Influence of Public Transportation in Munich: An Empirical MFD Traffic Analysis

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ABSTRACT

Public transportation strikes have a long-standing tradition in transportation research for analyzing their impact on individual mode choice and collective traffic performance, e.g., congestion levels or traffic speeds. In March 2023, Munich was twice affected by a one-day strike of almost all road-based transportation services. We use this natural experiment to empirically analyze the impact of public transportation operations on Munich's network traffic using the macroscopic fundamental diagram (MFD) and data from 770 loop detectors. The MFD theory predicts that the MFD's shape also depends on public transportation operations, the so-called 3D-MFD: the absence of public transportation is expected to increase network capacity and critical density. We find that on strike days, the inflow of cars into the city increases by around 15%, suggesting that some previous public transportation travelers changed to the car. Further, we find the expected change in the MFD shape, with the MFD capacity increasing by 4.7% and the critical occupancy by 8%, while data also suggests a slight increase in free-flow speeds. Interestingly, we see that on the Friday strike day compared to the Monday strike day, peak spreading behavior in the afternoon avoided a network breakdown. Overall, we conclude that the increase in the capacity in car passenger travel production due to the absence of public transportation was only one-third of the lost capacity in public transportation passenger travel production based on conservative estimates of bus occupancy levels.

Keywords: Strike; Public Transportation; Traffic Analysis; Capacity; Speed; Moving Bottleneck; MFD

INTRODUCTION

Strikes are considered natural or forced experiments and have been used in transportation research to investigate various aspects, such as their impacts on congestion and travel mode choice. For example, analyses of the 2003 Los Angeles public transportation strike show that congestion worsened substantially even though public transportation usually sees only a small fraction of the overall travel demand (*1, 2*). The "congestion relief" benefit of public transportation and the external cost of strikes are found to be substantial, stressing the importance of public transportation provision and subsidies in reducing car externalize (*2–4*). While the reasons for a behavioral change during a public transportation strike presumably only be obtained through questionnaires (*5, 6*), the primary data source for assessment of strike impacts on traffic performance are loop detector data (*2, 7*) and floating car data (*4*).

Strike-related traffic analyses have mainly focused on arterials or highway speeds, presumably as economic assessments are based on losses in travel time and the value of travel time savings (*3, 8*). While speed might be informative from an economic perspective and for individual travelers, public transportation operations impact traffic flow, e.g., reduced corridor capacity due to mixed traffic (*9, 10*) as buses have additional stops (*11*), buses are moving bottlenecks (*12–14*) and some even designated time-table speeds (*15*), and public transportation priority at intersections (*16–19*). In other words, there is an impact on the network performance too. However, there has been, so far, less focus on this collective impact on traffic flow and network performance.

Here, the macroscopic fundamental diagram (MFD) provides a unique methodological opportunity to study the strike impact on the overall network performance in terms of demand and supply. The MFD is a network-wide relationship between the number of vehicles in the network and their collective travel production or average speed (*20*). This relationship is assumed to be a function of network structure and topology (*21–23*) as well as the presence of other modes of transportation, e.g., public transportation (*24, 25*). Consequently, if a public transportation strike occurs, the natural hypotheses are that some trips are shifted from public transportation to the car and that the absence of public transportation improves car travel and traffic through less moving bottlenecks, less public transportation service stops, and more green time at intersections due to less public transportation priority. So far, the MFD has been widely used to study, e.g., the impact of network topology (*26*), public transportation operations (*27, 28*), and the impact of road investment (*29*), but it has never been used as a method to empirically assess the impact of a public transportation strike on network traffic; in other words, comparing the same network with and without public transportation operations.

In March 2023, Munich, Germany, experienced twice a strike of all road-based public transportation and most rail-based services. We use this natural experiment to empirically investigate the impact of public transportation on demand patterns and network-wide traffic using loop detector data for an urban road network with and without road-based public transportation services. We have the following hypotheses (i) strike leads to demand shifts towards car travel, based on empirical evidence, e.g., (*1, 2*); (ii) strike results in changes in the MFD shape, with an increased capacity, critical density, and free-flow speed, based on MFD theory, e.g., (*30*).

This paper contributes with the first empirical assessment of the impact of a public transportation strike on network traffic flow using the MFD and data from Munich, Germany. By doing so, we also provide the first empirical analysis of network-wide traffic operations in a metropolis with and without public transportation operations, which allows us to approximate the benefit of public transportation in terms of passenger travel. The results show that, indeed the MFD shape is changed from a non-strike day to a strike day in terms of capacity, critical occupancy, and likely also in free-flow speed, as well as that the gains in car passenger travel production are only one-third of the losses in public transportation passenger travel using a conservative estimate of the average public transportation vehicle occupancy.

This paper is organized as follows and is further illustrated in Figure 1. First, we introduce the case study of Munich; next, we provide an overview of the dataset and the MFD-based analysis deployed in our study; later, we present the results from the Munich case and offer insights into the benefits of public transportation provision in terms of passenger travel; finally, we summarise future research directions and highlight important takeaways from the Munich case.

