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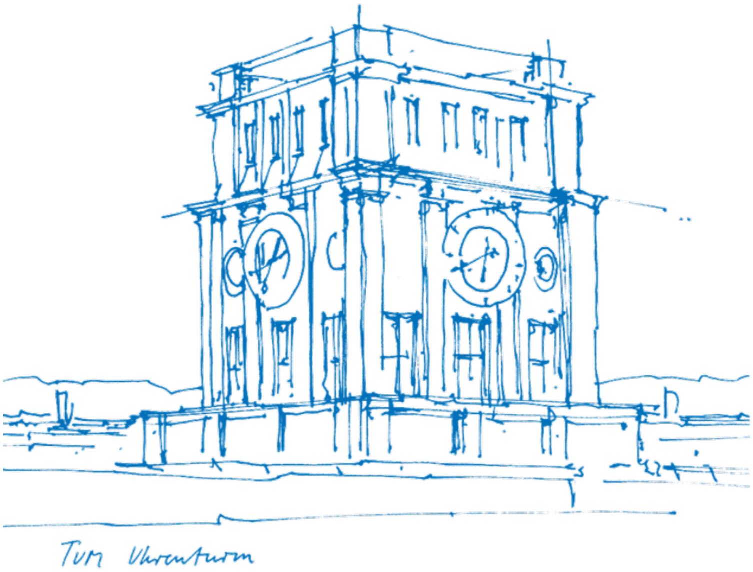

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Abstract

In recent years, Paris, France, transformed its transportation infrastructure, marked by a notable reallocation of space away from cars to active modes of transportation. Key initiatives driving this transformation included Plan Vélo I and II, during which the city created over 1,000 kilometres of new bike paths to encourage cycling. For this, substantial road capacity has been removed from the system. This transformation provides a unique opportunity to investigate the impact of the large-scale network re-configuration on the network-wide traffic flow. Using the Network Fundamental Diagram (NFD) and a re-sampling methodology for its estimation, we investigate with empirical loop detector data from 2010 and 2023 the impact on the network's capacity, critical density, and free-flow speed resulting from these policy interventions. We find that in the urban core with the most policy interventions, per lane capacity decreased by over 50%, accompanied by a 60% drop in free-flow speed. Similarly, in the zone with fewer interventions, capacity declined by 34%, with a 40% reduction in free-flow speed. While these changes seem substantial, the NFDs show that overall congestion did not increase, indicating a modal shift to other modes of transport and hence presumably more sustainable urban mobility.

