International Journal of Industrial Organization 96 (2024) 103080

Contents lists available at ScienceDirect

International Journal of Industrial Organization

journal homepage: www.elsevier.com/locate/ijio

Ownership frictions in a procurement market: Evidence from London buses

Marleen Marra *, Florian Oswald

Department of Economics, Sciences Po, 28 rue des Saints-Pères, 75007 Paris, France

ARTICLE INFO

JEL classification:
D44
L11
L92
R41

Keywords:
Procurement auctions
Public transport
Urban
Network industry

ABSTRACT

This paper investigates the efficiency impact of garage ownership frictions in the procurement of public bus transportation services in London. In this market, operators are less competitive for routes far from their garages, leading to local monopoly rents. Empty bus travel between garages and routes (*dead miles*) is found to account for about 13 percent of driving time in this market. Consequentially, sizeable effects of dead mile minutes on bids and procurement costs are estimated. Taking the urban context and the demand side as given, and treating this market as a typical network industry, counterfactual simulations evaluate the effect of unbundling the ownership of bus garages from the operation of the bus routes. Letting a central dispatcher allocate buses to garages would reduce total dead miles by 14 percent, with corresponding reductions of operating costs and of polluting exhaust emissions.

1. Introduction

Public services are outsourced to private firms on a massive scale across all industries of our economy. This is done primarily to save costs. However, for the case of public bus transportation, the literature documents many cases where private bus companies do not operate more efficiently than public ones (Gagnepain et al., 2011). As in other sectors where services are delivered through a network (like energy, water, and communication services), the associated fixed costs introduce elements of natural monopoly and market failure to the transport market. A common solution is to unbundle the ownership of the network infrastructure from competitive elements of the market (Newbery, 2004; Florio, 2013). In this paper we study the degree to which such unbundling could improve the outcomes for the procurement of bus transportation in the city of London.

In a setting where firms supply vehicles to the bus route network from proprietary bus garages, we focus on the efficiency implications of the associated ownership frictions and quantify their magnitude for the London bus transportation market. We study this issue in the context of competitive tendering of bus route operation contracts in London, where such ownership frictions arise. Specifically, bus operators are less competitive in auctions for routes which are far away from their garages, due to costs associated to what the industry refers to as *dead miles* – transporting empty vehicles between the startpoints of the route and the garage. As we show in our companion paper Marra and Oswald (2023), this generates local monopoly rents, as the equilibrium mark-up is also higher when the bus garages of competing firms are further away from the route.

Consequently, operators enjoy some degree of market power from owning garages, especially when positioned favorably. Moreover, firms don't have access to *all* garages when optimizing the logistics of operating routes but can only park buses in their own

* Corresponding author.
E-mail addresses: marleen.marra@sciencespo.fr (M. Marra), florian.oswald@sciencespo.fr (F. Oswald).

https://doi.org/10.1016/j.ijindorg.2024.103080

Available online 25 June 2024

depots – which we refer to as "ownership frictions". Buses are therefore not always allocated to the garage which lies closest to a certain route. This implies that empty buses need to be driven from garages to route starting points for longer distances without generating any revenue (hence, *dead miles*), creating additional operating costs and harmful pollution on London roads. That a firm's spatial location interacts with intensity of competition has been established in prior work, including Miller and Osborne (2014) (cement market), Davis (2006) (movie theaters), Houde (2012) (gasoline), and Seim (2006) (video rental). The distance to the final consumer is also known to affect bids for auctions, such as for school milk (Porter and Zona, 1999), school meals (Olivares et al., 2012), and bus transportation (Marra and Oswald, 2023; Cantillon and Pesendorfer, 2006, 2007). Here, we approach the interplay between competing firms and travel distance from a different angle, estimating to what extent transportation costs are inflated due to plant (garage) ownership frictions.

While studying this issue in the London bus market, we make several contributions to the literature. First, we collect and assemble a unique dataset on the garage ownership history in the London bus market since privatization in 1994. The data is constructed by combining archival data from the London Omnibus Traction Society and hobbyist (*bus spotters*) websites. Geo-coding the garages and adding data on the location of all 55,578 bus stops in London, we develop precise measures of dead miles as incurred by operators. Specifically, this delivers the number of minutes that a bus is driving empty in between the garage where the bus is stationed and various points of interest on the bus route.[1]

We obtain the dead miles for all 1,457 garage-routes pairs from publicly available tender data, for which the route is tendered between 2003 and 2019 and for which we observe the operating garage. Buses drive empty for 13 minutes on average, each time a bus is moving between the garage and a bus route. There is a large variation across the garage-route network, with dead mile minutes ranging from 3 to 40 minutes. Under the assumption that bus drivers operate a single route for 3.5 hours without interruption and that they drive from and to the garage for their scheduled breaks, this also implies that each 100 contractable route minutes require on average 13 minutes empty driving time. As such, dead miles make up a sizeable share of the cost to fulfil bus operation contracts in our empirical setting. The number of dead miles over contractable miles is naturally larger in bigger cities due to, for instance, non-residential land scarcity or the need to operate lengthy routes from points in space. Taking the urban context as given, we are particularly interested in the extent to which the fraction is driven by (endogenous) garage ownership frictions, motivating our economic policy experiments.

The notion that dead miles affect the costs to provide public transportation is corroborated with empirical evidence based on bids in route auctions. For this purpose we exploit a second novel dataset with the private bids of two operators, for all London bus route auctions that they participated in between 2011 and 2018 (i.e. not only winning bids). The garage where the route would be operated from when winning the contract is also listed, so that the associated dead mile measures can be computed. Each additional dead mile minute is estimated to increase the bid by £50,000 when also controlling for firm, garage, route, and auction characteristics. We confirm that dead miles are economically relevant also in the larger sample of *winning* bids mentioned above, although the interpretation is less obvious in this dataset due to potential selection issues.

We evaluate the effect of unbundling the ownership of bus garages from the operation of the bus routes. This policy is comparable to the introduction of a universal dispatcher or central platform in other decentralized transport markets (see e.g., Frechette et al., 2019; Brancaccio et al., 2020) but without fluctuations in demand or supply. We simulate this policy by solving a constrained optimization problem that minimizes the dead miles across the route network, allocating buses to garages irrespective of whether the route operator owns that garage or not. When determining which buses are stationed where, the maximum capacity of each garage and the number of buses required to operate each route are respected. We find that this experiment reduces the total amount of dead miles driven by 14% across the network. The associated costs in terms of increased pollution and higher operational costs (and hence, bids) represent a reduced form estimate of the costs of allowing private ownership of garages in this setting – as opposed to, say, public ownership of this critical infrastructure. These results speak to earlier studies highlighting factors that can diminish the advantages of public procurement, such as moral hazard of winning bidders related to imperfect contracting (e.g., Decarolis, 2014; Bajari and Tadelis, 2001, and Andreyanov et al., 2023).

We do not endogenize the choice of garage location by the bus operators. When firms face transportation costs and compete in price, they face a trade-off between being close to consumers while being isolated from each other, as in the canonical location-choice models (e.g., Hotelling, 1929; Salop, 1979). In addition to travel costs to the route and local monopoly rents associated with being isolated from competitors, firms in the London bus market, like those in the airline (Brueckner and Spiller, 1994) or retail (Holmes, 2011; Jia, 2008) industry, likely face economies of density of operating multiple routes from near-by garages. Spatial location choice models become quickly intractable when economies of density generate spillovers across locations (see, e.g., Oberfield et al., 2024). In Marra and Oswald (2023) we provide a framework to assess a rich location choice model for the industry that addresses these issues. In the present paper we focus on efficiency properties of the current network in terms of generating excessive transportation costs relative to a setting where we assign all garages to a single entity.

The paper is conceptually close to the trade literature concerned with location choice and (optimal) transport networks, e.g. Fajgelbaum and Schaal (2020), or the efficient provision of transport infrastructure in a developing country setting as in Balboni (2019), or indeed the provision of public transport in a highly urbanized setting in a developing country as in Gaduh et al. (2022). While this last paper analyses a recent extension of the Jakarta bus network and studies optimal network configurations, we take the

[1] It is not given at which bus stop the bus starts servicing the route, but as TfL imposes schedule requirements in both directions, our preferred dead miles measure is the average number of minutes driven between the garage and the two endpoints of the route, which we refer to as "Start-Stop Minutes".

Table 1
Summary statistics route auction data.