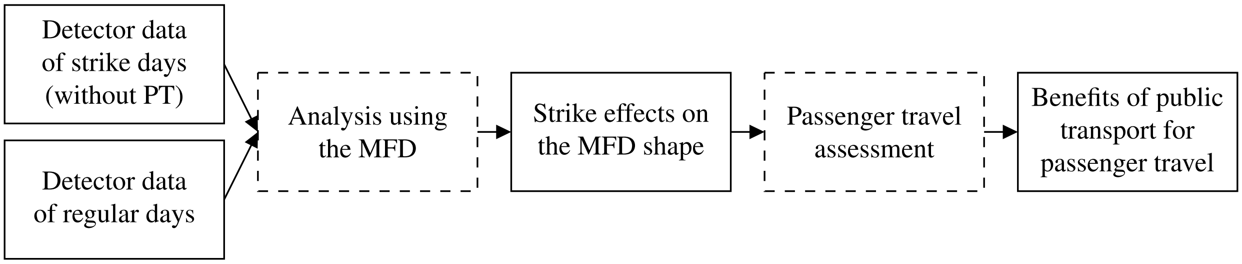


FIGURE 1 : Organization of this study

CASE STUDY MUNICH

The city of Munich, Germany, covers an area of 310 km^2 with a population of approximately 1.6 million inhabitants. Excluding motorways and minor residential roads, Munich road network is 740 km-road long. The city of Munich and its metropolitan region is characterized by three ring roads: around the city, a highway beltway connects seven highways and allows to bypass the city for through traffic. The second ring road is the “Mittlerer Ring” (middle ring road), road number “B2R” surrounds the inner part of the city and also connects to the same highways that are connected to the highway beltway. The third ring road is the “Altstadtring” that surrounds the old city core, which is predominately pedestrianized. Moving between the highway beltway and the B2R is possible on highways, while moving between the B2R and the Altstadtring is only possible on signalized arterials. Figure 2a shows the road network at the level of B2R, the middle ring road. The B2R acts as a natural boundary separating the CBD from the city suburbs. Complementing the extensive road network is a public transportation network operated by Munich Transport and Tariff Association (MVV). The Public transportation network comprises eight suburban train lines and eight subway lines that connect the suburbs of the city by crossing the B2R. In addition, the network is enhanced by 18 tram lines and 118 bus lines, shown in Figure 2b, operating with headways between five and fifteen minutes. Many services operate in mixed traffic conditions and not on dedicated lanes. Table 1 shows the operational characteristics of road-based public transportation within the B2R. To promote sustainable modes, most road-based public transportation lines are prioritized at signalized intersections across the city. Nevertheless, the network-wide effect of public transportation and related prioritization strategy has never been investigated.

In March 2023, Munich encountered two significant strikes by public transportation personnel, resulting in severe disruptions to transportation services. The first strike occurred on Friday, the 3rd, impacting the subway, trams, and buses. Subsequently, on Monday, the 27th, a broader strike affected all public transportation services, including rail-based services. These strikes, announced well in advance by the labor union, persisted for a full day. It should be noted that a few buses operated by private companies with sub-contracts from MVV continued to run. The snowy weather on the second strike date further limited accessible alternative transportation modes, such as walking or cycling. This network-wide natural experiment gives a unique opportunity to apply an MFD-based analysis to investigate the impact of public transportation.

Previous work involving the estimation of the MFD in Munich includes (*31*) simulation-based MFD model for the city, (*23*) empirically MFD for Schwabing sub-network, (*32*) analytical and empirical MFD for Leopoldstraße corridor. While these studies offer valuable insights, they also leave space for a broader empirical investigation.

In this study, we focus on the area inside the B2R, the colored area shown in Figure 2a. The B2R can be considered a natural urban boundary, not only in terms of urban structure but also in terms of traffic flow. The region inside is one large reservoir. The inflow and outflow to this network is limited to a few locations, usually connected with ramps to the B2R. In addition, the B2R region sees substantially more public transportation operations on almost all major streets in the network. Note that we exclude the B2R ring road itself from this analysis because it is a dual carriageway and almost unsignalized, being more an urban highway than an urban street.

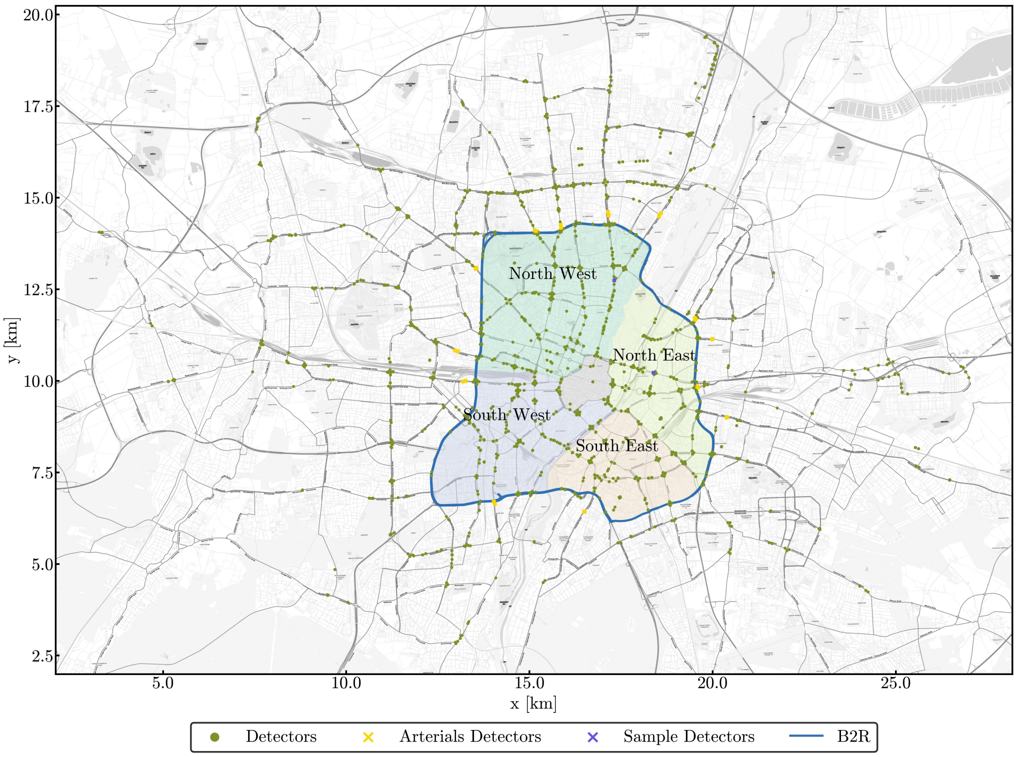
TABLE 1 : B2R Regions Characteristics

	Area [km^2]	Road Length [km]	Stops No. [#]	Routes Length [km]
North West	15.2	72	256	129
South West	11.0	43	174	90
North East	8.8	48	166	99
South East	7.0	24	110	47
Full region	43.6	188	735	376