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1 Introduction

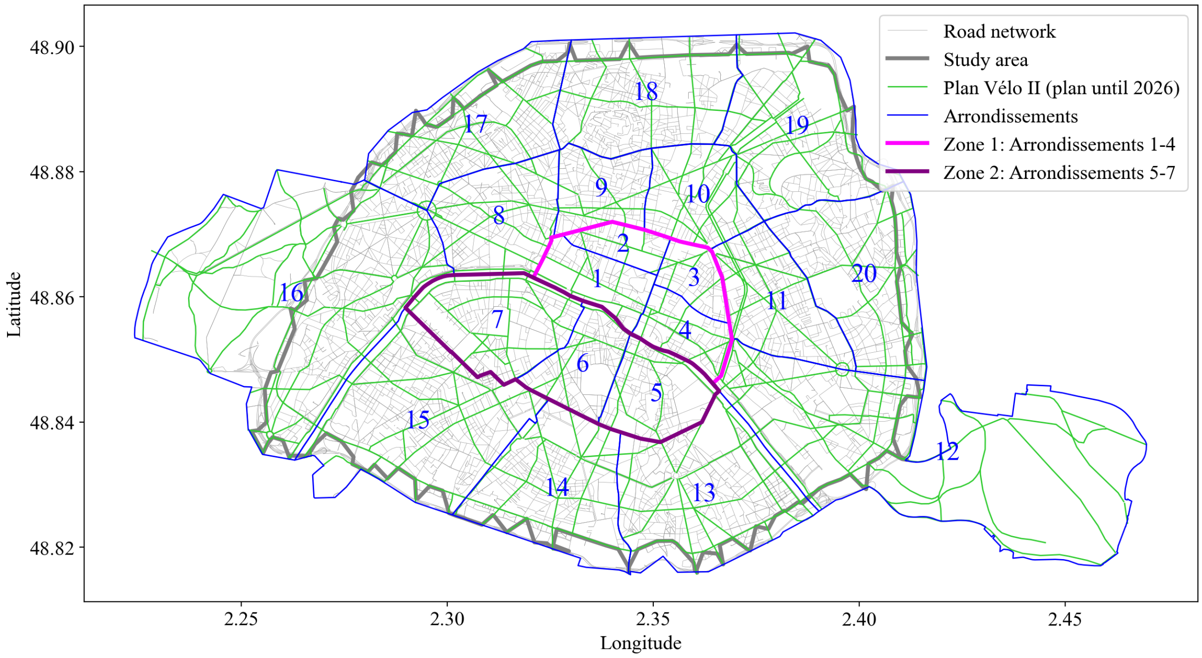
The capital of France, Paris, is frequently said to be a pioneer in the reallocation and reconfiguration of road space to other transport modes. But it is not only its pioneering role, but also the speed and magnitude of this transformation that attracts interest. Paris plans to completely eliminate local emissions by 2050, making the city emission-free. They also aim to reduce the carbon footprint by 80% compared to 2004 levels. Plan Vélo I and II encompass a range of initiatives aimed at encouraging cycling, including the removal of parking spaces and the implementation of bike rental systems. However, the primary focus lies in the establishment of bike paths. Under these plans, the city claims to have constructed approximately 1,000 kilometres of bike paths between 2015 and 2020 as part of Plan Vélo I, with an additional 180 kilometres slated for completion by 2026 under Plan Vélo II. These substantial interventions impact traffic capacity as well as how cars behave in the network, in terms of speed, route choice, etc.

Paris' transformation stands as a compelling case study for cities confronting emission reduction goals in the face of the climate crisis. The substantial shifts in its transportation infrastructure provide an invaluable opportunity to empirically study their effects on traffic operations and travel behaviour, essentially functioning as a real-world experiment.

Existing research primarily focuses on the impact of cycling infrastructure on cycling patterns and bike traffic. One review highlights the role of public policy in promoting biking, emphasizing the need for diverse interventions like infrastructure enhancement and pro-bicycle initiatives (Pucher *et al.*, ????). Another study finds that investments in bicycle highways increase cycling commuters and reduce car dependency (Haar, 2023). Additionally, research examines the quality of bicycle infrastructure and its effect on bike lane usage (Hull and O' Holleran, 2014). Comparative analysis between classical and recent studies on urban bicycle infrastructure interventions is also conducted (van Goeverden *et al.*, 2015). Finally, studies explore factors contributing to a city's cyclability and introduce methodologies to evaluate cycling quality based on user preferences (Reggiani *et al.*, 2022).

However, the impact of these policy interventions on car traffic at the network level has not been much explored in literature. While studies have investigated the immediate impacts of bicycle traffic on car traffic in Shanghai (Huang *et al.*, 2021), there is a lack of research on long-term effects similar to those observed in Paris over a 14-year period. This information holds significance for policy making, planning, and traffic operations. The Network Fundamental Diagram (NFD) serves as a novel tool for assessing such policy interventions (Daganzo, 2007). The NFD is a reproducible curve between urban traffic density and traffic flow within

Figure 1: Paris map and its Arrondissements



a network. According to its principles, modifications in the transportation system, particularly in the infrastructure, significantly impact a network's capacity and critical density. In this paper, we contribute with an empirical application of the NFD to the study of the impact of the policy interventions on network-wide vehicular car traffic in Paris with data from 2010 and 2023. We estimate NFDs using the loops method (Leclercq *et al.*, 2014) and the "re-sampling" methodology (Ambühl *et al.*, 2018) to approximate the upper NFD.

Given the considerable number of policy interventions and their implications for the network, it's plausible to expect a decrease in NFD capacity. Regarding the impact on the critical density, effects depend on public transport operations and the corresponding "corridor effect" (Geroliminis *et al.*, 2014; Castrillon and Laval, 2018). All changes have profound implications for network operations, as one can align city's control strategies accordingly.