Winning Group	Total Earnings 2003–2019 (m£)	Routes Awarded 2003–2019
GoAhead	1,205.7	441
Arriva	1,069.7	338
Stagecoach	854.0	318
Metroline	765.9	237
RATP	449.8	191
Abellio	403.3	138
First	382.0	149
TowerTransit	124.0	25
HCT	49.8	30
NCP	12.8	7
SullivanBuses	12.7	26
TGM	6.4	5
Connex	2.9	1
Uno	0.5	1
Routes auctioned/year	112.2	
Number of Bidders/year	312.6	
Bidders per Auction/year	2.9	
Median Revenue/year (m£)	2.3	
Total Revenue/year (m£)	273.0	
Total Revenue 2003–2019 (m£)	5,339.5	

Notes. Based on TfL tender data for routes tendered between March 2003 and October 2019.

network as given and study the implications of private versus common ownership of the main infrastructure – bus garages – in terms of operating cost and environmental damage from excessive dead miles.

Finally, the paper needs to be placed within the literature on efficient mass transit provision. Gagnepain and Ivaldi (2002) is a relevant precursor which investigates a principal-agent theory after Laffont and Tirole (1986) for the case of the French urban transport industry, and estimates the shape of the best regulatory policy for each network (each city). Wunsch (1996) estimates the cost function of 177 mass transit firms in the same spirit. In those models, transport firms use *hard capital* K (rolling stock and infrastructure) amongst other inputs to provide the contracted service. Our case investigates the case where K is indivisible and location specific – owning K_i is fundamentally different from owning K_j for locations $i \neq j$. There is also a small literature dedicated to the London bus market, which focuses on aspects of the auctioning stage (Cantillon and Pesendorfer, 2006, 2007) as well as potential collusion (Waterson and Xie, 2019). Iossa and Waterson (2019) study long-term effects of the repeated contracting in this market. We add significant empirical detail to the stock of knowledge in this literature, and focus in this paper on a narrow and well-defined measure of efficiency: the amount of dead miles arising from different garage ownership arrangements.

In the remainder of the paper, section 2 describes the London bus market and the garage-route network dataset compiled for this study, section 3 describes the quantification of travel distances suitable for the empirical setting, section 4 documents the novel dataset of bids by two firms competing in this market, section 5 provides empirical evidence about the importance of the distance for public transportation costs, section 6 implements a counterfactual policy experiment to assess the degree to which ownership frictions inflate travel times, operator costs, and local air pollution, and section 7 concludes.

2. Industry description

London Bus Services Ltd (London Buses) is part of Surface Transport within *Transport for London (TfL)*, in charge of delivering the Mayor's Transport Strategy. This involves transporting over six million passengers on 7,700 scheduled buses and 675 different routes stretching over 490 million kilometers of road, each weekday.[2] From our data on bus route procurement auctions, we compute an average expenditure on procuring bus operations of £273m annually over the period 2003–2019 (see Table 1), paid for by UK taxpayers.[3]

Historically, many different independent companies owned and operated public transport in London and the UK, providing potentially wasteful duplicate services while competing for passengers.[4] From 1933, the state took an active role in the coordination of services with its successive transport authorities. The National Bus Company was created in 1969 in a wave of nationalizations. It owned a number of locally managed subsidiary companies who were in charge of bus operation. The London Regional Transport Act

[2] Over 120 routes are 24 h per day, seven days a week operations. See TfL's London's Bus Contracting and Tendering Process for more details.

[3] About one third of TfL funding comes from ticket fares, Congestion Charge, Ultra Low Emission Zone etc, with the remainder being split into grants funded by business taxation and borrowing (https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-funded). Assuming for illustrative purposes that 2/3 of the £273m bus operating cost is funded only via business taxation, one finds a contribution to bus services of roughly 262 Pounds per London business, per year (there were 1.04 million businesses registered in London in 2022, see https://researchbriefings.files.parliament.uk/documents/SN06152/SN06152.pdf).

[4] Incidentally, one company (London General Omnibus Company) painted its buses bright red to stand out and later became the largest operator in London, which is the foundation for the current-day cherry red London bus.

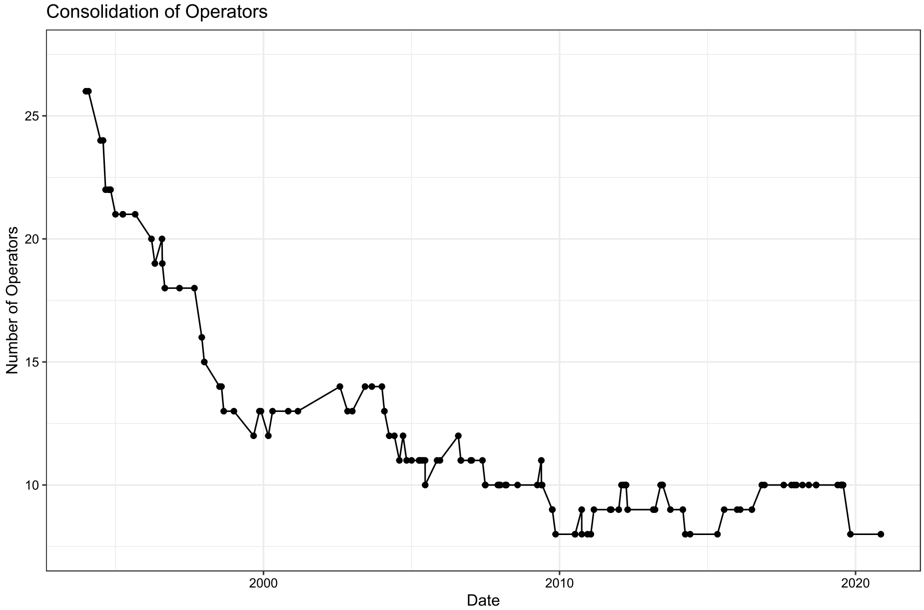


Fig. 1. Time series of Ownership consolidation. Over time, through merger and acquisition as well as exit from the market, the number of active operators falls.

Table 2
Privatization of 12 divisions London Regional Transport.

Division	Area	Original buyer	Current owner
CentreWest	West	management	Metroline & Tower Transit
East London	East	Stagecoach	Stagecoach
Leaside	River Lea	Cowie Group	Arriva
London Central	South Central	Go-Ahead	Go-Ahead
London General	South West	management	Go-Ahead
London Northern	North	MTL	Metroline
London United	South West	management	RATP
Metroline	North West	management	Metroline
Selkent	South East	Stagecoach	Stagecoach
South London	South	Cowie Group	Arriva
Westlink	Kingston	employees	RATP
London Coaches	Central	management	Arriva

Notes. Source for original buyer and current (2019) owner: this Wikipedia page, and the area denomination obtained from: this Fandom page.

of 1984 started deregulation of the transport sector, calling for public tendering of bus routes and opening the market for independent operators. London's state-run entities were first divested along geographical lines into 12 companies before being fully privatized in 1994/1995. The geographical split of the 12 divisions of London Regional Transport is relevant for the analysis in this paper, as it likely causes the current operators to gravitate towards a part of the city.

The tendering of bus routes allowed a great number of smaller operators to enter the market in or after 1994, which was indeed a design objective of the auction setup, as explained in detail in Cantillon and Pesendorfer (2007). The competitive landscape has changed substantially since that time after a series of consolidations, which is illustrated in Fig. 1. Table 2 documents the current ownership structure of the 12 initial divisions. Today, the market is dominated by six large (international) transport firms and a few smaller operators.

2.1. Route auctions

TfL runs a continuous programme of tendering bus routes, offering contracts for about 15% of the system's routes per year. In practice, an invitation to tender is sent out every 2–4 weeks to a set of pre–approved operators. Winning firms receive their bids as financial compensation, while all ticket fares go to TfL. Contracts typically start 8 to 10 months after the award date, so that winning bidders can reorganize, update their bus fleet if needed, and (in rare cases) obtain the necessary garage space. The tendered contracts fully specify routes, schedules, minimum performance standards, and bus specifications. In practice, this means that bus operators have only few margins of adjustment, and it is likely that none of them are systematically related to quality of service, as all relevant aspects of the operation are contractually fixed. As such, the distance of an operator's garage to the bus route in question can be considered an important determinant of bidding behavior.[5]

To study the link between the garage network and rents from the route auctions more formally, we obtain tender data from the TfL website.[6] The outcomes of all tenders since 2003 are available, and we gather information about the winning bidder, the contract value, cost per mile of route, and the number of bidders for all 1907 routes tendered between March 13th 2003 and October 19th 2019. Routes are typically tendered for a period of 5 years, with a 2 year extension conditional on meeting certain performance standards, and on average a route shows up 2.5 times in the full sample. In addition, we obtain additional route characteristics from the London Bus Routes website, including each route's peak vehicle requirements (PVR, the number of buses that are needed to drive the schedule specified by TfL), length in miles, and frequency of service. Any missing route information is complemented using data web-scraped from a site for bus hobbyists.[7] We give an overview of 2003–2019 route procurement data in Table 1.

