

Evaluating London's congestion charge – an approach using the macroscopic fundamental diagram

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Abstract

The rationale of road-pricing schemes is to reduce the negative externalities of road traffic by increasing costs to decrease demand. Although in the transportation literature this is a well-acknowledged means of relieving cities from congestion, only few cities have introduced such schemes so far. One of the most notable examples in Europe is London's congestion charge. Motorists entering London's city center are required to pay a fixed levy during working hours. The revenue generated by this levy is partly dedicated to improvements of the public transport system. The benefits of this congestion charge have only been analyzed from an economic perspective without reference to its impact on macroscopic traffic indicators. The recently introduced macroscopic fundamental diagram (MFD) and its extension to multimodal traffic, the 3D-MFD, offer a novel framework to address this gap.

In this paper, we analyze the performance of London's overground traffic with the empirical 3D-MFD covering both car traffic and buses. Data is acquired from loop detectors (for car traffic) and automated vehicle location devices (for buses).

Keywords: Road pricing, MFD, 3D-MFD, public transport, traffic flow, congestion, London

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Nomenclature

T	Length of aggregation time interval [min]
L_{car}	Car network length [lane-km]
L_{bus}	Length of bus network [km]
q_{car}	Flow of cars [veh/h-lane-km]
o	Occupancy [%]
k_{car}	Density of cars [veh/lane-km]
v_{car}	Network average speed of cars [km/h]
t_j	Time travelled by bus j in time interval T
d_j	Distance travelled by bus j in time interval T
q_{bus}	Flow of buses [veh/h-lane-km]
k_{bus}	Density of buses [veh/lane-km]
v_{bus}	Network average speed of buses [km/h]
s	Space effective mean length of a car

1. Introduction

London introduced its “Congestion Charge” in 2003 as a means to reduce congestion and improve speeds in downtown London. All vehicles entering the area encircled by the Inner Ring road (approximately following clockwise the Tower Bridge Road, the Underground station Elephant and Castle, Hyde Park and along the Marylebone Road) are charged today £ 11.50 from 7am to 6pm on weekdays, but exceptions apply for residents.

The London congestion charge is a simplified version of the earlier electronic road pricing (ERP) system in Singapore, which is a combination of a cordon and a corridor pricing scheme with dynamic charges depending on real-time traffic conditions (Goh, 2002) (Olszewski & Xie, 2005; Santos, 2005; Santos & Shaffer, 2004). Following the lead of Singapore and London, other cities such as Milan, Stockholm (Eliasson, 2009) and Gothenburg have implemented similar schemes. Despite the success stories from the cities with a congestion charge, several attempts to introduce congestion charges in other cities have failed, e.g. in Hong Kong, Manchester or New York City (Schaller, 2010).

The congestion charges implemented in the cities above follow the principle of (second-best) marginal cost pricing and charges for the time loss externalities imposed to other drivers (Anas & Lindsey, 2011; Small & Verhoef, 2007; Vickrey, 1969). In this vein, the political argument of the London congestion charge was to relieve congestion and to improve travel by other modes, most notably walking, cycling and bus transport. This is also reflected in the partial transfer of car levies to public transport. Early evaluations of this scheme confirming this impact followed an economic perspective by analyzing changes in congestion, using aggregate traffic indicators, e.g. average speeds and total vehicle kilometers traveled (Leape, 2006; Prud'homme & Bocarejo, 2005). However, a macroscopic traffic analysis consistent with the physics and dynamics of traffic has not been reported yet.

Given the recent advances in empirical macroscopic fundamental diagrams accounting for bi-modal interactions (3D-MFD) (Loder, Ambühl, Menendez, & Axhausen, 2017; Smeed, 1968) such a macroscopic traffic analysis has now become possible. For car traffic, the macroscopic fundamental diagram relates average network density with average network flow with a reproducible and well-defined curve (Geroliminis & Daganzo, 2008). The MFD is consistent with the physics of traffic and captures the dynamics of macroscopic traffic and overcrowding in the network (Geroliminis & Levinson, 2009).

We use empirical loop detector data from May 2016 to analyze the effects of London’s Congestion Charge from a macroscopic perspective using the MFD. We compare congestion and interactions inside and outside the cordon area. This study’s contribution to the literature is twofold. First, it provides an empirical assessment of a road-pricing scheme from the perspective of traffic performance. Second, it provides an empirical MFD exhibiting large-scale congestion.