2 Methodology

We examine the impact of Paris' urban road space transformation on traffic operations using the Network Fundamental Diagram (NFD) as a city-scale assessment method. Table 1 lists all symbols used in this analysis.

The NFD provides an aggregated, network-wide perspective on the relationship between the number of vehicles in the network and their average speed and their collective production of travel (Geroliminis and Daganzo, 2008; Daganzo, 2007). This relationship arises from a combination of network topology and the dynamics of multimodal traffic operations (Daganzo and Geroliminis, 2008; Laval and Castrillón, 2015; Loder *et al.*, 2019; Geroliminis *et al.*, 2014). Utilising this network-wide perspective facilitates a comprehensive assessment of the impacts of large-scale transportation policies that affect the allocation of road space (Ortigosa *et al.*, 2017; Dantsuji *et al.*, 2021; Loder *et al.*, 2022).

To estimate the Network Fundamental Diagram, we use the "re-sampling" method (Ambühl *et al.*, 2018), which provides robust estimations of network capacity and critical density even under real-world traffic conditions. This method proves particularly useful for assessing alterations using empirical data, as it helps mitigate any potential inaccuracies in the empirical dataset. The idea of the re-sampling approach is to identify the most homogeneous sub-samples of all roads by first creating many random sub-samples of the network, estimating for each an NFD, and extracting the smooth upper bound from the superposition of all NFDs. When the re-sampling parameters are chosen appropriately, all points on the upper bound represent the most homogeneous traffic states. (Ambühl *et al.*, 2018) The aim of re-sampling is to approximate the NFD to achieve the best possible performance given the available infrastructure (Ambühl *et al.*, 2021).

In our analysis, we adopt the NFD's representation of density versus vehicle flow per lane-kilometre. We employ a method that utilises loop detector data and network data from OpenStreetMap (OSM) at different time points. Loop detectors, integrated into street infrastructure, provide counts of passing vehicles over time, yielding flow (q) in vehicles per hour and vehicle occupancy (o) as a percentage. These metrics are recorded across Paris at various measurement locations ($i \in N_y$), every hour ($h \in H$), and every day ($d \in D$). It's important to note that loop detectors are typically installed on selected roads (denoted as N_y), assumed to be representative of the broader network. To ascertain the number of lanes on streets where detectors ($i \in N_y$) are placed, we reconcile traffic data with OSM's network information.

2.1 Normalization of measurements

For every year $y \in Y$, consider the set B of those observations which have measured the flow q and the occupancy o at every relevant hour $h \in H$:

Table 1: List of symbols used in this analysis

Symbol	Unit	Description
Z	-	Zones considered: $Z = \{Z_1, Z_2\}$
Y	-	Set of years: $\{2010, 2023\}$
y	-	Year index
D_y	-	Set of days in year y
d	-	Day index
H	-	Set of hours in the day (24-hour clock) with elements $\{5, \ldots, 22\}$
h	-	Hour index
N_y	-	Set of detectors in year y
N_{yz}	-	Set of detectors in year y, zone z
i	-	Detector index
l_i	km	Length of road segment of d. i
n_i	-	Number of lanes in the road segment of detector i
o_{ihd}	-	Detector occupancy
q_{ihd}	veh/h	Flow of vehicles
k_{ihd}	veh/lane-km	Density
K_{zhd}	veh/lane-km	Aggregated density in zone z
Q_{zhd}	veh/lane-km/h	Aggregated flow in zone z

$$B = (q_{ihd}, o_{ihd}) \quad i \in N_y, h \in H, d \in D_y$$

The measurements are available per link and can result from the aggregation of several detectors on this link, that is, not per lane. Analysis using street images from Paris suggests that each lane of a link is monitored by a detector, that is, if a link has three lanes, one detector is placed on each lane. This results in the following units for q and o. Flow q is reported as the number of vehicles per hour and link, that is, unit veh/h, and occupancy o is reported as the average detector occupancy of all detectors on that link during an hour. Note that this measurement is without a unit.

