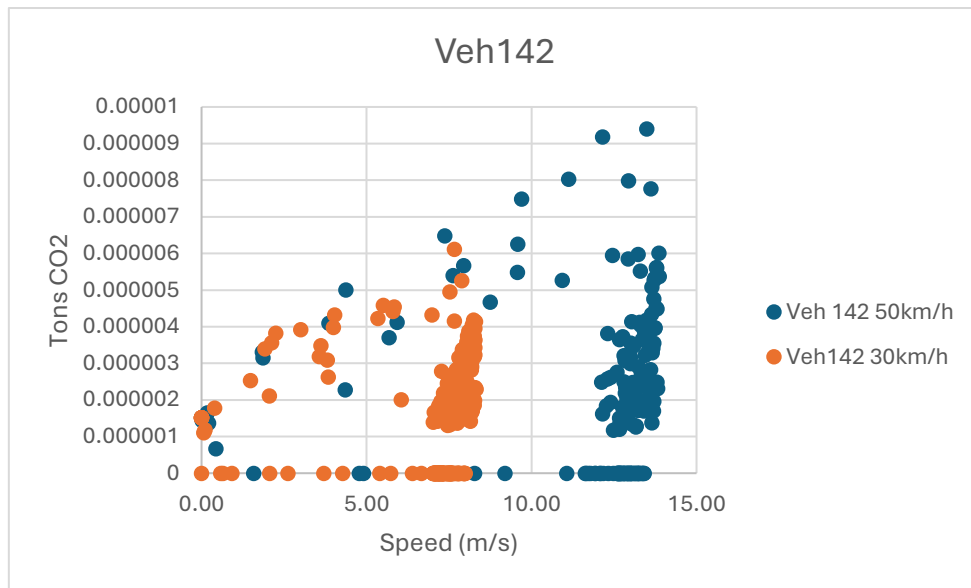


Fig 85: Scatter plot of CO2 emissions and speed variation for vehicle 142

The resulting regression line also suggests a fairly linear relationship between the two variables, more clearly in the 30 km/h scenario compared to the 50 km/h one.

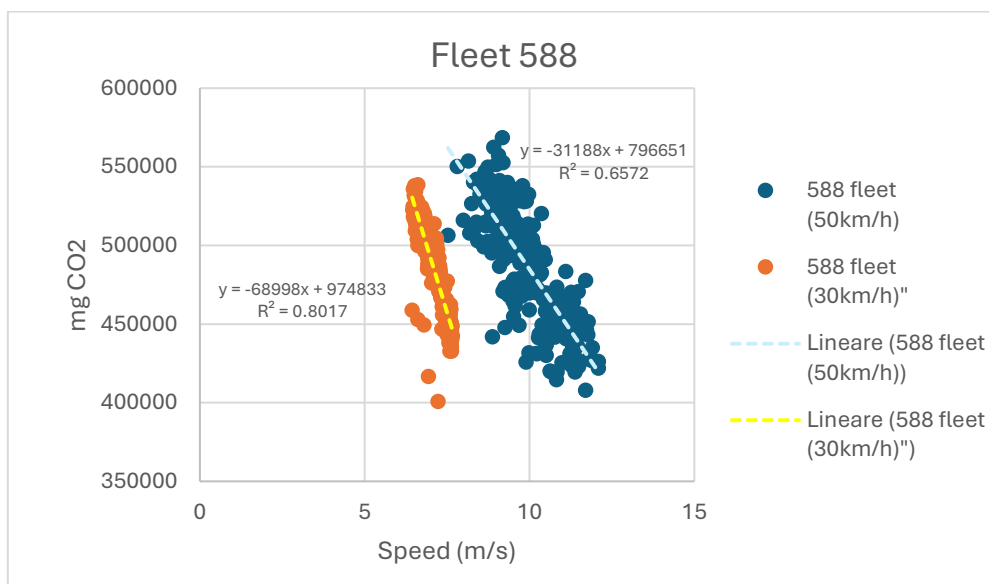


Fig 86: Scatter plot of CO2 emissions and speed variation for fleet 588

In the case of the smaller fleet, once again, not all vehicles complete the simulation, reflecting the stochastic nature of the SUMO model. As expected, the emission values are lower than in the other two scenarios, simply because fewer vehicles are circulating.