This paper is organized as follows: In the next section, the concept of the MFD and its extension to capture the multimodal interactions of road surface transport in the 3D-MFD are explained. Section 3 introduces the available

empirical data and Section 4 the applied method. Then, Section 5 presents the preliminary results of the analysis. This paper closes with a discussion and concluding remarks in Section 6.

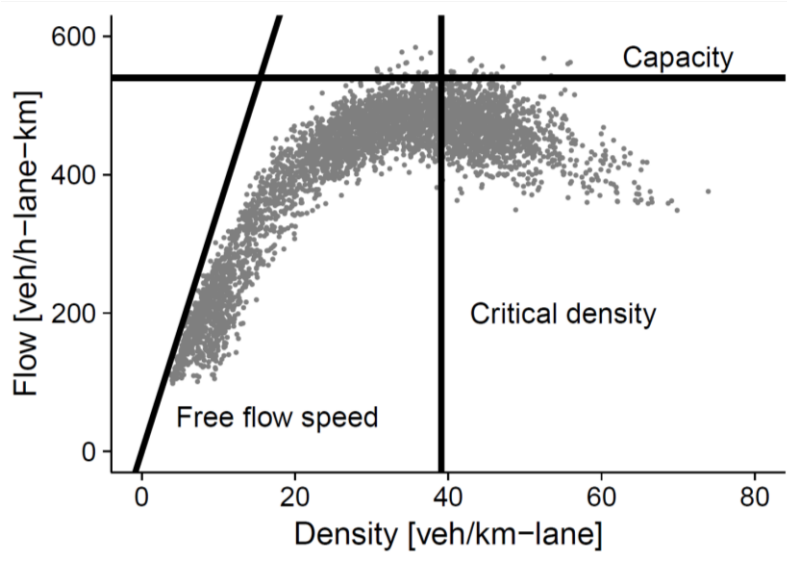


Fig 1 The MFD of London, St. Pancras. The three lines added to the MFD represent characteristics of the MFD, namely the free flow speed in the network, the critical density of vehicles where the flow is operating at capacity.

2. Background

The MFD models the relationship between the accumulation (density) of vehicles and travel production (flow) at the network level with a well-defined and reproducible curve (Geroliminis & Daganzo, 2008). Fig 1 shows for illustration purposes an MFD of a region in London. The concept of the MFD is the most recent advance in a line of research that aims to describe the macroscopic behaviour of vehicles in a network (Herman & Prigogine, 1979; Smeed, 1961; Thompson, 1967; Wardrop, 1968). In contrast to previous work, the MFD – represented as the upper bound in the flow density relationship – can be derived using only characteristics of the road network and signal settings (Daganzo & Geroliminis, 2008; Geroliminis & Boyaci, 2012; Leclercq & Geroliminis, 2013). However, in networks with adaptive traffic control and large variation in traffic control parameters, this methodology is not trivial anymore and the derivation of a tight MFD is almost impossible, although the empirical MFD still follows a well-defined and reproducible curve (Ambühl, Loder, Menendez, & Axhausen, 2017).

In most cities, vehicles in overground transportation can be classified at least into two categories: (1) cars that travel from origin to destination and (2) public transport vehicles that frequently stop in between. When the networks of cars and buses are not fully separated, both vehicle types interact in mixed traffic. The effects of these interactions on overall vehicle and passenger flow can be illustrated in the 3D-MFD, where the accumulation of cars and buses are treated separately, but the flow of vehicles and passengers are considered jointly (Chiabaut, 2015; Geroliminis, Zheng, & Ampountolas, 2014). This representation of multimodal urban traffic can then be used to identify the optimal modal share for given demand levels (Loder et al., 2017; Smeed, 1968).

3. Data

This analysis, is based on two data sources: individual traffic data from loop detectors located on many streets within London, and the travel times and speeds of all buses circulating in greater London. Both data sets are available from the same observation period in May 2016. Section 3.1 describes the loop detector data set for car traffic and the computation of the relevant variables, while Section 3.2 introduces the public transport data set in a similar manner. All data sets are georeferenced and thus allow any selection of regions.