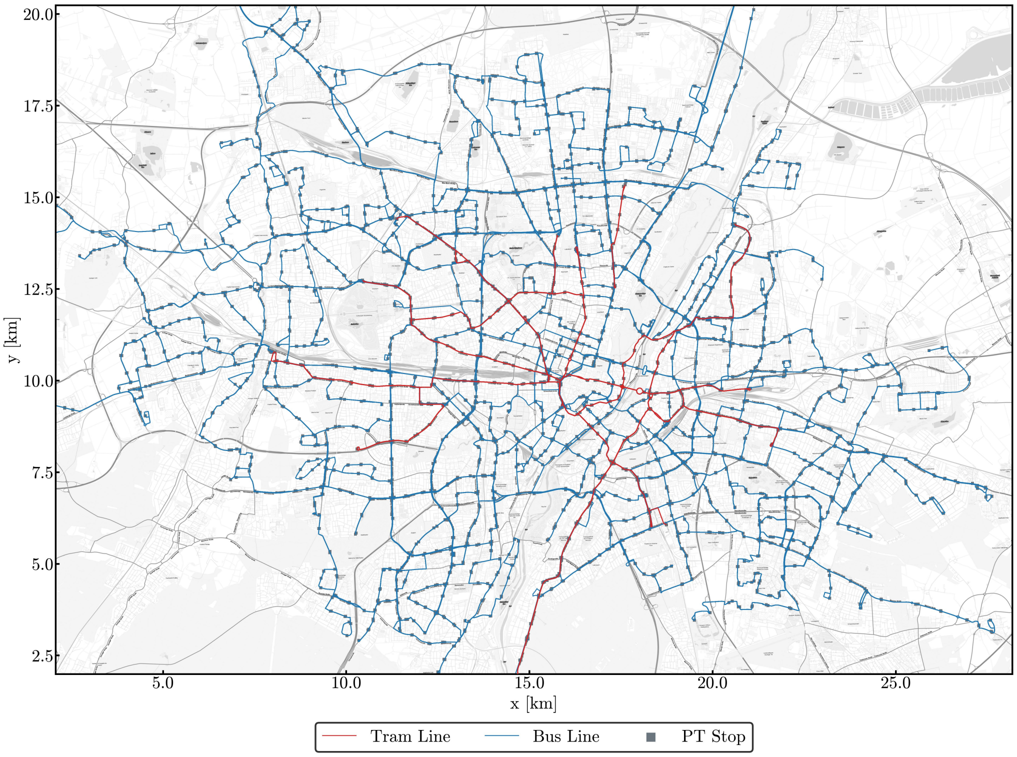
METHODOLOGY AND DATA

An MFD-based Approach

The large extent of both strike days as well as their level of impact makes the application of the MFD theory appealing. As the MFD provides an aggregated, macroscopic and urban-scale perspective on the dynamics of multi-modal traffic in urban road networks (*33*), it allows to focus on the main or "first order" effect of the strike at an urban level. The MFD extends naturally to several modes of transportation, where the "multi-modal" MFD then captures the interaction costs between modes of transportation at the network level. In an urban environment, the most relevant multi-modal MFD captures the interactions between car traffic and road-based public transportation (*25, 30, 34*), also called the "3D-MFD". It quantifies the impact of the number of cars and public transportation vehicles in a network on the joint travel production of all vehicles in the network. Considering an urban road network with substantial public transportation operations, the 3D-MFD predicts that in case of a strike, the capacity, as well as the critical density, increases (*30*). In this analysis, we investigate how the capacity and the critical density are affected by the strikes. If an effect can be found, the effect size, together with the 3D-MFD theory, then allows to make an assessment of the cost and benefits of public transportation operations in Munich from a traffic engineering perspective without using operational public transportation data.



(a) B2R road network



(b) B2R road-based public transportation network

FIGURE 2 : B2R region under study

A key underlying assumption of the MFD is that homogeneous network characteristics as well as homogeneous traffic load exist in order to make the estimated MFD representative of the average traffic conditions in the network. The literature presents several approaches to obtain sub-networks within a city that satisfy the homogeneity assumption (*35*–*38*). In this analysis, we first estimate the car MFD for the entire core urban region within the B2R as shown in Figure 2 and then partition the entire region into four sub-networks by following the natural borders of the four reservoirs.

We estimate MFDs for strike days and non-strike days using the "re-sampling" method (*39*), which has shown to reveal a smooth upper bound to all possible states, potentially describing the network's upper MFD, as well as the networks' pockets of congestion, leading to an observed congested branch (*23*).

Traffic Data

The city of Munich utilizes 9,815 loop detectors, mainly for traffic signal control purposes, hereafter, we focus on the 3,300 geo-referenced detectors. We obtained nine weeks of traffic data between January 28th and April 13th; each detector has a record of traffic flow (count of vehicles passing the detector) and occupancy (proportion of time the detector is occupied by a vehicle), updated in an interval of 15 minutes.