Input cars number	Actual cars number	Ended cars	Average speed (m/s)	Total Co2 (tons)	Average CO2 single vehicle	Total NOx (tons)	Average NOx single vehicle	Total PM (tons)	Average PM single vehicle
147	138	130	7.14	0.066	0.00047	0.000025	$1.8 \cdot 10^{-7}$	$1.2 \cdot 10^{-6}$	$8.6 \cdot 10^{-9}$
147	138	130	9.98	0.067	0.00048	0.000026	$1.9 \cdot 10^{-7}$	$1.2 \cdot 10^{-6}$	$8.6 \cdot 10^{-9}$

Table 16: CO₂, NO_x and PM emissions for actual cars (fleet 147) and for a single vehicle (on average)

The individual vehicle selected in this case is vehicle 90, which behaves quite consistently with the two previously analyzed vehicles, showing emission peaks corresponding to braking and acceleration events.

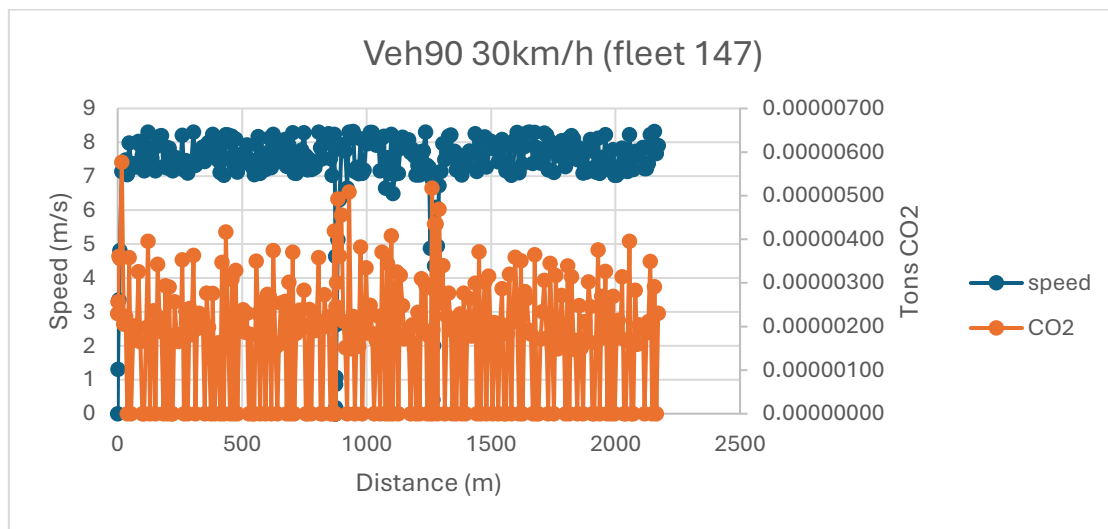


Fig 87: Comparison between CO₂ emissions and speed variation for vehicle 90 at 30km/h (Fleet 147)