2.2. Garage-operator network

Bus garages can be considered part of the productive assets needed to fulfil bus route contracts (together with the fleet of buses and the drivers). The garages are private property of the bus operator, meaning that the operator is either the freehold owner or long leaseholder (e.g., the government remains the primary owner of the land).[8] We refer to the firm operating buses from the garage as the garage *owner* – regardless of the freehold or leasehold contract status – and exclude the few cases where a garage is shared between two operators.[9]

We compiled a comprehensive dataset of the operator and bus garage network in London between 1994–2019 from various sources. Information about which routes were run from which garage comes from the London Omnibus Traction Society, the UK's largest bus enthusiasts' organization. They provided valuable input by constructing historic data for this study based on their archive of bus schedules. The data that they provide matches the majority of routes tendered since 2005 to the garage that it was operated from.[10] The data also shows when a new garage was put into use or an old garage closed down. Matching this data to the tender data furthermore tells us when a garage changed ownership. Garage locations are obtained from the London Bus Routes website.[11] The website contains a file with – for the majority of garages – full information about the operator currently owning it, it's address, and TfL garage code. Missing addresses were completed manually, and corresponding longitude-latitude information is collected from the Google Maps API. We also obtained geo-coded locations of all bus stops and their sequences for each route from TfL's Open Data Initiative platform.[12]

3. Quantifying distances

An obvious conjecture that we want to confirm in our data is that operators in general minimize the distance between route and garage. This reflects the notion that it is costly to operate a route from a far-away garage, because the bus has to travel empty until revenue-generating operation can start. Conforming to industry practice, we use the term *dead miles* to describe the associated costs.[13]

A crucial input to assess this is a precise measure of distance between points of interest in the garage-route network. In particular, simple straight-line distance between points would miss a great deal of nonlinearities arising from geography and, ultimately, the shape of the London road network. We therefore compute optimal drive times between all bus garages and between all garages and all 55,578 bus stops on the road network, relying on the Open Source Routing Machine (OSRM).[14] A visual illustration of the distance a bus (or car) can cover on London's route network in a given amount of time is provided via so-called *isochrones* in Fig. 2.

Next, we determine the dead mile minutes between each route and each garage. As routes are long and garages are points in space, it remains to be determined *where* buses access the route. Routes have known start- and endpoints, which are obvious candidates

---

5 Cantillon and Pesendorfer (2007) estimate that a one percent increase in closest distance between a route's endpoint and the operator's garage increases the bid by 0.68 percent. Their analysis abstracts from possible agglomeration benefits from having multiple garages clustered together as well as competitive effects from the operating garage being isolated in the garage-operator network. We explore these elements explicitly in section 5, while accounting for the geography of the market by using driving time on the road as distance measures.

6 See https://tfl.gov.uk/forms/13796.aspx.

7 See https://bus-routes-in-london.fandom.com/wiki/Bus_Routes_in_London_Wiki.

8 TfL remains the primary owner of the land for the garages Ash Grove, Brixton Tramshed, Edgware, Fulwell, Twickenham, Walworth, West Ham, and Uxbridge, as documented in this Freedom of Information Request: https://tfl.gov.uk/corporate/transparency/freedom-of-information/foi-request-detail?referenceId=FOI-2567-1617.

9 We failed in our attempts to obtain prices for all transactions since 1994 but we can report a median price of £1.4m for the sale contracts that we found through the UK Land Registry portal.

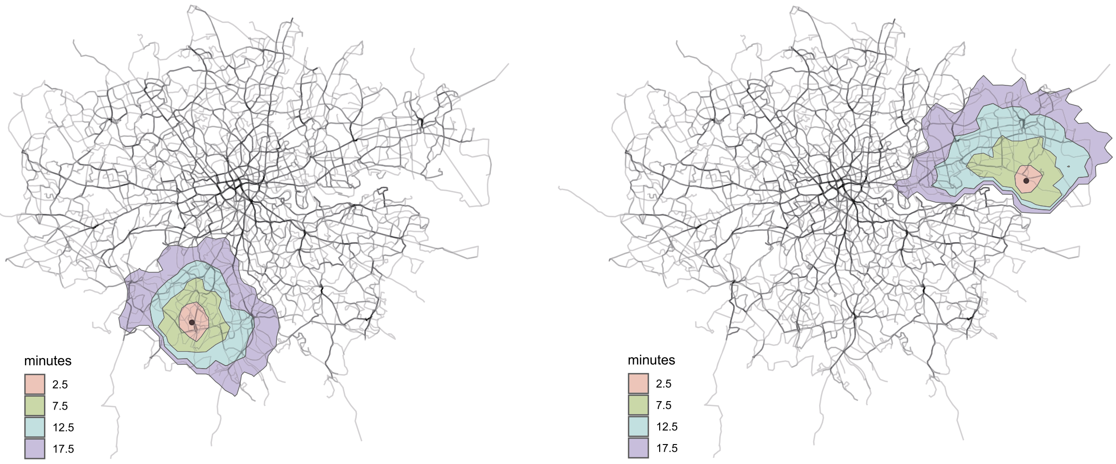
10 The matching covers 85% of all routes, see Table 6. See http://www.lots.org.uk/ for Society memberships.

11 See http://www.londonbusroutes.net/index.htm.

12 See https://api-portal.tfl.gov.uk/docs.

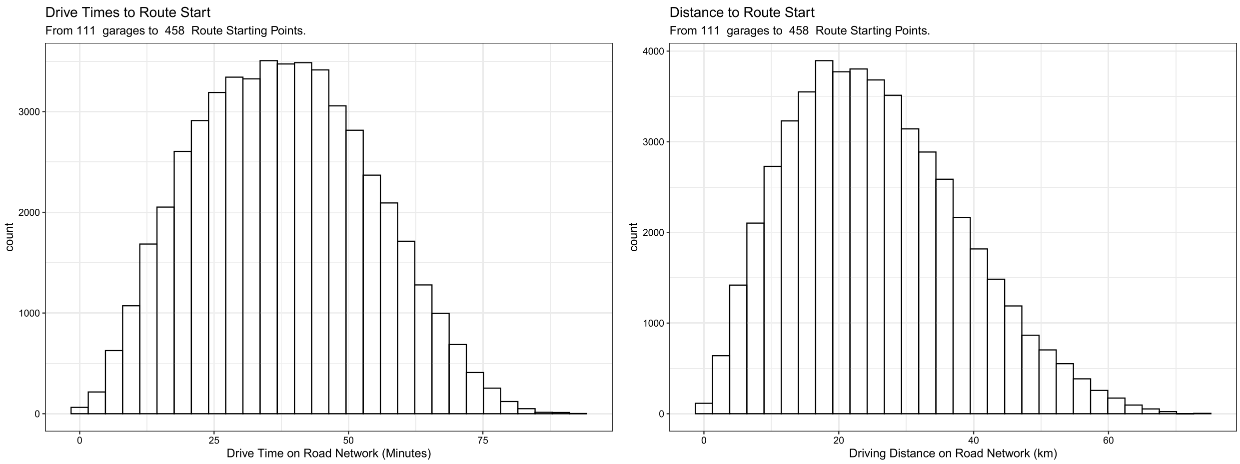
13 According to https://en.wikipedia.org/wiki/Dead_mileage: *"Dead mileage, dead running, light running, empty cars or deadheading in public transport [...] is when a revenue-gaining vehicle operates without carrying or accepting passengers, such as when coming from a garage to begin its first trip of the day."*

14 In terms of functionality, this is identical to the google maps routes API, with the exception of information of congestion of roads at different times of the day, which is absent from OSRM. The benefit of OSRM is that it can be run for free on a local machine, so that computing a great number of optimal routes is feasible. The underlying maps are from OpenStreetMap. We compute 6.5 million optimal routes, which for the basic request on the google maps routes API (USD 5 per 1000 Queries – one route is one query) would cost USD 32,000.



(a) Isochrones for garage *Sutton*. (b) Isochrones for garage *Rainham*.

Fig. 2. Isochrones for two example garages. An Isochrone connects all points reachable within a given time threshold on London's route network by bus/car. The solid black point represents the location of the garage.



(a) Distribution of drive time. (b) Similar but for driving *distance* instead of time.

Fig. 3. Distribution of Driving Time (Start Minutes) and Distance from all garages to all potential route starting points.

especially as the auctioneer dictates when the route should be operated in both directions. Bigger bus stops where many routes intersect, are also relatively important points along the route. As another candidate route entry point we also identify any big bus stops with at least 5 intersecting routes (henceforth "stopover point") and compute the drive time between the garage and the closest stopover point of the route ("Stopover Minutes").