3.1. Car traffic data

Transport for London installed more than 10.000 loop detectors throughout the city for an adaptive signal control system, *Split Cycle Offset Optimization Technique (SCOOT)*. These detectors report the count of vehicles (flow,

q_i) and the fraction of time the detector is occupied (occupancy, o_i) during an aggregation interval of one minute. In most cases, the detectors are located downstream of an intersection.

For the data set preparation, we referenced each detector location to the underlying road network, identified the monitored lane and the length of the monitored link l_i . We consider a link as ranging from one major intersection to another major intersection. See Ambühl, Loder, Bliemer, Menendez, and Axhausen (2017) for more details on the data preparation.

The MFD of car traffic is calculated using the space means from flow and occupancy using Eq. 1 for the network flow q_{car} and Eq. 2 for the network average density k_{car} . Note that we use here a scalar transformation from occupancy to density with $s = 0.0062km$ (Coifman, 2001).

$$q_{car} = \frac{\sum_i q_i l_i}{\sum_i l_i} \quad (1)$$

$$k_{car} = \frac{1}{s} \frac{\sum_i o_i l_i}{\sum_i l_i} \quad (2)$$

With the fundamental equation of traffic flow, the network average space mean speed v_{car} is obtained by Eq.3.

$$v_{car} = \frac{q_{car}}{k_{car}} \quad (3)$$

3.2. Bus data

In London, all buses are equipped with automated vehicle location (AVL) devices that record the arrival and departure times at each stop. The time difference between the departure time and the arrival time at the next stop corresponds to the travel time of the bus t_j . When considering the driving direction, the dataset has around 1800 routes, serving more than 19000 stops. We calculate the distance d_j from stop to stop following the designated route path on the road network to obtain the average speed of the bus between two stops. The network average speed of buses, v_{bus} , is obtained according to Eq. 4 by dividing the total travelled distance by the total travel time within a time interval.

$$v_{bus} = \frac{\sum_j d_j}{\sum_j t_j} \quad (4)$$

With information on the bus network length L_{bus} , and the duration of the aggregation interval T , the density of buses in the network can be computed according to Eq. 5.

$$k_{bus} = \frac{\sum_j t_j}{T L_{bus}} \quad (5)$$

Last, using the fundamental equation of traffic flow again, we can compute the flow of buses, q_{bus} , with Eq. 6.

$$q_{bus} = k_{bus} v_{bus} \quad (6)$$

3.3. Network production and accumulation

The relationship between traffic flow and total travel production P is established by scaling the average flows with the respective network length L_{car} for cars and L_{bus} for buses according to Eq. 7.

$$P = L_{car} q_{car} + L_{bus} q_{bus} \quad (7)$$

The total accumulation of each mode is also obtained by scaling each mode's density by the respective network length (analogue to Eq. 7). Note that this approach assumes that the trip lengths by mode are constant (Geroliminis & Daganzo, 2008).