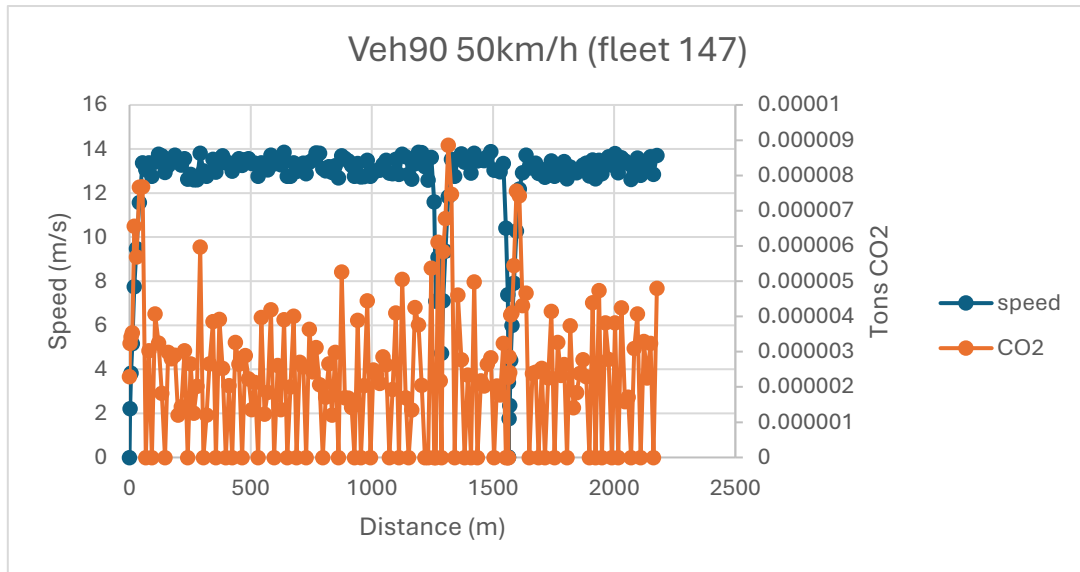


Fig 88: Comparison between CO2 emissions and speed variation for vehicle 90 at 50km/h (Fleet 147)