The driving time from all garages to the start points of all routes in the auction data, regardless of whether the route is operated from that garage, is called "Start Minutes" and is plotted in Fig. 3a (Fig. 3b gives the associated driving distances). The average is around 40 minutes. Clearly, the realized drive time that needs to be covered – once a route is won and assigned to a garage of the winning operator – is much lower. On average, about 14 minutes (or 8 km) are actually driven empty, each time a bus is moved between the garage and the route, regardless of whether we use drive time to the route start or the average between start and endpoint. In other words, operators select routes to bid on, based on the proximity of these routes to their garages. The maximum number of dead mile minutes, as revealed in this sample of bids, is 32.75 minutes. One interpretation of this number is that the costs of operating routes further away are too high for the operator to be competitive, and, consequently, the likelihood of winning such routes is too low to place a bid. In our analysis below, our preferred measure of dead miles is the actual driving time on London roads between a garage and the average between the two endpoints of the route, as buses need to be supplied from both directions. This measure is referred to as Start-Stop Minutes in what follows. We also provide estimates based on Start Minutes.

Table 3
Number of Bids for each Vehicle Type, firm A.

Double Decker, (New) New Routemaster	2
Double Decker, Electric	1
Double Decker, Existing	4
Double Decker, Existing + New Diesel	1
Double Decker, Existing Diesel	13
Double Decker, Existing Hybrid	3
Double Decker, Existing New Routemaster	4
Double Decker, New Diesel	11
Double Decker, New Hybrid	73
Single Decker, Electric	2
Single Decker, Existing Diesel	8
Single Decker, New Diesel	85
Single Decker, New Hybrid	1

The total dead mile costs per route accumulate because multiple vehicles are employed on each route (to adhere to TfL's schedule requirements in both directions) and buses also return to the garage to facilitate meal breaks and shift changes of the drivers.[15] We approximate that each 100 contractable route minutes require an additional 13 minutes empty driving time on average, assuming drivers operate a single route for 3.5 hours without interruption and that they drive from and to the garage for their scheduled breaks[16] Running empty 13 percent of the time amounts to a sizeable cost, and this figure is in line with survey-based evidence for other urban areas.[17]

4. Exploiting firm-level individual bids

In addition to the TfL auction data we also obtained bid data from two operators, who will be referred to generically as firm A and firm B.[18] The data contains, for all routes where the firms submitted bids for between 2011 and 2018, the bid of the operator as well as the garage where the route would be operated from. We exploit the individual bid data to study the relationship between dead miles costs and the bid, setting aside the selection issues associated with using the winning bid from the auction data.

The raw data contains 208 bids of firm A and 115 bids of firm B, on 272 routes. There are more bids than routes due to the auction mechanism; a combinatorial auction where both bids on individual routes and route packages are allowed. Hence this data gives a unique insight into the cost synergies to operate multiple routes at the same time as perceived by the firm. Firm B submitted bids with a "joint bid discount" only and the other firm submitted both individual bids and the bid on the route with the discount applied. The average joint bid discount applied by that firm equals 0.55 percent of the individual route bid. If firms follow equilibrium strategies (Cantillon and Pesendorfer, 2006, 2007), this discount is a combination of actual route synergies and a strategic bid inflation to make the individual bids more successful (so the true synergies can be higher than 0.55 percent of route operation cost).

There are also more bids than routes because sometimes both firms bid on the same route, and sometimes a firm submits bids for different options (when sollicited by TfL); most commonly bids for different vehicle types are submitted. Firm A included the Vehicle Type together with each bid, providing another data point that usually remains obscure, and which is particularly interesting in relation to the issue of pollution associated with driving buses empty between garage and route. The bids by firm A have been mostly for new Single Decker buses with a Diesel engine (85 bids) and new Double Decker buses with a Hybrid engine (73), as reported in Table 3. We regress the bid on the vehicle type and the coefficients of these regressions, reported in Table 4, reflect the average bid for that Vehicle Type relative to the bid for a *New Routemaster* Double Decker bus type.[19] Variation in the bus type explains roughly 33 percent of the variation in the bids by firm A. The average bid (meaning operating costs and markup) is significantly lower when the route will be serviced with existing double or single decker buses with a diesel engine, and for new single decker buses with a diesel engine – although bear in mind that these regressions involve few observations for some vehicle types.

To use this data for our garage-route analysis, we take out the few rows with a (marginal) joint bid discount by firm B, average over bids for different options for the same route, remove one instance where two different operating garages were proposed, and match on route and date with the TfL auction data described above. The result is a sample with 353 bids by these two firms between 2011 and 2019 for 222 different routes in 82 auctions. Across the 13 proposed operating garages in this sample, there is substantial

[15] The average PVR (or *Peak Vehicle Requirement*, measuring the number of buses that is needed to operate the route at the busiest time – this is a contractual obligation for each route) for the routes in our auction data is 12.

[16] Two times 13.59 dead mile minutes per 210 contractable route minutes.

[17] While representative statistics are unavailable, buses have also been estimated to drive empty between 12–28 percent of their trip duration in cities in Australia, see https://humantransit.org/2011/06/dead-running.html. Unfortunately, the UK Public Service Vehicle survey of over 500 local bus operators specifically instructs responders to exclude any kilometers "'dead running' between depot and start or end of routes" when answering how many kilometers were operated on local bus services (https://www.gov.uk/government/publications/buses-statistics-guidance/annual-bus-statistics-quality-report-2022).

[18] All operators were approached to share their bids for tenders held between 2011 and 2018; firms A and B responded favorably.

[19] The *New Routemaster* is also referred to as the "Boris Bus" by residents, due to the involvement of Boris Johnson (former major of London) in introducing it in 2012 as an environmentally friendly and accessible version of the classic front-engine double-decker *Routemaster* bus that operated in London since 1968. Despite being considered a low emission bus type, widespread battery malfunctions and consequently over-reliance on the Diesel back-up engine have been reported in 2015 (https://www.standard.co.uk/news/transport/faulty-new-routemasters-emit-74-more-harmful-particles-than-old-buses-10412858.html).

Table 4
Effect of Bus Vehicle Type on Bid (in million £), firm A.

	Bid
Double Decker, Electric	0.133
	(2.170)
Double Decker, Existing	−1.124
	(1.535)
Double Decker, Existing + New Diesel	0.452
	(2.170)
Double Decker, Existing Diesel	−3.493**
	(1.346)
Double Decker, Existing Hybrid	−0.543
	(1.618)
Double Decker, Existing New Routemaster	0.398
	(1.535)
Double Decker, New Diesel	−1.119
	(1.362)
Double Decker, New Hybrid	−0.629
	(1.270)
Single Decker, Electric	−1.205
	(1.772)
Single Decker, Existing Diesel	−3.007**
	(1.401)
Single Decker, New Diesel	−2.911**
	(1.268)
Single Decker, New Hybrid	−2.002
	(2.170)
Constant	5.222***
	(1.253)
Observations	208
R^2	0.329

Notes. Based on individual bid data of firm A. The reference category is a Double Decker, (New) New Routemaster bus.

variation in terms of how close they are to the route. For example, the dead miles between the route endpoints and the garage vary between 9 minutes (on average across all bids for which the operating garage was indicated to be this garage) for Garage 7 and 23 minutes for Garage 10 (see Table 5). The house price index, our best measure of ward-level average land costs, is relatively comparable across the sample. Garage 12 is built in the cheapest location, where the house price index is 87 percent of the average HPI in the sample, and Garages 4, 8, and 9 all have HPI's that are 19 percent above the mean. The capacity of the garage varies between 59 and 134 buses. There is no immediately obvious relationship between either of these variables and the average bid, and we investigate the role of dead miles, land value, and capacity further in the next section.

Regarding garage ownership, our data tells us that firms A or B plan to park buses for the routes that they bid on in one of their 13 garages at the time of bidding. For a broader perspective on the garages in this bid sample we identify them in our garage-operator network dataset. We infer that these 13 garages have changed owners on average 2.8 times between 1995 and 2019, varying between 1 and 5 (see Table 5). How many different firms have owned a certain garage can be informative about the attractiveness of this garage for serving routes. For instance, if routes closer to more popular garages are cheaper to operate, including the popularity of the garage in the analysis helps control for otherwise unobservable cost-related factors. We therefore include this data point in the regression analysis, taking out variation based on the number of ownership changes occurring during the estimation sample period to avoid reverse causality. The garages had between 1 and 2 operator changes (1.15 on average) during the 8 years covered by the estimation sample (see Table 6).