The detectors were filtered in two stages, first, by removing the daily record for any detector if (i) the detector was off or reported an error for more than 20% of the day, (ii) if either the flow or occupancy measurements did not change for more than 80% of the day. Second, by removing detectors if the 98th-percentile of all its records for the nine weeks is less than 300 veh/hr-ln. This resulted in removing around 47% of the geo-referenced detectors; the final number of detectors was 1,555, out of which 770 are within the B2R region, as illustrated in Figure 2a.

The resulting sample of loop detectors covers the road network inside the B2R region well. Almost any major urban street is monitored in our study. Residential streets are not monitored but also not considered in the MFD analysis. Thus, we consider the traffic data sample representative, although the known location bias of loop detectors is still present in the data (*40*–*42*).

RESULTS

The absence of public transportation services is expected to shift commuters towards cars, consequently increasing the traffic flow per lane. We estimated the average cumulative count of detectors on arterials connecting the B2R region, Figure 2a, to assess the demand for commuting to and from the CBD. Figure 3 illustrates the average detectors' cumulative count for both strike days and non-strike reference days, considering the corresponding weekday from one week before and one week after each strike. Notably, the number of vehicles entering the B2R network significantly increased on strike days, with an average inflow per lane rise of approximately 15.7%. The number of vehicles leaving the B2R network was also consistent and comparable, with an average outflow per lane rise of around 16.4%. Interestingly, the increase in demand for cars was more pronounced on the first strike day compared to the second, despite the latter including all available public transportation options. It appears that individuals who experienced significant travel delays on the 3rd strike day chose to refrain from traveling altogether on the 27th strike day. The increase in demand for private vehicles, a trend reported in previous studies, is also evident in Munich. Considering that the accessibility to alternative modes like walking and cycling was limited due to severe weather, these results indicate the cancellation of many trips. This suggests that the newfound flexibility in working locations, arising from the changes brought about by the COVID-19 pandemic, contributed to these travel behavior shifts.

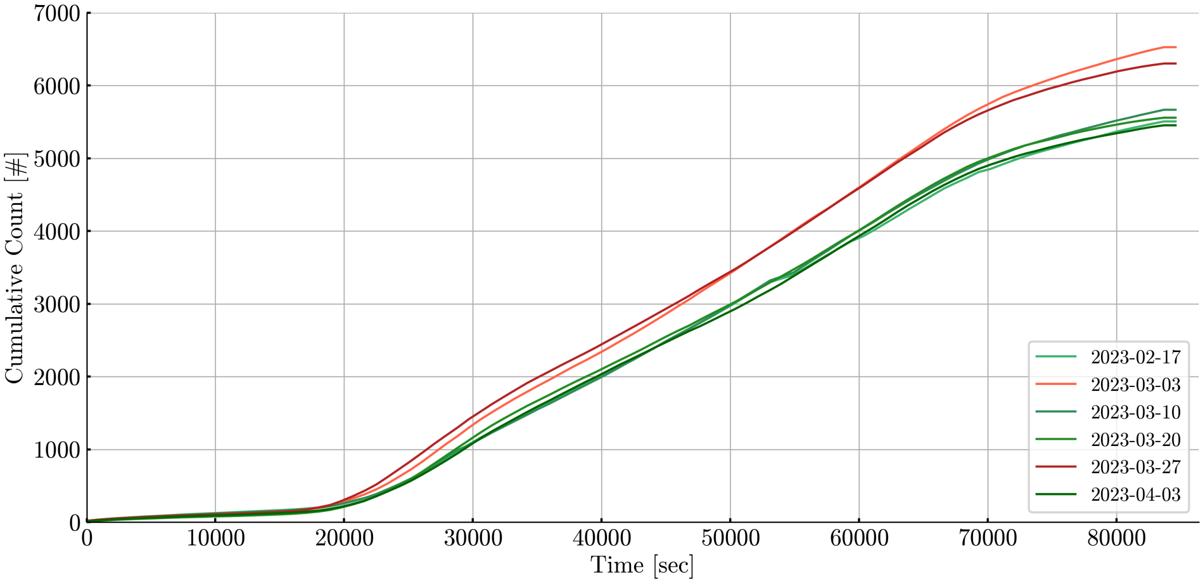


FIGURE 3 : Average cumulative inflow into the B2R network per lane on strike days and non-strike days

Additionally, we estimated the difference in peak flow for each detector within the B2R region, Figure 2a, on each strike day, comparing it to its corresponding weekday in the following week. The distribution of these differences for both strike days is shown in Figure 4. On average, the detector's peak flow was higher by around 76 and 69 veh/hr-ln for the first and second strike day, respectively, compared to the same weekday in the following week. It's clear that the distribution is skewed towards positive changes in the detectors' peak flow, with only around 13%, experiencing a negative change.

The increase in peak flow can be attributed to the observed increase in demand for some detectors. However, for others, it represents an actual increase in the link capacity due to the absence of public transportation services. This distinction becomes clearer when examining the Fundamental Diagram (FD) of individual links with high private car demand and frequent public transportation services. To estimate the FD, we pooled the detector's flow and occupancy measurements from strike dates. We, also pooled the traffic measurements from corresponding days in the dataset to serve as reference days. An example of the obtained FDs is shown in Figure 5, with the detectors highlighted in Figure 2a. Notably, an increase in capacity is evident in Figure 5a, while an increase in speed is observed in Figure 5b. This demonstrates the varying effects of the absence of public transportation services on capacity and speed at the link level.