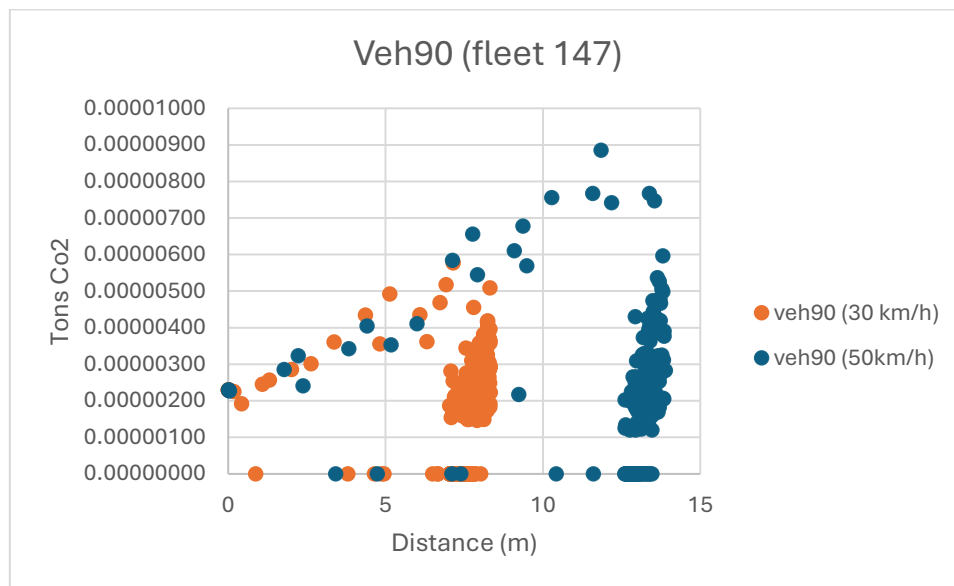


Fig 89: Scatter plot of CO2 emissions and speed variation for vehicle 90

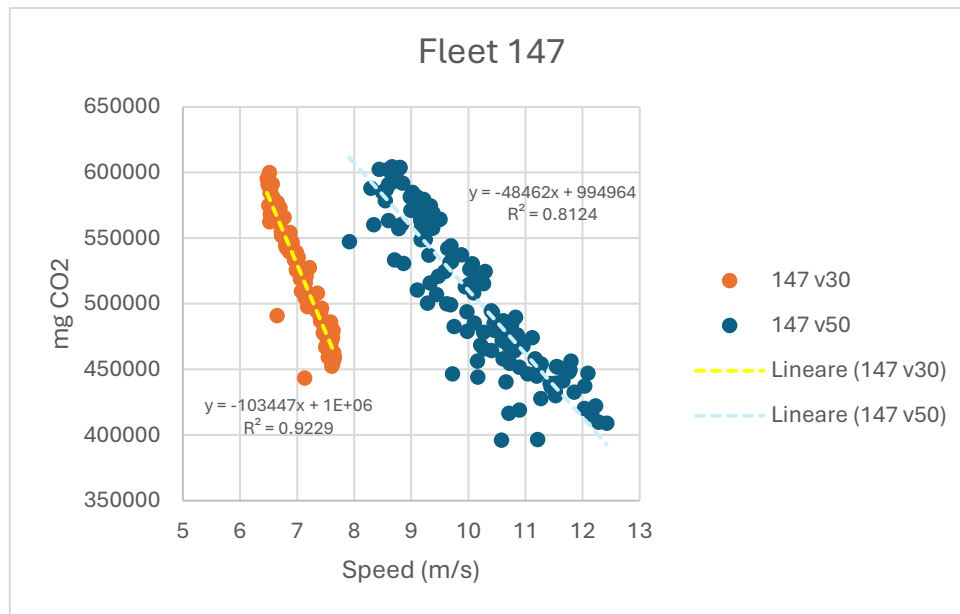


Fig 90: Scatter plot of CO₂ emissions and speed variation for fleet 147

Also in this case, the regression line indicates that the linear relationship appears to be reasonably valid. Moreover, as in the previous cases, the steeper slope of the regression line in the 30 km/h scenario suggests a greater sensitivity of emissions to speed variations. This may imply that small increases in speed at lower driving conditions have a more significant environmental impact compared to already higher speeds. The higher degree of linearity observed (higher R^2) further supports the idea that vehicle behavior is more predictable and stable at lower speeds.

5. Conclusions

It is well known that emissions from road traffic are one of the main sources of air pollution, causing significant problems for human health and the environment. Turin, the case study for this thesis, is one of the cities most affected by this issue due to its geomorphological configuration and the large number of circulating vehicles.

Literature has shown that some of the major cities in Europe and beyond have already considered and, in some cases, implemented measures aimed at limiting and reducing the levels of these pollutants. The strategy discussed in this thesis is the creation of 30 km/h low-emission zones (commonly referred to as '30 zones'). The results obtained are not uniform and can vary depending on several factors, such as the urban context, driving style, or appropriate road redesign. Consequently, a rigorous methodology for calculating the exact effect of a targeted project on pollution reduction has not yet been established; each city must be considered a separate case study.

However, by also considering secondary measures to mitigate the consequences of a low-emission strategy, for example redistributing traffic following the creation of a new pedestrian zone, and by taking the necessary precautions, traffic emissions can be controlled and reduced. Furthermore, the case study of Milan showed that implementing multiple strategies together can be a greater strength.

To reduce traffic pollution, and after analyzing the strategies already in place in Turin—specifically in the San Salvario district, which is the focus of this thesis—the most suitable strategy is the creation of a 30 zone on Via Madama Cristina.

To create a 30 zone, it is necessary to model a scenario where speed is reduced. This model must be specific to the vehicle fleet in the San Salvario district. Initially, the software COPERT was used due to its familiarity and practicality. However, because of some limitations, it was supplemented with the more comprehensive and complex software SUMO.