In addition, route characteristics are (partly mechanically) related to our main dead mile driving time measure – the average distance between the two endpoints of a route – and are controlled for when inferring the effect of dead miles on the bid in the next section. Specifically, the scatter plots in Fig. 4 show that more empty miles need to be covered for routes that are longer, and, as longer routes require more vehicles, also for routes that have a larger Peak Vehicle Requirement.

5. The effect of Dead Miles on procurement outcomes

Next, we assess the importance of dead miles for procurement costs, using our linked route-garage network dataset merged with the individual bid data.[20] Specifically, we regress the cost per mile of the winning operator on route characteristics, the number of bidders, and our dead miles metric. Table 6 provides summary statistics of the variables used in estimation, and the estimation results are reported in Table 7. The results show that the relationship between the size of the winning bid for a tendered route, and

[20] The aim of this analysis is to demonstrate that dead miles as measured have an economically important role in the overall cost to procure bus route operation services. Determining the causal impact of dead miles on (winning) bids is beyond the scope and requires a model of equilibrium bidding.

Table 5
Descriptive statistics for firms A and B by garage identifier.

Firm	Garage	Capacity	Bids	Bid (avg)	DM (avg)	DM (max)	HPI	Changes
A	1	134	14	3.472	12.65	18.8	1.059	2
A	2	134	15	3.214	14.993	24.8	0.973	2
A	3	134	18	4.331	14.415	30.6	1.059	5
A	4	98	38	2.476	12.128	17.75	1.049	3
A	5	95	15	2.983	11.597	20.4	1.187	2
A	6	93	14	4.338	11.365	17.2	0.883	2
A	7	84	27	2.714	11.931	20.25	1.08	3
A	8	69	14	1.879	11.235	32.75	1.166	3
A	9	68	7	4.175	13.37	16.3	1.187	2
A	10	59	19	3.322	13.421	30.55	1.187	5
A	11	55	12	1.397	23.167	25.5	1.181	2
B	12	79	129	3.123	14.737	22.45	0.866	4
B	13	59	31	2.784	10.46	14.55	1.039	1
Avg.		89.308	27.154	3.093	13.497	22.454	1.07	2.769

Notes. The column "Capacity" reports the maximum number of buses that the garage is licensed for (i.e., the maximum Peak Vehicle Requirement). The column "Bids" reports the number of bids placed on routes for which the garage was indicated to be the operating base. The column "Bid" reports average bids in million £. "DM" are the Dead Miles between the garage and the route for which a bid is placed, reported in minutes drive time between the garage and the average of the two endpoints of the route (e.g.; our Dead Miles Start-Stop variable), and both the average and the maximum across all bids (routes) are reported. "HPI" is the House Price Index normalized by the average HPI in the sample. The column "Changes" records the number of ownership transitions that occurred between 1995 and 2019. It also includes instances where a garage either becomes vacant or is first occupied within this timeframe.

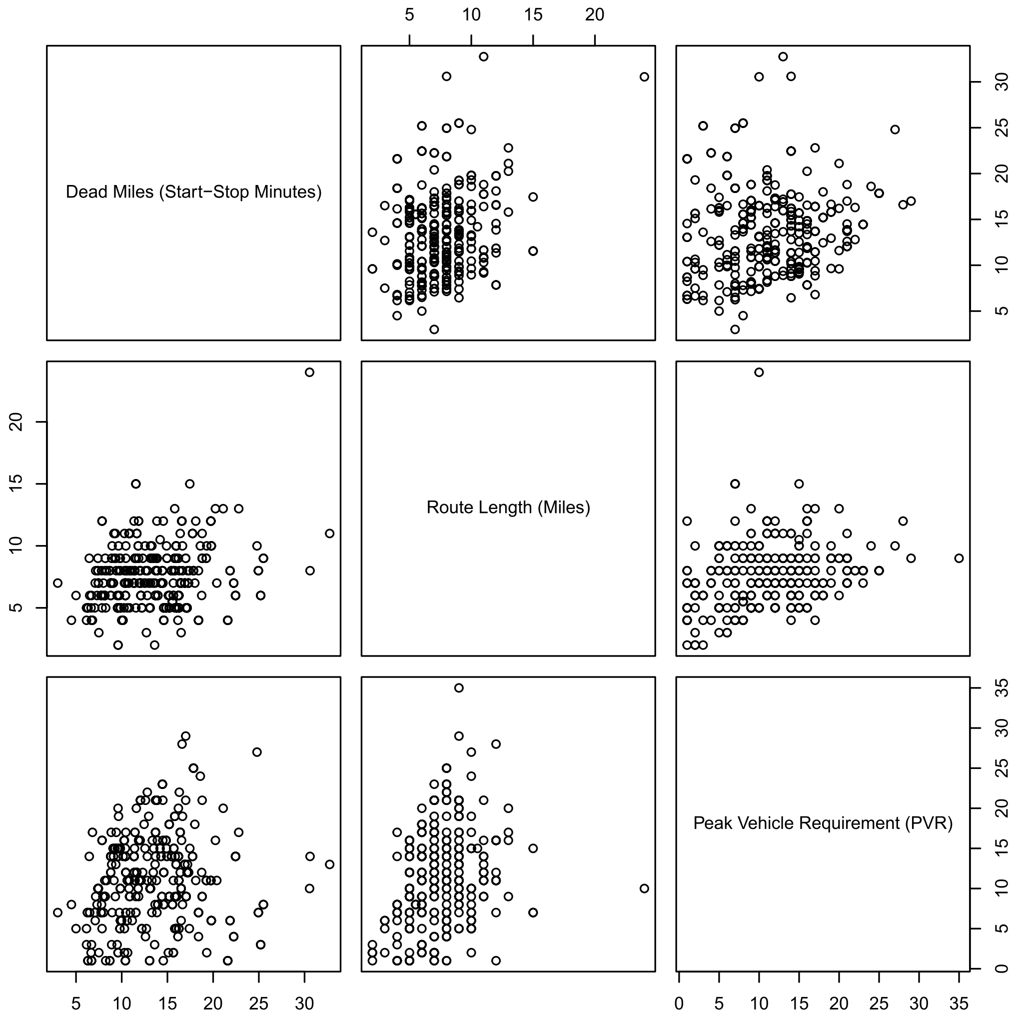
Table 6
Summary statistics of variables used in regression in Table 7.

	N	Mean	SD	Min	Max
Bid (Million Pounds)	350	3.04	1.86	0.06	10.22
Bid by Firm A	353	0.55	0.50	0.00	1.00
Dead Miles (Start-Stop Minutes)	332	13.59	4.60	3.00	32.75
Dead Miles (Start Minutes)	338	13.70	7.16	0.50	51.30
Dead Miles (Stopover Minutes)	305	8.51	5.71	0.30	29.10
Route Length (Miles)	345	7.41	2.47	2.00	24.00
Number of Bidders	353	3.28	1.16	1.00	6.00
Peak Vehicle Requirement (PVR)	349	11.34	5.80	1.00	35.00
House Price Index	353	56.06	6.78	48.56	66.52
Garage: Capacity	353	85.72	22.38	55.00	134.00
Garage: Nr Ownership Changes (2011–2019)	353	1.15	0.35	1.00	2.00
Garage: Nr Ownership Changes (1995–2010)	353	2.03	1.26	0.00	4.00
Total auctions	82.00				
Total routes	222.00				

Notes. Based on individual bid data of firms A and B. *Dead Miles (Start-Stop Minutes)* is the average of time in minutes from garage to start or end point of a given bus route. *Dead Miles (Start Minutes)* is the time in minutes from the garage to the start point of a given bus route. *Dead Miles (Stopover Minutes)* is the time in minutes from the garage to the closest stopover point of a given bus route, which is defined as a bus stop where at least five routes intersect.

the location of the garage where the route is subsequently operated from. The outcome variable is the submitted bid measured in million pound sterling, as provided by the firms. We report specifications with only the Dead Mile distance between the garage and the route (columns (1), (3), and (5)) and with additional controls for the route length, the number of buses needed to operate it (Peak Vehicle Requirement of the route), the capacity of the garage, the house price index of the ward where the garage is located, and firm- and year fixed effects (columns (2), (4), and (6)). Results are obtained for the three measures of distance discussed in section 3.