To assess the impact of the absence of public transportation services at a network level, we estimate the MFDs for the B2R region and sub-regions, using the re-sampling method proposed by (*39*). The re-sampling method is designed to produce results that are less impacted by small demand variations, to consider pockets of congestion in the network, and to produce a smooth upper bound of the MFD. Considering the changes in demand due to the strike as seen in Figure 3, using the re-sampling method can be expected to make the results and implications less sensitive

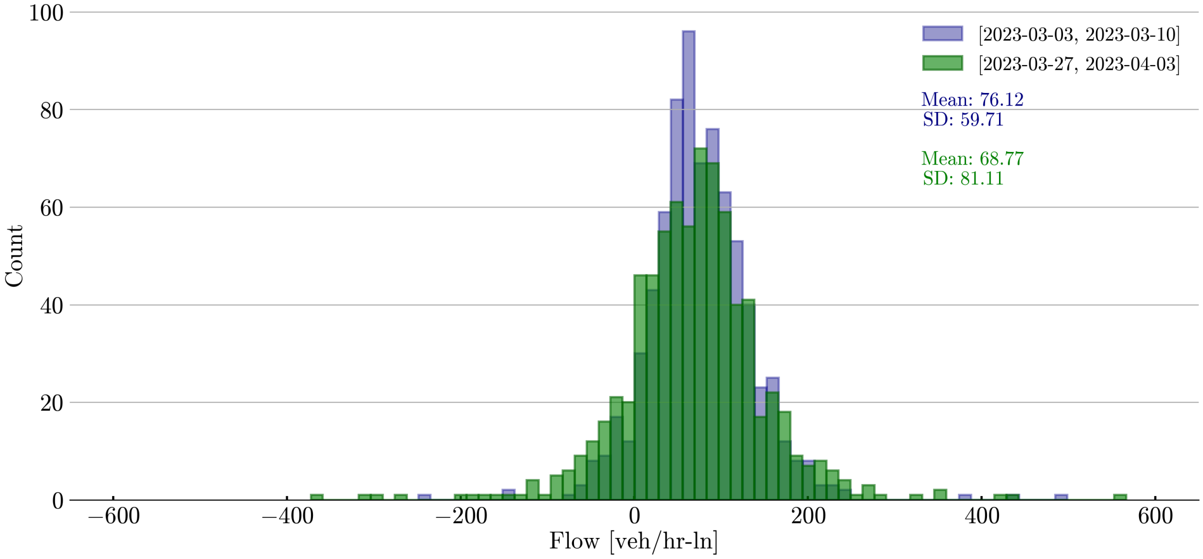
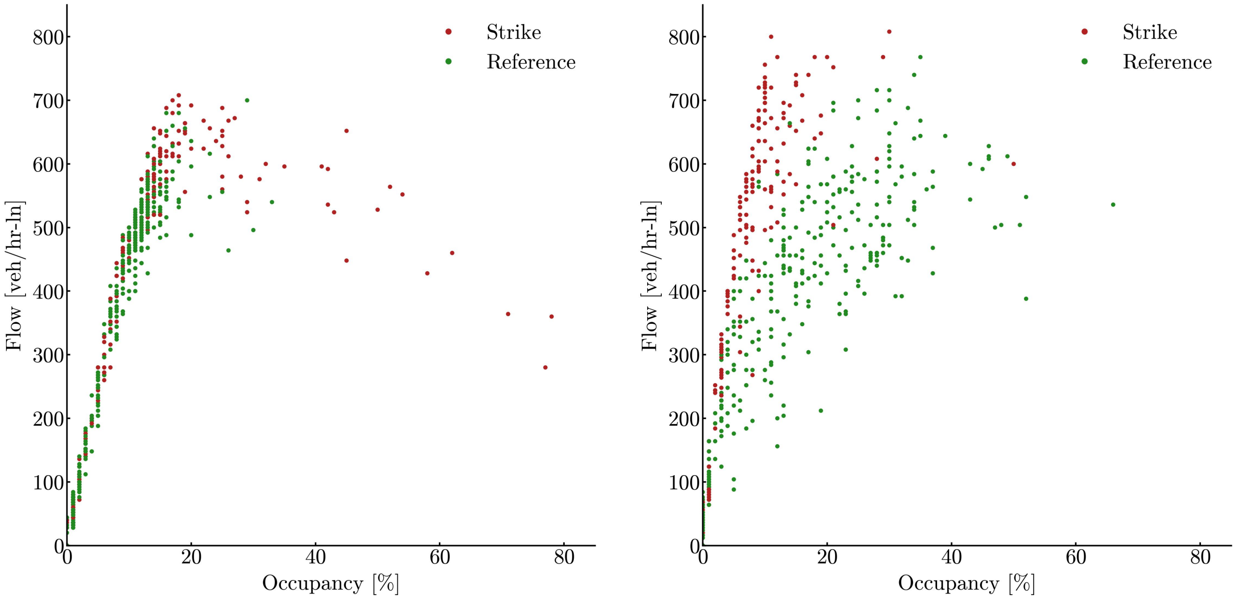


FIGURE 4 : The difference in flow 95th-percentile between strike days and non-strikes for all detectors