The available Parisian data does inform about the length l_i of the road segment i that is monitored by a set of detectors, but not about the number of lanes n_i at the present location. This information is important for computing the total travel production and speed on that link and capture the network impact of lane removal, for example, if one out of three lanes is reallocated to other modes of transport. In Section 3.2, we elaborate on retrieving information for the lane-kilometres from OSM.

For every detector $i \in N_y$, we are given its length l_i and the number of lanes n_i. For every element in B, we normalize q and o in order to get the values per lane-km. We use the formula for loop methods (Leclercq *et al.*, 2014) for the NFD estimation. Q is in units flow per hour and lane-kilometre, aggregated over all detectors in the zone:

$$Q_{zhd} = \frac{\sum_i l_i \cdot q_{ihd}/n_i}{\sum_i l_i} \tag{1}$$

$$k = \frac{o}{s} \tag{2}$$

We convert occupancy, denoted as o, into density, represented by k, Utilising Equation 2, along with a scalar s. We elaborate on the calibration of this scalar in Section 2.2. The NFD density K aggregated over zone z can then be computed in units vehicles per lane-kilometre:

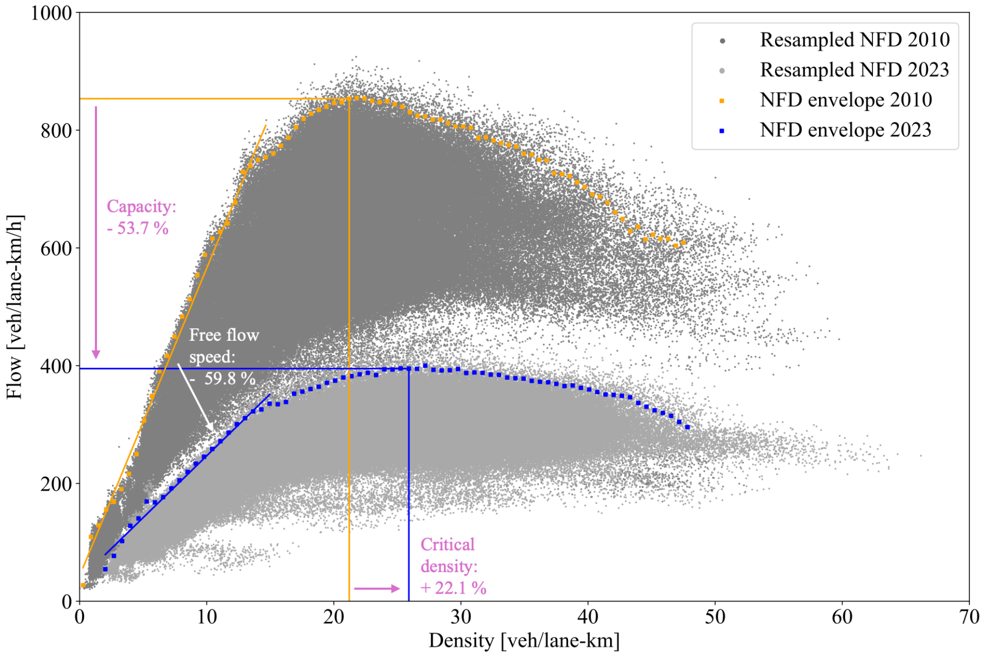
$$K_{zhd} = \frac{\sum_i l_i \cdot k_{ihd}}{\sum_i l_i} \tag{3}$$

2.2 Conversion of occupancy to density

As previously mentioned, detectors in Paris measure flow q per link and average occupancy o, where both measures are available only per hour. To derive meaningful implications, occupancy must be transformed into average vehicle density k with units of vehicle per lane-kilometre. This is conventionally achieved by a linear transformation using the space-effective vehicle length s, which includes the detector and vehicle length. For both, no official values are available and hence we make the assumption that $s = 0.0055$ km.

We corroborate this transformation using public data from TomTom on speeds in Paris. The source reports an average speed of approx. 38 km/h at 5 am and approx. 34 km/h at 6 am, that is, before the onset of the morning peak hour. It is not reported whether these values are time-mean or space-mean speeds, presumably time-mean speeds (Ambühl *et al.*, 2017). Note that the time-mean speed is usually larger than the space-mean speed.