The average bid in the full sample is £3m. In the sample where we record the Start-Stop distance, the bid for a garage that would have no Dead Miles would be £2m (Constant in column (1) of Table 7). Each additional minute of dead mile driving time from operating garage to midway between start and endpoint of the route is associated with a bid that is between £74,000 (column (1)) and £50,000 (column (2)) higher, depending on whether we control for the number of bidders and exogenous route (length, PVR) and garage (capacity, local price index, number of ownership changes) characteristics. Similar effects but of smaller magnitude are estimated when using the dead miles driving time to the route start, where each additional minute is associated with a £36,000 (column 3) to £26,000 (column 4) higher bid. The larger models control for a substantial share of the observed variation in bids, with the R^2 exceeding 0.7 in columns 2 and 4. In other words, after we control for exogenous route (length, PVR) garage, and market characteristics (number of bidders), and firm and year fixed effects, the location of the garage – and thus the time it takes to



Notes. Based on individual bid data of firms A and B (353 observations), displaying unconditional scatter plots between *Dead Miles (Start-Stop Minutes)*, *Route Length (Miles)*, and *Peak Vehicle Requirement (PVR)*.

Fig. 4. Relationship between Dead Miles and route characteristics.

drive on London's road network to the starting point of the tendered route – seems to have an economically important impact. The relationship with the Stopover minutes measure is less clear in this data.

Various factors could drive a wedge between the estimated effect of dead miles in Table 7 and the causal impact of dead miles on bids. Garages are not randomly placed in the network of routes and bids are not made randomly on route contracts. If garages are placed in lower-density areas with lower land values, and if route contracts in those areas are also less valuable, this introduces a negative bias in the coefficient on Dead Miles. The scope of this bias is limited in the more extensive specifications that include the local area's house price index, the garage capacity, it's popularity (in terms of number of ownership changes prior to the sample period), the route's length and peak vehicle requirement. The house price index captures the land value around the garage and it is highly correlated with population density. The peak vehicle requirement (maximum number of buses needed) and length of the route capture to a large degree the size (costs) of the contract.[21] In addition, any remaining negative correlation between dead miles and contract value would imply that the estimated coefficient on Dead Miles in Table 7 is conservative. The same conclusion can be drawn when garages are built specifically close to high-value routes. Finally, as mentioned above, the regression analysis is done to illustrate the economic importance of our measure of dead miles and abstracts from strategic factors that affect the equilibrium bid (mark-up).

Using individual bid data of firms A and B, as we do here, rather than TfL winning bid data, avoids selection issues which could obfuscate the impact of dead miles on public service provision cost. For instance, the transportation authority might select the

21 Note that the population density does not directly impact the value of a contract as all bus ticket revenues go to TfL; the operator merely operates the contract as specified.

Table 7
Relationship Between Dead Miles and Bids (Firms A and B).

	Bids (in Million Pounds Sterling)					
	Start-Stop minutes		Start minutes		Stopover minutes	
	(1)	(2)	(3)	(4)	(5)	(6)
Dead Miles (Minutes)	0.074***	0.050***	0.036**	0.026**	-0.039*	0.011
	(0.021)	(0.013)	(0.014)	(0.009)	(0.018)	(0.011)
Route Length		0.032		0.038		0.055*
		(0.027)		(0.027)		(0.028)
Number of Bidders		-0.180**		-0.173**		-0.148*
		(0.066)		(0.066)		(0.071)
Peak Vehicle Requirement (PVR)		0.249***		0.251***		0.248***
		(0.011)		(0.011)		(0.012)
House Price Index		-0.001		0.004		-0.013
		(0.017)		(0.017)		(0.018)
Garage: Capacity		0.005		0.005		0.002
		(0.004)		(0.004)		(0.004)
Garage: Nr Ownership Changes (1995–2010)		-0.059		-0.053		-0.030
		(0.049)		(0.049)		(0.053)
Constant	2.043***	-0.674	2.530***	-0.803	3.473***	0.585
	(0.306)	(1.299)	(0.215)	(1.327)	(0.190)	(1.364)
Year FE	–	✓	–	✓	–	✓
Firm FE	–	✓	–	✓	–	✓
Num.Obs.	329	328	335	331	302	297
R2	0.036	0.715	0.020	0.709	0.014	0.696
RMSE	1.77	0.96	1.79	0.96	1.81	0.99

Notes. This table shows results from regressions of route and garage characteristics on all recorded bids of firms A and B. Table 6 provides summary statistics of the variables used in the regressions, including the number of bids for which these variables are observed. See the footnote for dead mile variable definitions. Statistical significance: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 8
Confirming Importance of Dead Miles with TfL tender data.

	Accepted Bids (in Million Pounds Sterling)					
	Start-Stop minutes		Start minutes		Stopover minutes	
	(1)	(2)	(3)	(4)	(5)	(6)
Dead Miles (Minutes)	0.088***	0.019**	0.012	0.007+	0.042***	0.015**
	(0.011)	(0.006)	(0.007)	(0.004)	(0.010)	(0.005)
Num.Obs.	1457	1457	1476	1476	1333	1333
R2	0.059	0.748	0.019	0.746	0.028	0.740
Year FE	–	✓	–	✓	–	✓
Firm FE	–	✓	–	✓	–	✓
Route and auction controls	–	✓	–	✓	–	✓
RMSE	2.08	1.08	2.12	1.08	2.15	1.11

Notes. This table shows results from regressions run at the winning bid level data obtained from TfL. This data includes all participating firms in the market, not only firms A and B. *Route and auction controls* are: route length (in km), the number of bidders, and the route's Peak Vehicle Requirement. We observe the identity of the operating garage for 592 out of 698 total routes, and not all routes have stopover points. Statistical significance: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

winning bidder based on a combination of low bid and proximity to route, in which case a higher winning (accepted) bid might be associated with relatively low dead mile costs. In that case regressing the accepted bid on the dead miles underestimates the true effect of distance on costs. Another issue is that the data is generated by a combinatorial auction format, so that the winning bid is selected to minimize the sum of (package) bids on all routes in the auction. As established in Cantillon and Pesendorfer (2006, 2007), in the combinatorial auction format the relationship between bids and costs is distorted as firms partly bid against themselves. With these limitations in mind, we repeat the regression analysis with TfL winning bid data. This is done to confirm that the dead mile measures affect the procurement costs also for other firms and other route-garage pairs in this larger sample.

The estimation results with TfL winning bid data are reported in Table 8. The results confirm that dead miles have a sizeable effect on procurement costs. Depending on the dead miles measure, controlling for year and firm fixed effects and route and auction variables in columns (2), (4), and (6), the accepted bid increases by £7,000–19,000 for each additional minute of drive time. Looking at our preferred measure of Start-Stop minutes, each additional minute is estimated to reduce the bid in Table 7 by £50,000 and the accepted bid in Table 8 by only £19,000. To the extent that this is not due to selecting particular garage-route combinations in the individual bid data, it suggests that the transportation authority has a preference for routes that require fewer dead miles, c.p.

6. Policy experiment: unbundling network infrastructure

In this section, we gauge the first order impact of a policy to unbundle the ownership of the network infrastructure (garages) from the competitive element in the market (operating the bus routes). Like the UK systems operators for the network of railroads (*NetworkRail*) or electricity transmission lines (*National Grid*), in the counterfactual one entity owns and manages all bus garages in London. This entity is tasked with stationing buses in their garages, in a way that minimizes the total amount of dead miles in the system, while the private operators continue to operate the route according to their contracts with TfL from wherever their buses are stationed. This policy is comparable to the universal dispatcher/central platform counterfactuals in Frechette et al. (2019) and Brancaccio et al. (2020), although without demand or supply fluctuations.

When minimizing the total dead miles in the system, both contractual and operational constraints are respected. Hence, we take into account how many buses a given route requires (PVR) and we take into account the capacity of each garage. Confronting this counterfactual with the status quo will allow us to proxy an efficiency loss in terms of non-revenue generating minutes of bus drive time in the London bus market, stemming only from firm boundaries – what we refer to as (garage) *ownership frictions*.

Of course, driving buses on busy roads imposes also other costs on local residents; especially congestion and pollution. We quantify the reduction in Nitrogen Oxides (NOx) emissions saved in this policy experiment. Those emissions, together with congestion can be considered as pure deadweight losses from the viewpoint of city residents.[22]

To implement the counterfactual, we focus on the observed garage-route network allocation since it was last tendered, i.e. we focus on one (the latest) tender round for each bus route so that we observe unique route-garage pairs. In doing so, we observe $G = 72$ garages to which $R = 533$ routes have been allocated. We observe the required number of buses of each route $PVR(r)$. In total, $N = 6{,}377$ buses are required to service these routes, under the assumption that a bus runs on a single route only. We also observe the capacity $cap(g)$ of each garage in terms of the maximum number of buses it can station. Our measure of dead miles in terms of minutes drive time, Start-Stop Minutes, between garage g and route r is denoted by $DM(g,r)$.