5.1 COPERT Results

Using the number of vehicles traveling on Via Madama Cristina, which was chosen as a plausible street for a 30 km/h conversion, the COPERT software model was applied to assess how emissions of CO₂, NO_x, and PM₁₀ would change. The speed has been changed from the standard urban 50 km/h to the 30

km/h recommended for such zones and several parameters related to the vehicle fleet and the city's context were used as input.

In the first base scenario, input parameters specific to Turin (Mean Activity = 10,000 km/y, Lifetime Cumulative Activity = 120,000 km, Trip Length = 20 km) were used. The results showed that at lower speeds, pollutant emissions were higher.

As explained in the previous section, this outcome reflects how the COPERT algorithm works. The software does not allow for the evaluation of a precise scenario tailored to a specific city. Instead, it uses pre-implemented emission factors. Considering a vehicle starting from a standstill, the model associates higher emission factors with the initial low-speed phase, as it considers engine warm-up to be a significantly emissive stage, often accompanied by frequent start-and-stop cycles, according to Figures 39 and 40. This conclusion is consistent with what has been found in scientific literature and the case studies analyzed in previous chapters: reducing speed alone is not enough to solve the problem of road traffic pollution. Speed is a fundamental factor, but it must be accompanied by an appropriate driving style in order to be truly effective. Indeed, what led to success in most of the cities analyzed was an adequate road redesign that allowed for smoother traffic flow and promoted an eco-driving style, free from abrupt accelerations and braking.

In the two subsequent scenarios, further considerations were made regarding the vehicle fleet type. Analizzando una flotta realistica, questa sarà composta da veicoli con diverso standard Euro e alimentazione. I risultati sono quindi fortemente correlate anche alla quantità di veicoli di quella categoria, specifically, the number of Euro 6 cars and trucks is greater than the number of vehicles in lower Euro standards.

Additionally, it was found that emissions are directly correlated with the Mean Activity and Trip Length parameters. Increasing the Mean Activity (and therefore the annual kilometers traveled by vehicles) will inevitably lead to higher emissions. However, the situation is slightly different when increasing the Trip Length due to the specific settings of COPERT and its calculation model, which heavily considers cold-start emissions, regulated by the beta coefficient.

Overall, the software is very useful for calculating pollutant emissions in different environments (urban, rural, or highway) because it is programmed to account for the fundamental characteristics of each. However, for evaluating a new 30 km/h zone, it would be more appropriate to use a model that considers all the specific characteristics of the urban context being studied.

Also to mitigate the increase in emissions in 30 km/h zones, COPERT suggests evaluating measures that improve traffic flow and reduce the need for abrupt accelerations and braking. Some solutions could

be, for example, using electric vehicles, which have zero tailpipe emissions, or transitioning to newer EURO standards and diesel/hybrid vehicles.

However, the main limitation of COPERT is that it does not allow for a precise understanding of how accelerations and braking affect the urban context of our case study. This is because COPERT only considers these factors in relation to emission values that are strictly tied to average speed. To account for the specific urban context, the more advanced software SUMO was therefore used.

5.2 SUMO Results

By simulating a road network that reflects the specific urban elements of the case study, SUMO proves to be better suited to evaluating what would happen if the speed were to vary on Via Madama Cristina. When the sole purpose is to assess how emissions change in relation to speed, SUMO provides more promising results.

In a real-world scenario, speed is not uniform. Each instance of acceleration or braking generates a peak in emissions, as calculated by the HBEFA model. The key finding for the software is that reducing the speed to 30 km/h on the selected road section leads to a smoother driving style with less drastic peaks, and consequently, lower emissions. This reinforces the argument for implementing a new 30 zone.

The two models, HBEFA and COPERT, differ fundamentally in how they calculate emissions.