Figure 2: Zone 1 - Resampled NFD 2010 and 2023



It's anticipated that in 2023, average speeds closely match those reported by TomTom, potentially even slightly surpassing them, given the likelihood of additional speed reductions. Upon comparing TomTom speeds with calibrated speeds during the same time periods using the NFD's k and q parameters, remarkable proximity is observed: 38.51 km/h at 5 am and 34.17 km/h at 6 am. Hence, $s = 0.0055$ km is appropriate for estimating the density in the Paris region.

3 Data

This section presents the available data set from Paris. There is an extensive network of loop detectors installed, which are mainly installed for traffic control and congestion identification purposes. They measure traffic flow (number of vehicles passing the detector) and occupancy (fraction of time the detector is occupied by a vehicle) in one-hour intervals since 2010.

We only considered data from “complete days": Those values for which detectors delivered data for flow and occupancy from 5 am to 11 pm on a weekday.

In order to infer the number of lanes of the street that a detector measures, we geolocated all spatial information of loop detector positions in reference to the whole road network, as described in Section 3.2.

3.1 Selecting the areas for investigation

As the “re-sampling” method works best on homogeneous areas of approximately $5-10$ km^2, we select areas on which we apply the method. Paris is divided into multiple districts known as “Arrondissements” (districts), which we use as a boundary. We employ the method on two zones:

1. Zone 1 encompasses Arrondissements 1 - 4. These central districts, situated north of the Seine, have been focal points of Parisian policy interventions. They were also the first ones in which measures such as car-free Sundays have been implemented. This zone represents a “progressive transformation" of the city.
2. Zone 2 comprises Arrondissements 5 - 7. Located south of the Seine, these districts have also undergone significant revitalization endeavors. Zone 2 embodies transformation endeavors more in line with the rest of the city.

Zones 1 and 2 are depicted in Figure 1. We investigate the impact of implementing varying degrees of progressive political measures in Paris on traffic and travel behaviour, utilising these two zones as our study areas.

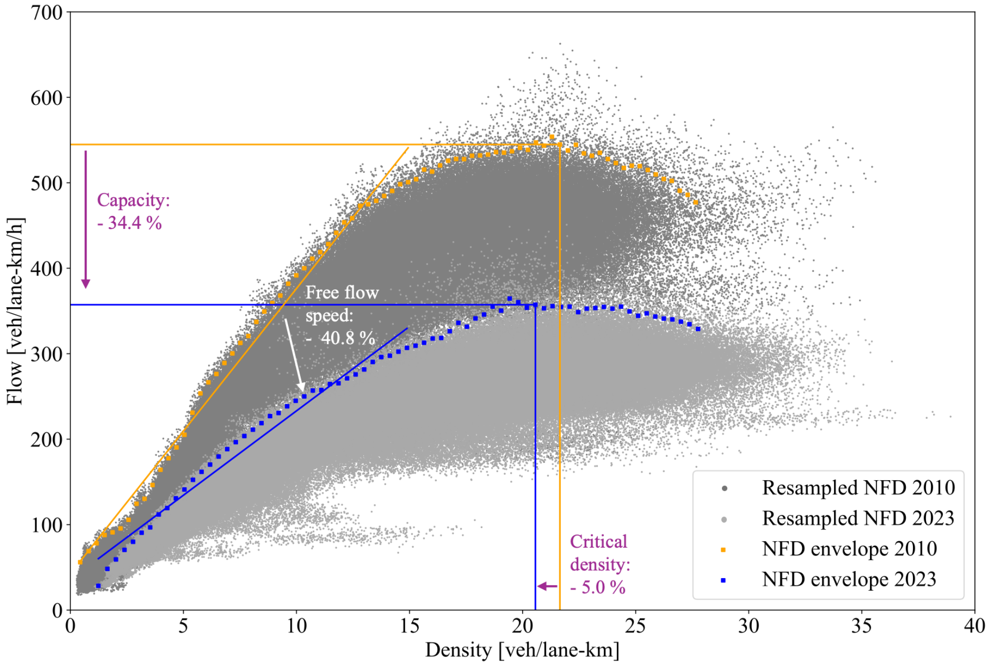
3.2 Data for lane-kilometres from OpenStreetMap

Since we want to estimate the NFD for lane-kilometres, we are interested in the number of lanes of the road on which the detectors are located. To determine this, we employ information from OSM for the Parisian road network as of 01.01.2013 and 01.01.2024. Unfortunately, earlier records were unavailable. Therefore, we utilise lane information from 2013 to infer values for 2010, which sufficiently serves our analytical objectives.