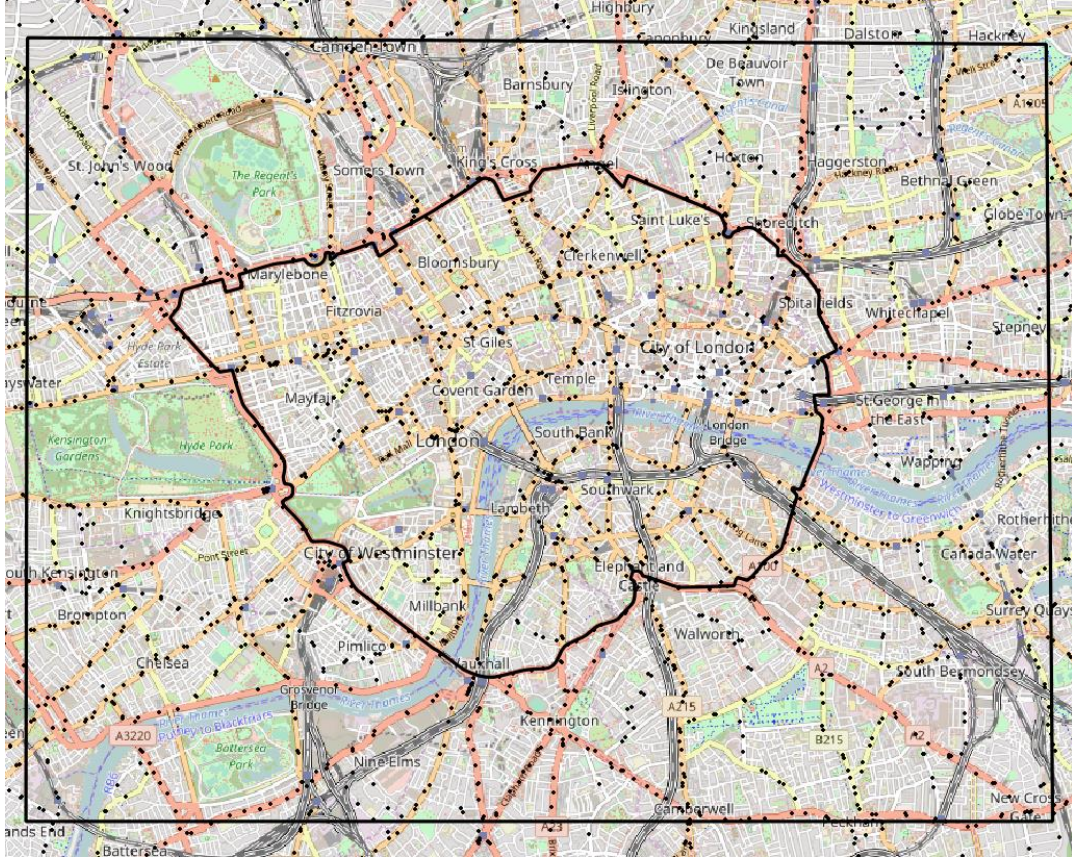


Fig 2 The two zones of analysis in London. The inner part corresponds to the Congestion Charge area. Map by OpenStreetMap, 2017.

4. Methodology

In this section, the available data is used to determine the macroscopic relationships with a statistical model. The method follows an earlier approach on estimating an empirical 3D-MFD for the city of Zurich (Loder et al., 2017; Smeed, 1968), where the model is based on vehicle densities rather than accumulation (Geroliminis, Zheng, & Ampountolas, 2014). As a first order approach, Greenshields' linear model between density and speed is used. Moreover, the speed of public transport is modeled by a linear relationship with car speed and covers mode interactions (Zheng & Geroliminis, 2013).

Hence, as in (Loder et al., 2017; Smeed, 1968), the 3D-MFD is modeled with two equations, the first of which links the free-flow speed of cars v_c to the density of cars k_c and public transport vehicles k_{pt} . In addition, β_c and β_{pt} capture the marginal effect of each mode on car speeds. For this analysis, we normalize car speeds by the maximum speed observed, so, the highest value is one and lower values indicate lower speeds.

Assuming that the speed of public transportation can be defined as a function of car speeds (Zheng & Geroliminis, 2013), allows us to express the public transport speed as function of the vehicle densities and hence, allows us to estimate the coefficients $\beta_{c,pt}$ and $\beta_{pt,0}$. Here, $\beta_{c,pt}$ captures the effect that public transport vehicles typically move slower than cars due to more frequent stops and $\beta_{pt,0}$ adjusts for the fact that public transport speeds on dedicated lanes may exceed car speeds during congested times. The resulting macroscopic relationship reads:

$$v_{car} = \beta_{c,0} + \beta_c k_c + \beta_{pt} k_{pt} \quad (8)$$

$$v_{pt} = \beta_{c,pt} v_c + \beta_{pt,0} \quad (9)$$

The model is estimated for two areas as depicted in Figure 2. The first area is the area for which the congestion charge is levied and the second area is a belt just around the congestion pricing area.