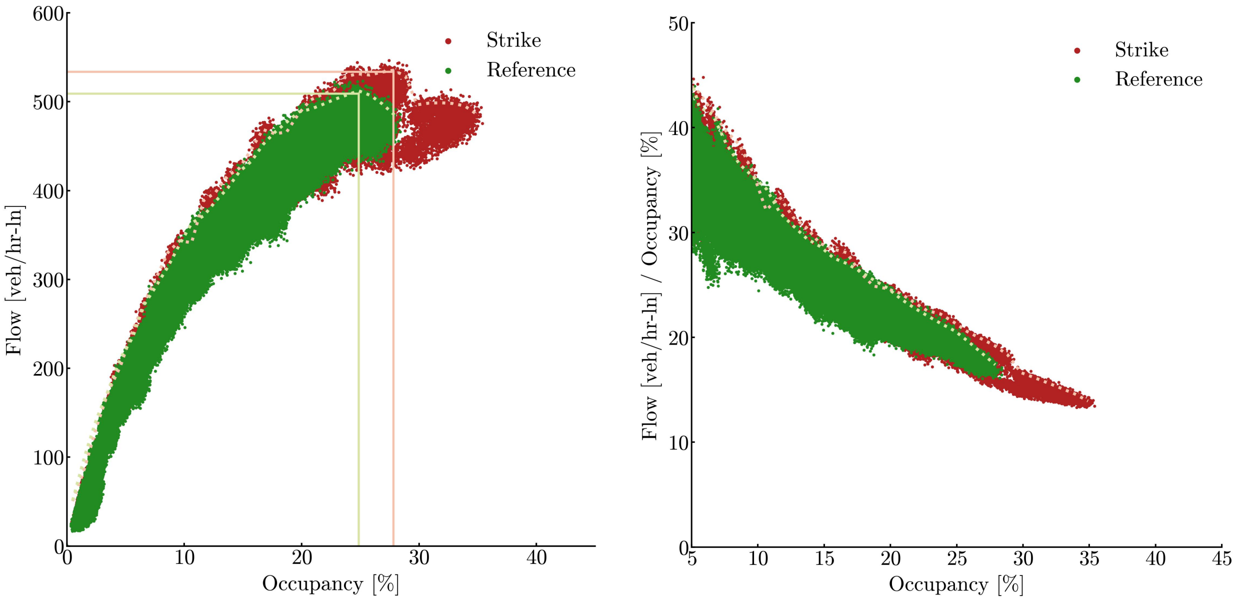
(a) A detector placed at Leopoldstraße

(b) A detector placed at Prinzregentenstraße

FIGURE 5 : The FD for sample detectors

to the changes in demand. After evaluating various parameter values, we ultimately selected a sample size of 500 subsamples with a fraction size of 0.6, enabling us to resample 60% of the aggregated data for each subsample. Figure 6 presents the resampled MFDs for both strike days and all corresponding weekdays in the dataset. For the pooled strike and reference MFD, the upper profile represents the median flow value of the highest 50 values in each occupancy bin of 1%, while the critical occupancy is determined at the 97.5$^{\text{th}}$-percentile of the upper bound flow.

Intuitively, the re-sampling method obtains more scatter and the upper bound is less smooth when using only a few days instead of several weeks, as it is the case in our analysis with only two strike days compared to several weeks of non-strike days. The strike MFD reveals a rise of capacity flow by 4.7%, in addition to an 8% rise in the critical occupancy in the absence of public transportation vehicles. Table 2 presents the change in capacity and critical occupancy for the partitioned sub-regions of the B2R, where all sub-regions showed a considerable increase in the capacity flow on the strike days, but the increase in critical occupancy didn't follow the same pattern. However, it's essential to note that our sample size was limited, consisting of only 4 regions. These findings of the resampled MFDs are in line with the 3D-MFD theory, stating that the maximum vehicular flow occurs when no public transportation vehicles operate.



(a) Flow-Occupancy

(b) Speed-Occupancy

FIGURE 6 : B2R MFD

To better understand the variation in demand during the strikes, we analyzed the flow-time series shown in Figure 7. It is evident from the figure that on the first strike day (Friday, March 3$^{\text{rd}}$), commuters exhibited greater flexibility by avoiding peak hour congestion and leaving earlier than usual. However, the slightly higher demand on that date than on the second strike day (Monday, March 27$^{\text{th}}$) led to a prolonged peak period.

This demand pattern significantly influenced the resampled MFD for the strike days, depicted in Figure 8. The figure illustrates a clear clockwise hysteresis pattern for the second strike day, characterized by a higher increasing branch during loading and a lower decreasing branch

TABLE 2 : B2R Regions Change in MFD Characteristics

	Capacity [veh/hr-ln]			Critical Occupancy [%]		
	Non-Strike	Strike	Increase [%]	Non-Strike	Strike	Increase [%]
North West	431	472	+9.5	26	28	+7.7
South West	475	519	+9.2	23	26	+13.0
North East	452	479	+5.6	28	29	+3.6
South East	413	448	+8.5	26	26	+0.0
Full region	509	533	+4.7	25	27	+8.0

during recovery. Such a hysteresis loop becomes evident as the network transitions from free flow to saturation and persists until all congestion effects have dissipated. Notably, this phenomenon was not observed when the demand spread over a longer peak period on the first strike day. This finding highlights the potential of a simple demand management scheme, such as flexible working hours, to avoid pushing the network into a congested state that takes a longer time to recover from.