Loop detectors are typically installed on roads which have the highway classification primary, secondary, tertiary, trunk, or motorway in OSM. Therefore, we focus on the network of those roads, the higher-order road network.

A one-to-one mapping does not exist between the higher-order road network and the detector

Figure 3: Zone 2 - Resampled NFD 2010 and 2023



network. This is due to inaccuracies in OSM but also to different representations of the network - for example, the network in OSM consists of smaller road segments.

Our methodology involves a mapping process based on centroid distances and angles. Specifically, for each detector, we identify the most compatible road segment within the OSM network in terms of both centroid proximity and angle alignment. We provide the code for mapping road segments to (historical) OSM data on Github.

3.3 Examining the evolution of the cycling infrastructure

We conducted an analysis of the evolution of Paris's bicycle network, using publicly available data (Open data Paris, 2024a) spanning from 2000 to 2022. Cycle paths are categorized into four types: “Pistes cyclables" for lanes exclusively for cyclists with physical separation from other traffic; “Bande cyclables" for lanes on roads open to general traffic; “Couloir de bus ouvert aux vélos" for bus lanes open to cyclists; and “Autre itinéraires cyclables" encompassing routes closed to general traffic, such as pedestrian areas and contraflow cycle lanes.

Of particular significance for our analysis are the “Pistes cyclables", which stand out as the only bike paths featuring physical separation. The creation of these paths consistently involved

Table 2: Bike network length 2010 and 2022 (Open data Paris, 2024a).

Area [1]	**Length 2010**	**Length 2022**	**Increase**
Paris region	422.25 km	1083.09 km	257 %
Zone 1	44.37 km	115.12 km	259 %
Zone 2	30.23 km	104.46 km	346 %
Paris region: S.	170.42	333.99 km	96 %
Zone 1: S.	4.10 km	19.51 km	476 %
Zone 2: S.	1.78 km	16.22 km	911 %

S. stands for “separate bike paths”: Pistes cyclables

the removal of at least one car lane.

The development of the bike network length over time is illustrated in Table 2. Plan Vélo II (Open data Paris, 2024b) is depicted in Figure 1, illustrating the expansion of the “Pistes cyclables" network. This network is projected to span 447 km upon its completion by 2026, in alignment with official reports indicating a coverage of 334 km as of 2022.

4 Results

In this section, we present the results of applying our methodology from Section 2 to the data in Section 3. In Figure 2 and 3, we show the resampled NFD for zones 1 and 2, respectively. It’s important to note that every point in the NFD represents a macroscopic traffic state in terms of vehicle density and vehicle flow. We computed the free-flow speed as the speed at a density of 0 - 15 veh/km.

The NFD envelope is defined as the median of the top M flow values per density bin, where the value of M depends on the number of observations within each bin. We select $M = 100$ to ensure a smooth upper bound. Using this upper bound, we define capacity as the flow value at the 97.5th percentile to mitigate the influence of outliers. The critical density is the mean density corresponding to this capacity.

Remarkably, both NFDs exhibit a smooth upper bound, which supports the general theory of the NFD, defined as a tight upper bound relatively independent of demand. For Zone 1, we found that the capacity dropped in the considered time frame from 854 veh/lane-km/h to 395 veh/lane-km/h, a substantial decrease of 53.71%. The critical density increased from 21 veh/lane-km to 26 veh/lane-km, representing a 22.12% increase. This phenomenon is commonly referred to as the “corridor" effect (Geroliminis *et al.*, 2014). In Zone 2, capacity dropped from 545 veh/lane-km/h in 2010 to 357 veh/lane-km/h in 2023, marking a drop of 34.41%. The critical density decreased only slightly, from 21.65 veh/lane-km in 2010 to 20.57 veh/lane-km in 2023. This trend is likely attributable to reduced space for cars and an increase in viable alternatives (Castrillon and Laval, 2018). Both zones experienced a significant drop in free-flow speed. In Zone 1, it dropped from 52.25 km/h in 2010 to 21.00 km/h in 2023, representing a reduction of about 60%. In Zone 2, it decreased from 33.36 km/h to 19.75 km/h, a decrease of about 40%.