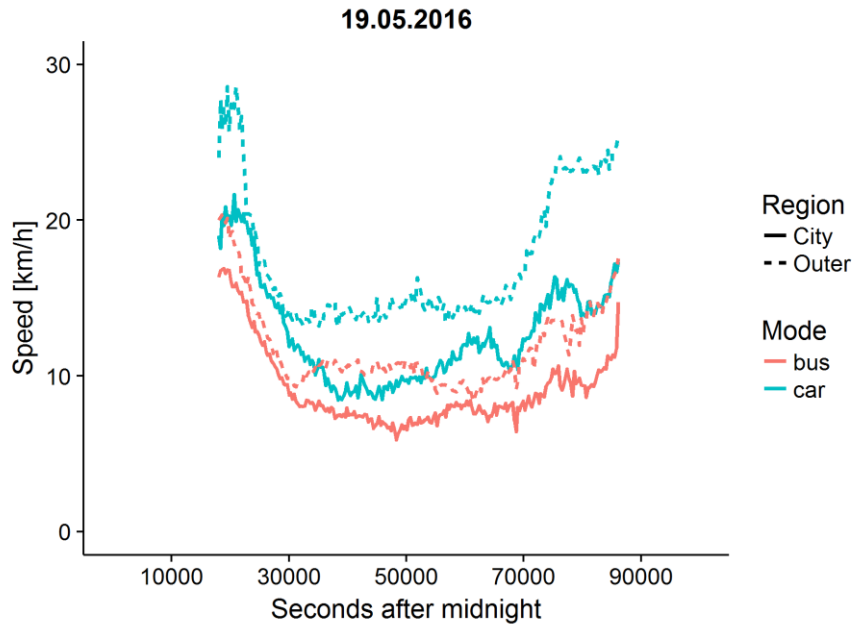


Fig 4 Comparison of speeds in central London during a typical day of buses and cars.

5. Results

The data gives us various insights into the macroscopic traffic states observed in London. For example, Fig 3 shows that in general, bus and car speeds follow a similar daily pattern. However, the difference between car and bus speeds is substantially larger outside of the congestion charge area. A possible explanation for this behaviour is that there are more dedicated bus lines in the city centre, which help to increase bus speeds. Another observation is that the drop in car speeds during the day is lower within the city centre, which may be attributed to the congestion charge, that aims to maintain a certain level of network speeds.

Fig 4 adds further insights on the relationship between bus and car densities. It indicates that outside of the congestion charge area, the bus density scales linearly with the car density. Within the congestion charge area, however, this relation follows the same pattern only up to 20 cars per lane km, where the bus density increases up

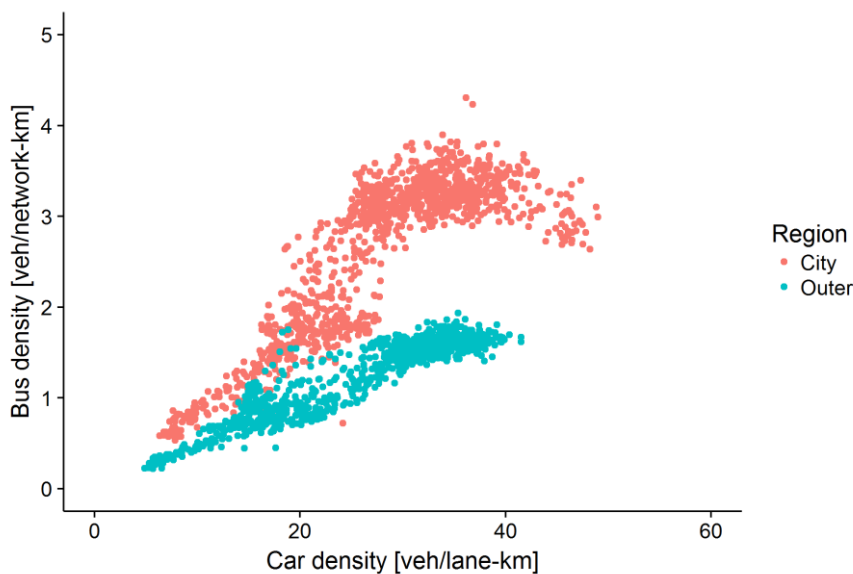


Fig 3 Comparison of both modes densities in the congestion charge region and outside

Table 1 3D MFD estimation results		
	Car speed ratio	
	Congestion charge area	Surrounding area
Car density	-0.018***	-0.021***
	(0.0001)	(0.0001)
Bus density	-0.007***	-
	(0.002)	-
Constant	1.194***	1.226***
	(0.004)	(0.004)
Adjusted R2	0.959	0.955
	Bus speed	
Car speed	0.513***	0.329***
	(0.009)	(0.009)
Constant	2.335***	5.601***
	(0.128)	(0.157)
Adjusted R2	0.738	0.575
Number of observations	991	991
Standard errors in parentheses. *p<0.1; **p<0.05; ***p<0.01		

to around 3 vehicles per network kilometres and 30 cars per lane km. It can be expected that a higher density of buses would lead to considerable bus bunching if no additional lanes are exclusively dedicated to public transport.