- **HBEFA** uses a more detailed approach, focusing on specific traffic situations and vehicle dynamics. It considers not only average speed but also accelerations, decelerations, "stop-and-go" phases, and the type of road (e.g., urban, highway). It's a highly detailed model, often used with microsimulation software like SUMO to get a precise picture of these dynamics.
- **COPERT** uses a more "macro" approach, primarily based on average speed. It calculates emissions using average speed values without accounting for peaks in acceleration and deceleration. It's a useful tool for broad, national or regional studies where detailed, microscopic traffic data isn't available.

It's also worth noting that just like in COPERT, each Euro standard and vehicle type will produce a different scenario; with SUMO, more recent Euro standards lead to lower emissions. Therefore, when implementing a new strategy, it's crucial to evaluate every possible aspect to achieve the greatest success. The composition of the vehicle fleet, the urban context, and driving style have emerged as the

main factors influencing the creation of a 30 zone, proving that it's about more than just reducing vehicle speed.

A comparative analysis between COPERT and SUMO can be carried out by examining a Euro 6 petrol vehicle, as previously analyzed, and comparing the respective emission results. For COPERT, the emission data from the second simulated scenario were used, referring to a trip length of 2 km (corresponding to the length of Via Madama Cristina). These values were then divided by the 1.,000 km/year of Mean Activity and by the 2030 petrol Euro 6 vehicles, in order to obtain the emissions of a single vehicle traveling 2 km under typical annual mileage conditions.

Speed scenario	Average CO2 emitted	Average NOx emitted	Average PM emitted
30 km/h	0.0002	$5.4 \cdot 10^{-8}$	$3.2 \cdot 10^{-8}$
50 km/h	0.00017	$2.4 \cdot 10^{-8}$	$2.8 \cdot 10^{-8}$

Table 17: Summary of CO2, NOx and PM emissions for a petrol Euro 6 car in COPERT

The SUMO results, on the other hand, are summarized by dividing them according to the three vehicle fleets analyzed, considering the same case of a petrol Euro 6 car:

Fleet 294:

Speed scenario	Average CO2 emitted	Average NOx emitted	Average PM emitted
30 km/h	0.00049	$1.9 \cdot 10^{-7}$	$1.1 \cdot 10^{-8}$
50 km/h	0.00050	$2 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$

Fleet 588:

Speed scenario	Average CO2 emitted	Average NOx emitted	Average PM emitted
30 km/h	0.00046	$1.5 \cdot 10^{-7}$	$3.8 \cdot 10^{-8}$
50 km/h	0.00047	$1.6 \cdot 10^{-7}$	$4 \cdot 10^{-8}$

Fleet 147:

Speed scenario	Average CO2 emitted	Average NOx emitted	Average PM emitted
30 km/h	0.00047	$1.8 \cdot 10^{-7}$	$8.6 \cdot 10^{-9}$
50 km/h	0.00048	$1.9 \cdot 10^{-7}$	$8.6 \cdot 10^{-9}$

Table 18: Summary of CO2, NOx and PM emissions for a petrol Euro 6 car in SUMO

In conclusion, the values obtained from COPERT and SUMO are of a comparable order of magnitude, thus providing a reasonably realistic representation of the average emissions of this vehicle type within the case study analyzed. However, the modeling approaches used by the two software tools differ: in fact, COPERT tends to favor scenarios with higher speeds, whereas SUMO shows the opposite behavior.

COPERT allows us to state that reducing speed alone is not enough to lower emissions, especially considering that low initial speeds can lead to "cold start" emissions due to engine warming. However, as SUMO suggests, lower speeds are generally accompanied by a smoother driving style, with less harsh braking and acceleration, which leads to smoother traffic flow.

This smooth driving style is, in fact, the key to reducing vehicle emissions. To successfully implement a new 30 Zone project, it is essential to consider driving style. This may require redesigning urban elements like traffic lights and pedestrian crossings to create an environment that actively encourages a smoother, more consistent traffic flow. Moreover, following Milan's strategic model, an additional recommendation could be to complement this low-emission strategy with further measures, such as extending existing cycle lanes or creating new pedestrian areas.

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