These findings are consistent with our initial hypotheses - both zones experienced a substantial decrease in traffic flow and speed, with Zone 1 seeing particularly significant declines.

In terms of network supply, the interventions in Paris, including Plan Vélo I and II, led to an expansion of bike lanes and a reduction in space allocated to cars.

The cycling network has notably grown, according to cycling paths data from official sources (Open data Paris, 2024a), with detailed findings provided in Table 2. In particular, the establishment of separated bike paths, referred to as “Pistes cyclables" in Section 3.3, has notably increased. When analysing the relative increases, it seems that Zone 2 has experienced more significant developments. However, one must not overlook the absolute numbers: Despite its smaller geographical size compared to Zone 2, Zone 1 already had a more extensive bicycle network in 2010. This network comprised both overall routes and distinct cycling paths, which are especially noteworthy. This suggests that Zone 1 was already more bicycle-friendly and less reliant on cars compared to Zone 2 by 2010. Subsequent network modifications have likely only propelled this progress further.

Regarding the road network, it’s reasonable to expect a slight decrease in lane-kilometres. Natterer et al. showcased a 4.9% reduction in lane kilometres from 2015 to 2023 (Natterer *et al.*, 2023). Pinpointing the exact reduction from 2010 is challenging due to the continuous enhancements in OSM’s accuracy, notably considering that data is only available from 2013 onwards.

5 Discussion

We analysed the evolution of traffic behavior in Paris from 2010 to 2023 amid significant network changes, utilising the re-sampling method for NFDs based on empirical data. The impact of network changes on overall car travel, particularly network exit flows, also depends on average trip length. If short-trip car travelers switch modes, it reduces maximum trip production and increases average trip length, thereby decreasing network exit flows. Conversely, if long-trip car travelers, like inbound commuters, change modes, it can increase network exit flows. Unfortunately, data on average trip length for car users from 2010 to 2023 are unavailable, hindering conclusive insights.

Firstly, when it comes to data, using loop detector data may introduce errors. These could be reduced by increasing detector coverage and refining NFD estimation. Having accurate lane count information at measurement locations would enhance travel production estimates, alongside improved speed data for NFD calibration, ensuring consistency over time. Although OSM offers valuable insights, its lack of precise road network details, delays in updates, and limited availability of data starting only from 2013 hinder its verification with official sources. Secondly, in terms of findings, assessing Plan Vélo I and II necessitates considering broader impacts beyond immediate traffic effects. This includes health benefits and urban heat island mitigation. External factors like COVID-19 and remote work trends also influenced traffic from 2010 to 2023. This interim assessment underscores the importance of conducting comprehensive studies after full implementation to gauge effectiveness.

In summary, the interventions in Paris had a noticeable impact, leading to significant traffic flow reductions in both zones, albeit to different extents. In Zone 1, the higher congestion resulted mainly from reduced space for vehicles rather than increased traffic volume. Despite this increased congestion, traffic did not completely collapse, suggesting a shift in demand towards alternative transportation modes. In contrast, Zone 2 experienced lower congestion levels following the interventions. It is important to highlight that these effects can be attributed to overall policy interventions aimed at making the city more bicycle- and pedestrian-friendly. Plan Velo I and II were key components of this effort. Paris' approach to smart mobility underscores the importance of closely monitoring network changes to inform effective traffic management decisions.

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7 Author Contributions

The authors confirm their contribution to the paper as follows. Study conception and design, analysis and interpretation of results, draft manuscript preparation: E. Natterer, A. Loder, K. Bogenberger; data collection and engineering: E. Natterer. All authors reviewed the results and approved the final version of the manuscript.

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