The systems operator chooses an allocation $\mathbf{x}(g,r)$, e.g., the number of buses for route r to station at garage g for all (r,g) in the market, that minimizes the total amount of dead miles across the network. This problem is formalized in equation (1). The problem is subject to constraints which characterize operations in this market, concerning the required number of buses to operate on each route (2) and that the allocation will not exceed capacity at any garage (3).

$$\min_{\mathbf{x}(g,r)\in\{0,\mathbb{N}\}^{G\times R}} \sum_{g=1}^{G}\sum_{r=1}^{R}\mathbf{x}(g,r)\times DM(g,r) \tag{1}$$

$$s.t.$$

$$\sum_{g=1}^{G}\mathbf{x}(g,r) = PVR(r), \quad \forall r \tag{2}$$

$$\sum_{r=1}^{R}\mathbf{x}(g,r) \leq cap(g), \quad \forall g \tag{3}$$

This is an integer constrained optimization problem ($\mathbf{x}$ is a matrix of whole numbers) where we need to choose $R\times G = 38{,}376$ values for $\mathbf{x}$ in a constrained optimal way. We implement the solution using the Gurobi solver (Gurobi Optimization, LLC, 2023).

The results from this exercise are displayed in Table 9, where the unit of observation is the garage. First, we confirm that the observed allocation is *not* chosen according to our constrained optimization algorithm. This is visible by unequal values for total dead miles across scenarios: a larger value for total dead miles (86,771 vs 75,719 minutes in the policy). This implies 14% more dead miles in reality relative to our optimal solution. We see that the average reduction in dead miles is 153 minutes, but that there is significant reallocation: some garages have larger dead miles in the policy than before (minimum differences in dead miles are -1,765 minutes, maximum differences are 1,789 minutes). The sum of the difference in bus allocations is zero, which is indeed imposed by the constraints in the above problem. Besides the fact that firms do not station buses in each others' garages, which we consider to be a primary reason for the difference, firms may also act in more sophisticated ways that are not captured in the constrained optimization problem. But overall one would expect that the costs to operate bus routes decreases by 14% in the unbundling scenario, on average across all firms, of the share of costs that is made up of dead miles. Based on estimated dead mile cost share of 13% across the network derived in section 3, this implies an estimated 2% cost saving overall.[23]

The policy implies that two garages are left completely empty and hence are no longer part of the network. Also interesting is the implied reduction in emissions of harmful pollutants. We assume for simplicity that the bulk of London's buses perform up to Euro-3 emission standards, which implies 500 mg of NOx per km for diesel engines and 150 mg of NOx for petrol engines. Given that distance (km) scales linearly with duration (minutes), we obtain that NOx emissions directly resulting from dead mile bus movements are reduced by 14% as well. Table 9 shows the implied NOx quantities saved for reference.

[22] On the firm side, the immediate revenue loss from high dead mile costs may be justified on strategic grounds. In Marra and Oswald (2023) we show that high dead mile costs may be incurred when firms protect larger catchment areas, increasing expected profits from future route auctions. The results we present here abstract from such strategic motives.

[23] Notice that while in reality operators do *not* share garages, our experiment completely removes this decision from the firms and places them in the best garage in the eyes of the dispatcher. Table 14 gives a list of the resulting shared garage usage, which is substantial.

Table 9
Summary Results from Unbundling Policy.

	Sum	Mean	Median	Min	Max
Current Dead Miles (min. per garage)	86771.45	1205.16	1097.95	23.85	2923.60
Optimal Dead Miles (min. per garage)	75718.65	1051.65	965.88	0.00	2838.05
Difference Dead Miles (min. per garage)	11052.80	153.51	70.85	−1765.85	1789.20
Difference Dead Miles (km per garage)	6745.37	93.69	35.84	−920.95	1300.38
Difference Buses (num. per garage)	0.00	0.00	−7.50	−128.00	121.00
Garages closed down	2				
Annual Cost Savings (m£)	[3.8,8.6]				
NOx saved: Euro-3 Diesel Engine standard (kg)	3.37				
NOx saved: Euro-3 Petrol Engine standard (kg)	1.01				

Notes. Results of policy experiment. By optimally allocating garages to minimize drive time distance, one achieves a 14% reduction in dead miles (86771/75719). This implies that the share of harmful NOx emissions attributable to dead miles are also reduced by 14%. Fig. 5 illustrates variation in the effect of the unbundling policy across garages.

Table 10
Potters Bar and Hatfield Garage Example.

Garage	Buses	Average Duration
Potters Bar	95	18.25
Hatfield	108	13.17

Notes. This table illustrates the baseline for garages *Potters Bar* and *Hatfield*, annotated in Fig. 5, in terms of dead mile minutes per garage. Hatfield is more efficient in the current network configuration, which is the main reason that the system operator takes away buses from Potters Bar.

Fig. 5 gives a good overview of the workings of the policy implementation. First, the closed down garages are visible as either very isolated (large marker, bottom left), or in a dense cluster of garages, where reallocation of buses is relatively easy to achieve. The results reveal a certain tendency to concentrate buses in the southern half of the city, where red colors means more and blue means fewer buses than in the data (in plot (a)) that spend fewer minutes empty driving between the garage and the routes (in plot (b)). The northern most garage (garage *Hatfield*) is keeping an almost constant allocation of buses, but the garage below (*Potters Bar*) has a significant loss in allocated buses. As illustrated in Table 10, Potters Bar has higher average dead mile minutes in the baseline, given road network and available routes for auction at this point in time, which is the reason why it looses buses during the experiment, while the Hatfield garage further north stays at an almost constant allocation.

The reduction in net utility to the UK taxpayer, who ultimately finances the procurement costs, is harder to quantify. Currently, each additional dead mile minute is estimated to increase bids by £50,000 (column (2) of Table 7) and winning bids by £19,000 (column (2) of Table 8), both per five year contract period. The reduction in procurement costs of 11,052 fewer dead mile minutes across all buses in the network corresponds to a reduction of approximately 1,000 contract minutes (with on average 11 buses per route, both in the individual bid data sample (see Table 6) and in the tender data). With the estimated relationship to dead mile (contract) minutes, letting a systems operator assign the necessary buses across the garage network according to (1)–(3) corresponds to a reduction in procurement cost of £19–50 m for the contract period, or £3.8–10 m per year. These cost reductions are between 1.4–3.7 percent of the annual bus route procurement cost in our sample of routes (£273 m).

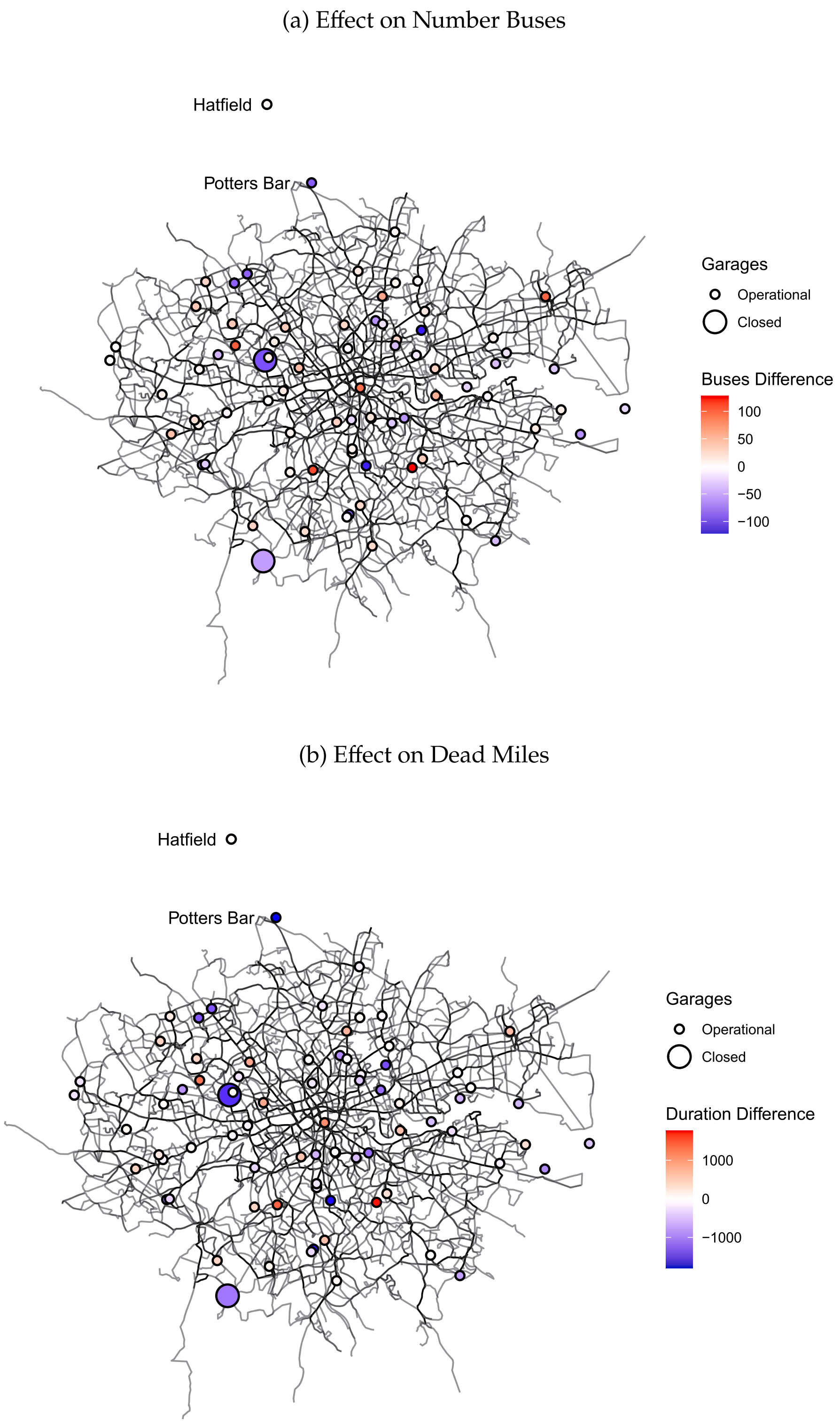
However, the gain would be lower when, for instance, private firms are more efficient at managing garages than a systems operator would be, or when the dissolving of firm boundaries in garage ownership also limits economies of density associated with operating routes from nearby garages. On the other hand, taxpayer gains would be higher when bids are currently inflated due to local monopoly rents associated with owning well-located garages, isolated from competitors.[24,25]