Table 1 presents the parameters of the 3D-MFD for London. It shows that – as expected – a higher car density leads to lower car speeds. However, it is notable that this effect is stronger outside of the congestion charge area, which might be due to longer links or streets with higher capacity. We could only estimate an effect of buses on car speed in the congestion charge area because the correlation with car density was modest compared to the area outside. This issue must be resolved in future research by finding instrumental variables or incorporating spatial effects.

Regarding bus speeds, we observe that the speeds in the surrounding area seem to be more decoupled from each other than in the congestion charge area (larger intercept and smaller value for the slope of the car speeds. A reason for this difference, despite the dedicated bus lanes in the congestion charge region, is bus bunching. We recommend to further investigate this issue in future research.

6. Discussion and conclusions

In this paper, we have presented the first preliminary results of an assessment of the multimodal traffic performance for the area of London's congestion charge. We used empirical data from loop detectors for car traffic and data from automated vehicle location devices of TfL buses for public transport to determine the three traffic variables speed, flow and density at the network level. From this information, we compute the 3D-MFD for London's bimodal urban traffic. In our first approach, we split the sample into the area within the Congestion Charge zone and an area surrounding this zone.

Geroliminis and Levinson (2009) applied Vickrey's bottleneck model to the MFD to obtain an estimate of how much a congestion charge for Yokohama must be to reduce congestion. We could use their model to obtain a value

for London and contrast it with the current price for entering London. Another interesting avenue would be to use the available data for an analysis of the morning commute problem (Gonzales & Daganzo, 2012) or the distribution of space between cars and buses (Zheng & Geroliminis, 2013).

In future research, it will be worthwhile to analyse the effect of the congestion charge on the average and marginal delays separately for each mode. In this context, we could study these delays also from a spatial perspective, e.g. by investigating the value based on a grid raster. The hypothesis would be that car delays are increasing towards the border of the congestion charge area, but the rate will decrease once inside the Congestion charge region. In addition, we could extend the analysis by making assumptions on the distribution of passengers across vehicles to obtain the passenger 3D-MFD as in (Chiabaut, 2015; Loder et al., 2017). In this vein, we could close the loop back to Smeed (1968) and Wardrop (1968).

Acknowledgements

This work was supported by ETH Research Grants ETH-04 15-1 and ETH-27 16-1 as well as the National Research Program NRP 71 of the Swiss National Science Foundation (project “Sharing is Saving”, grant number 407140_153807). We thank Transport for London (TfL), especially Ashley Turner and Andy Emmonds, for providing the data.