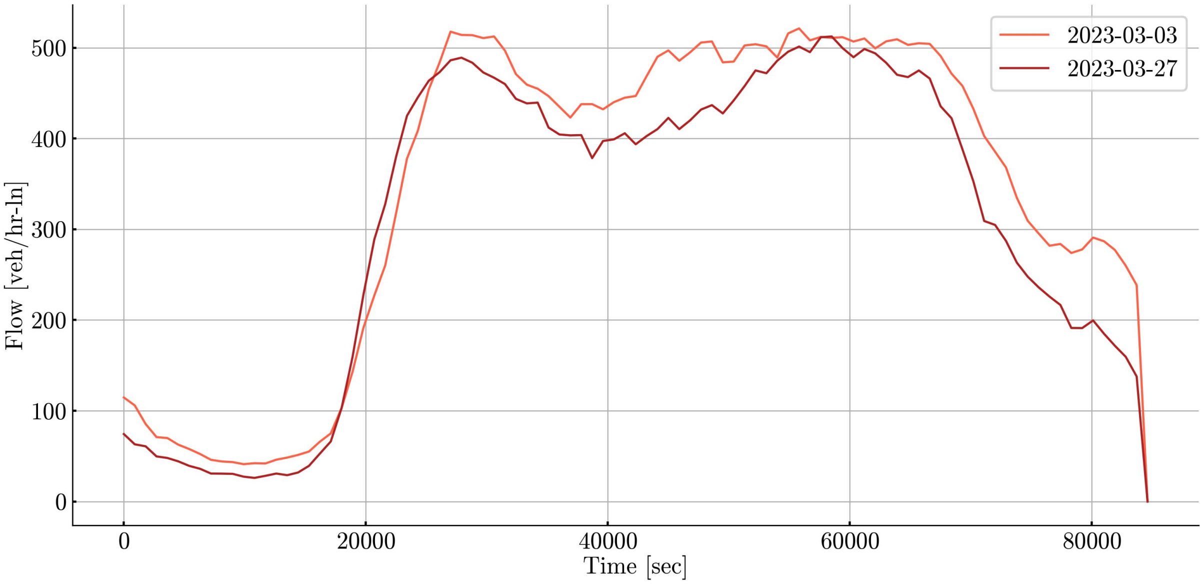
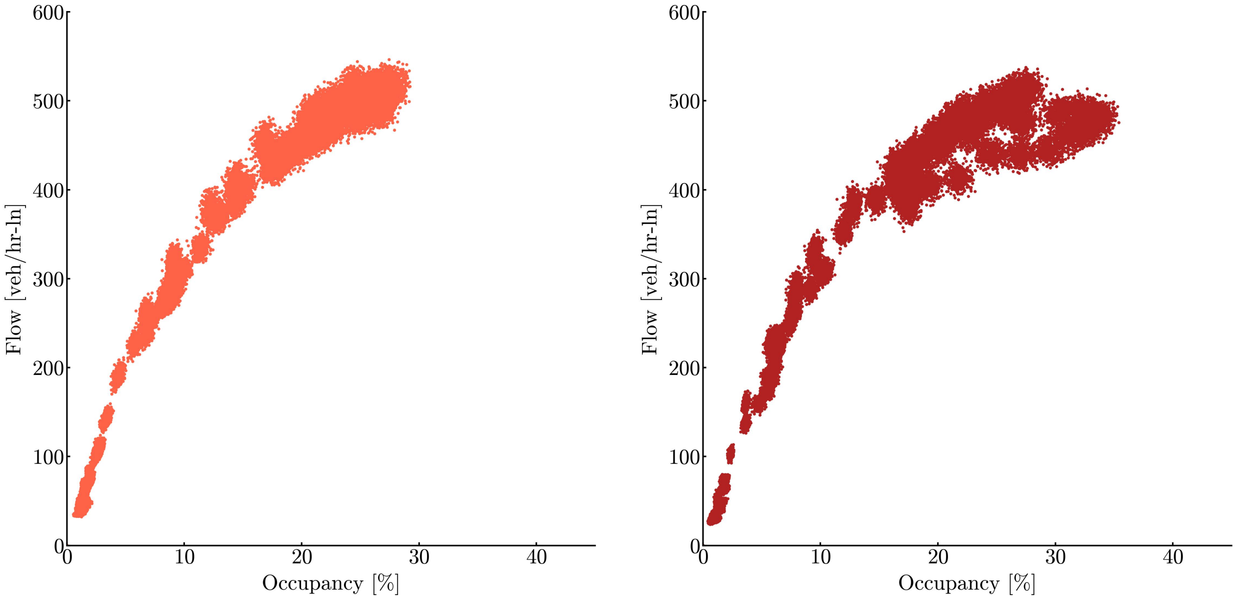


FIGURE 7 : Change in flow with time

ASSESSING THE BENEFITS OF PUBLIC TRANSPORTATION

We use the concept of the 3D-MFD (*30*) to make a macroscopic assessment of the cost and benefits of public transportation in Munich from a traffic engineering perspective. The total length of the relevant road network within the B2R area is around $R = 560$ lane-km (we multiply the road length from Table 2 by a factor of three). We approximate the average space-mean effective vehicle length with $s \approx 8$ m to estimate the accumulation of vehicles in the network

$$n_c = R \cdot \frac{o}{s}. \tag{1}$$



(a) The resampled MFD of the first strike day (b) The resampled MFD of the second strike day

FIGURE 8 : Strike MFD hysteresis

Using the values for the critical occupancy from Table 2, we obtain as critical accumulation for non-strike days $n^*_{c,r} =$ veh and for strike days $n^*_{c,s} =$ veh. In other words, the critical accumulation increases by $\Delta n^*_c =$ veh from a non-strike to a strike day. The relocation of the critical point in the MFD as seen in Figure 6 has implications on the critical speed too. During non-strike days, the critical speed is $v^* = 16.3$ km/h, while on strike days the critical speed reduces to $v^* = 15.8$ km/h, i.e., the critical speed reduces by $\Delta v^* = 0.5$ km/h. In other words, during strike days, the network falls into the congested regime at slightly lower speeds.

Using the average car passenger occupancy during peak hours and the measured MFD capacity (see Table 2), the car passenger travel production $\Pi_{p,c}$ in passenger-kilometers per hour can be computed by

$$\Pi^*_{p,c} = h_c \cdot R \cdot q_{max}. \tag{2}$$

Assuming $h_c = 1.1$ during peak hours, we obtain for strike days $\Pi^*_{p,c} = 328,328$ passenger-km/h and for non-strike days $\Pi^*_{p,c} = 313,544$ passenger-km/h. Consequently, the absence of public transportation in the network increases car passenger travel production by 14,784 passenger-km/h or 4.7%.