7. References

- Ambühl, L., Loder, A., Bliemer, M. C. J., Menendez, M., & Axhausen, K. W. (2017). Introducing a re-sampling methodology for the estimation of empirical macroscopic fundamental diagrams. *Arbeitsberichte Verkehrs- und Raumplanung*, 1271. doi:10.3929/ethz-b-000175247
- Ambühl, L., Loder, A., Menendez, M., & Axhausen, K. W. (2017). *Empirical macroscopic fundamental diagrams: New insights from loop detector and floating car data*. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington D.C.
- Anas, A., & Lindsey, R. (2011). Reducing urban road transportation externalities: Road pricing in theory and in practice. *Review of Environmental Economics and Policy*, 5, 66-88. doi:10.1093/reep/req019
- Chiabaut, N. (2015). Evaluation of a multimodal urban arterial: The passenger macroscopic fundamental diagram. *Transportation Research Part B: Methodological*, 81, Part 2, 410-420.
- Coifman, B. (2001). Improved velocity estimation using single loop detectors. *Transportation Research Part A: Policy and Practice*, 35, 863-880.
- Daganzo, C. F., & Geroliminis, N. (2008). An analytical approximation for the macroscopic fundamental diagram of urban traffic. *Transportation Research Part B: Methodological*, 42, 771-781.
- Eliasson, J. (2009). A cost-benefit analysis of the Stockholm congestion charging system. *Transportation Research Part A: Policy and Practice*, 43(4), 468-480. doi:10.1016/j.tra.2008.11.014
- Geroliminis, N., & Boyaci, B. (2012). The effect of variability of urban systems characteristics in the network capacity. *Transportation Research Part B: Methodological*, 46, 1607-1623.
- Geroliminis, N., & Daganzo, C. F. (2008). Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological*, 42, 759-770.
- Geroliminis, N., & Levinson, D. M. (2009). Cordon Pricing Consistent with the Physics of Overcrowding. In *Transportation and Traffic Theory 2009: Golden Jubilee* (pp. 219-240).
- Geroliminis, N., Zheng, N., & Ampountolas, K. (2014). A three-dimensional macroscopic fundamental diagram for mixed bi-modal urban networks. *Transportation Research Part C: Emerging Technologies*, 42, 168-181.
- Goh, M. (2002). Congestion management and electronic road pricing in Singapore. *Journal of Transport Geography*, 10, 29-38.
- Gonzales, E. J., & Daganzo, C. F. (2012). Morning commute with competing modes and distributed demand: User equilibrium, system optimum, and pricing. *Transportation Research Part B: Methodological*, 46(10), 1519-1534. doi:10.1016/j.trb.2012.07.009
- Herman, R., & Prigogine, I. (1979). A Two-Fluid Approach to Town Traffic. *Science*, 204, 148-151.
- Leape, J. (2006). The London Congestion Charge. *Journal of Economic Perspectives—Volume*, 20, 157-176. doi:10.1257/jep.20.4.157
- Leclercq, L., & Geroliminis, N. (2013). Estimating MFDs in simple networks with route choice. *Transportation Research Part B: Methodological*, 57, 468-484. doi:10.1016/j.trb.2013.05.005
- Loder, A., Ambühl, L., Menendez, M., & Axhausen, K. W. (2017). Empirics of multi-modal traffic networks – Using the 3D macroscopic fundamental diagram. *Transportation Research Part C: Emerging Technologies*, 82, 88-101. doi:10.1016/j.trc.2017.06.009
- Olszewski, P., & Xie, L. (2005). Modelling the effects of road pricing on traffic in Singapore. *Transportation Research Part A: Policy and Practice*, 39(7-9), 755-772. doi:10.1016/j.tra.2005.02.015
- Prud'homme, R., & Bocarejo, J. P. (2005). The London congestion charge: a tentative economic appraisal. *Transport Policy*, 12, 279-287.

- doi:10.1016/j.tranpol.2005.03.001
- Santos, G. (2005). Urban Congestion Charging: A Comparison between London and Singapore. *Transport Reviews*, 25(5), 511-534. doi:10.1080/01441640500064439
- Santos, G., & Shaffer, B. (2004). Preliminary Results of the London Congestion Charging Scheme. *Public Works Management & Policy*, 9(2), 164-181.
- Schaller, B. (2010). New York City's congestion pricing experience and implications for road pricing acceptance in the United States. *Transport Policy*, 17(4), 266-273. doi:10.1016/j.tranpol.2010.01.013
- Small, K. A., & Verhoef, E. T. (2007). The economics of urban transportation. 276 S.
- Smeed, R. J. (1961). The Traffic Problem in Towns. 59 S.
- Smeed, R. J. (1968). Traffic Studies and Urban Congestion. *Journal of Transport Economics and Policy*, 2, 33-70.
- Thompson, J. (1967). Speeds and flow of traffic in Central London. 2: Speed-flow relations. *Traffic Engineering & Control*, 8, 721-725.
- Vickrey, W. S. (1969). Congestion theory and transportation investment. *The American Economic Review*, 59, 251-260. doi:10.1126/science.151.3712.867-a
- Wardrop, J. G. (1968). Journey speed and flow in central urban areas. *Traffic Engineering & Control*, 9, 528-532.
- Zheng, N., & Geroliminis, N. (2013). On the distribution of urban road space for multimodal congested networks. *Transportation Research Part B: Methodological*, 57, 326-341. doi:10.1016/j.sbspro.2013.05.009