For public transportation, we estimate the travel production in vehicle kilometers per hour during peak hours using the official GTFS data (*43*). Here, we find the travel production to be $\Pi_{pt} =$ 1717 veh-km/h (at an average peak-hour service headway of $h = 8.2$ min). We conservatively estimate the average public transportation vehicle occupancy with $h_b = 25$ passengers per vehicle. This leads to the passenger travel production of public transportation during peak hours on non-strike days is (intuitively, on strike days, there are no public transportation operations, i.e., $\Pi_{p,pt} =$

0)

$$\Pi_{p,pt} = h_b \cdot \Pi_{pt} = 42,925 \text{ passenger-km/h}. \tag{3}$$

We can summarize that on strike days compared to non-strike days, car passenger travel production increases by 14,784 passenger-km/h, while public transportation passenger travel production is decreased by 42,925 passenger-km/h. In other words, at the critical point, public transportation operations in Munich's B2R area can produce almost three times the amount of passenger travel than car travel could do. This benefit, in terms of increased passenger travel production, comes at the cost of an increased critical speed of $v^* = 0.5$ km/h for all vehicles.

DISCUSSIONS

The strike as a natural experiment provided us with the opportunity to contribute to the understanding of changes in the MFD as a consequence of changes in the network as well as changes on the demand side. Although we use the re-sampling method to reduce the impact of demand changes on the results, data and methods of our study have limitations and require a discussion.

In general, as strikes are natural experiments, there is only little to no time in advance for thorough planning of the data collection. As loop detector data is continuously recorded and ubiquitously available, we can consider that the data source appropriate and its extent is sufficient to monitor all relevant effects of this natural experiment; still, as seen with the increased scatter in the re-sampled MFD on strike days, having more strike days in the sample is presumably increasing the quality in the MFD estimation. Nevertheless, this analysis would benefit from using other data sources as well, e.g., floating car data or automatic number-plate recognition data, which allow for obtaining (partial) trajectories to enrich the analysis and corroborate the findings. Further, it is known that loop detector data has biases in terms of location within the network as well within a link (*40–42, 44*).

Regarding the selected method of using the empirical MFD for the strike day analysis, other methods like calibrating a traffic simulation and/or deriving origin-destination matrices with the available loop detector data, e.g., (*45*), are another possibility to infer the impact on travel production between strike and non-strike days. Currently, there is almost no data on public transportation services and average vehicle occupancy of public transportation services available for Munich; consequently, the impact on passenger travel production can hardly be improved. Nevertheless, we requested data from the public transport operator to refine our estimates. Last, our analysis currently focuses on travel production, not trip production. Here, using data on average trip lengths would allow us to use the trip production perspective (*33, 46*), which would improve the assessment of the strike impact even further.

CONCLUSIONS

In this paper, we investigated the impact of public transportation on network traffic in Munich, Germany: we use two strikes of road-based public transportation services to compare network traffic on strike days, i.e., without public transportation operations, and non-strike days, i.e., with public transportation operations. Using empirical data from more than 700 inductive loop detectors in the central area of Munich, we found that on strike days the vehicle inflow into the area is increased by 15.7% and that the shape of the MFD is also altered as a consequence of the absence of public transportation services with the capacity increasing by 4.7% and the critical occupancy by 8.0%. These two estimated MFDs can be considered a partial 3D-MFD that describes the relationship between the numbers of cars and public transportation vehicles in the network and the total production of travel in the entire network. Using this partial 3D-MFD we estimate that the increase car passenger travel production at the capacity due to the absence of public transportation is at most one-third of the losses in public transportation passenger travel production at capacity. These findings emphasize the relevance of public transportation operations in cities. Nevertheless, our findings also showed that the adoption of demand management schemes are effective solutions to mitigate congestion. Implementing measures such as flexible working hours and hybrid work options can evenly distribute travel demand, resulting in a degree of improvement in network traffic flow without the need for extensive infrastructure or complex ITS systems investments.

In future research, we will aim to obtain additional data to enrich our analysis and to corroborate our findings, e.g., trajectory data and floating car data. Considering previous research on the impact of public transportation strikes on congestion and speeds, future research should also focus on using those methods to estimate the "congestion relief" effect of public transportation based on literature methods; then, a throughout economic assessment of the benefits and costs of public transportation operations are naturally to follow. In addition, using the estimates of the partial 3D-MFD for the central area of Munich, future research can use them as a starting point for optimizing network-wide traffic operations and space allocation in order to optimize vehicle and passenger throughput, e.g., using methods from literature (*47*). Last, the strike has been across the entire country, thus using traffic data from other cities, it would be of interest from a traffic flow and transport policy perspective to investigate the differences between cities.

In closing, our analysis quantifies the impact of public transportation on network traffic using the idea of the 3D-MFD and emphasizes the importance of public transportation for cities. While we do not focus on the typical congestion impact as measured in travel time losses (*1, 2, 4*), we use the MFD perspective to provide the first analysis of network traffic from a traffic flow perspective. We have shown that the MFD theory and 3D-MFD theory are appropriate for network-wide assessments of large-scale network changes. Thus, considering all the cities worldwide that are transforming their road-based transportation systems, these theory are of high value for them to navigating to optimal policy decisions.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Y. Alayasreih, A. Loder, K. Bogenberger; data collection: Y. Alayasreih, A. Loder; analysis and interpretation of results: Y. Alayasreih, A. Loder, K. Bogenberger; draft manuscript preparation: Y. Alayasreih, A. Loder, A. Takayasu. All authors reviewed the results and approved the final version of the manuscript.

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