7. Conclusions

This paper studies a procurement setting where network infrastructure is needed to supply the tendered service. This raises the question whether, like in other network industries, the competitive elements of the market should be separated from the ownership of the network. Specifically, we use the example of London bus route procurement, where the private ownership of bus garages introduces local monopoly rents.

[24] In Marra and Oswald (2023) we investigate these issues with a structural model linking the garage location (choice) to route auction revenues, and find evidence for both local monopoly rents and economies of density in garage ownership.

[25] In the appendix, we implement numerical simulations to enlighten some of those aspects: splitting the city into 4 quadrants, we find that restricting garages to lie in the same area as their respective routes lowers the aggregate dead mile measure.



Notes. Policy experiment illustrating reallocation of buses across garages according to the solution to problem (1). Large markers stand for closed down garages. In plot (a) the outcome mapped to the color scale is the difference in buses allocated to a given garage, and in plot (b) displays the difference in the total dead miles drive time between each garage and the routes it has been allocated buses to. Summary statistics of the effects of the policy for the entire network are given in Table 9.

Fig. 5. Mapping Results from the Unbundling Policy.

To study this issue, we assemble what is the first consolidated database of bus garages used by private firms for the operation of bus routes in the Greater London Area. In particular, the dataset contains details about the location and ownership of bus garages over time, starting from 1994 when the London bus market was privatized via a split into 12 geographical areas. The data is constructed by combining archival data from the London Omnibus Traction Society and hobbyist (*bus spotters*) websites.

Given the current allocation of buses to garages, buses need to cover substantial dead miles to service the bus route contracts. We document that the additional dead miles that buses drive empty between garage and route amount to about 13 percent of the distance that buses drive when loaded with passengers in London. This involves substantial costs, which is confirmed by a regression analysis based on both individual bid data (supplied by two firms in this market) as well as with publicly available tender data.

To some extent, dead miles are inherent to the urban infrastructure in a densely populated city and to the problem of supplying buses to long routes from points in space. Taken urban structure as given, we use a counterfactual policy simulation to assess how much of the (wasteful) dead miles can be ascribed to the fact that operators cannot station buses in each others' garages – which we refer to as *ownership frictions*. In essence, we unbundle the ownership of the network infrastructure (garages) from the competitive element in the market (operating the bus routes). A systems operator owns and manages all bus garages in London and is tasked with stationing buses in their garages, in a way that minimizes the total amount of dead miles in the system, while the private operators continue to operate the route according to their contracts with TfL from wherever their buses are stationed. As a result of this counterfactual, we conclude that about 14 percent of the dead miles are attributable to ownership frictions, so that removing the garage ownership constraints would have cost- and pollution reducing effects of similar magnitude.

Quantifying the effect of unbundling on the procurement costs (and hence, total welfare) requires additional structure, modelling how equilibrium bids change with unbundling, especially when accounting for economies of density in operation. We leave this for future work. We also refer to Marra and Oswald (2023) for additional analysis of the interaction between competition and the choice of garage location, accounting for spatial rents such as economies of density of operating bus routes from multiple near-by garages.

The estimated ownership frictions may partially explain why public entities are found to outperform private bus companies in various instances (Gagnepain et al., 2011), and help inform policymakers designing optimal public transportation markets.

CRediT authorship contribution statement

Marleen Marra: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Florian Oswald:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

Data will be made available on request.

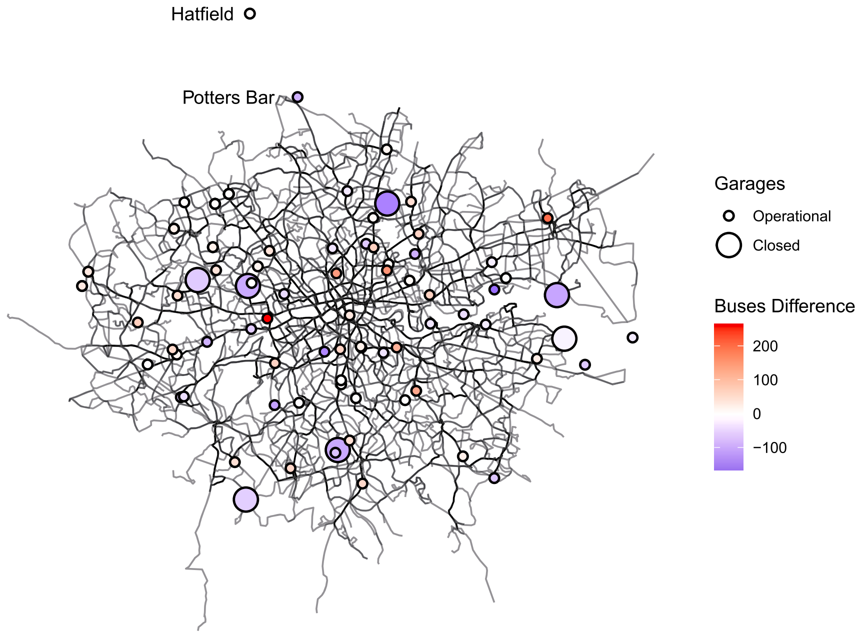
Acknowledgements

We thank Ian Hsieh, Xinyu Dai, Martin Bretschneider, and Aru Bhardwaj for excellent research assistance. We also thank participants at the TSE and UCL Econometrics of Games, Matching and Networks conference, EARIE, the NBER Design and Regulation of Transportation Markets Meeting, KU Leuven, as well as Estelle Cantillon, Gabriel Ahlfeldt, Milena Almagro, Pierre-Philippe Combes, Francesco Decarolis, Pierre Dubois, Michele Fioretti, and Emeric Henry for comments. We are very grateful to Les Stitson from the London Omnibus Traction Society for compiling a dataset for this study based on their archives and for generously answering numerous questions about the history of garage ownership in London. Thanks also to Robert Munster, the owner of LondonBusRoutes.net, for answering questions and sharing data on bus route characteristics with us. We gratefully acknowledge research funding from the Banque de France - Sciences Po partnership.

Appendix A. Unbundling constrained within quadrants

In this section, we change the setup from our main experiment in section 6 to illustrate how the outcome would change if operators were constrained to park buses in garages which lie within a certain area of the city. Instead of a single dispatcher assigning buses to the best location in terms of dead miles, now we can think of four dispatchers. A priori, splitting the city into different areas could lead to both an increase or a decrease in dead miles. We will show that, given the location of operators in the data and given the same operational constraints as above, forcing garages to be closer to routes will lead to a stronger reduction in dead miles than what the single dispatcher can achieve.

In more detail, we split London into 4 roughly equally sized quadrants, by assigning boroughs to one of 4 regions (NE, SE, SW, NW), as shown in Table 13. We assign to each bus route it's home quadrant, which is chosen as the region where most of the route comes to lie. Then we require that routes can only be assigned to garages which lie in their home quadrant. Formally, the problem is defined similarly to (1), with the exception for the capacity constraint (3), which is replaced by a constraint requiring that garage g and route r lie in the same quadrant:



(b) Garage Classification to quadrants

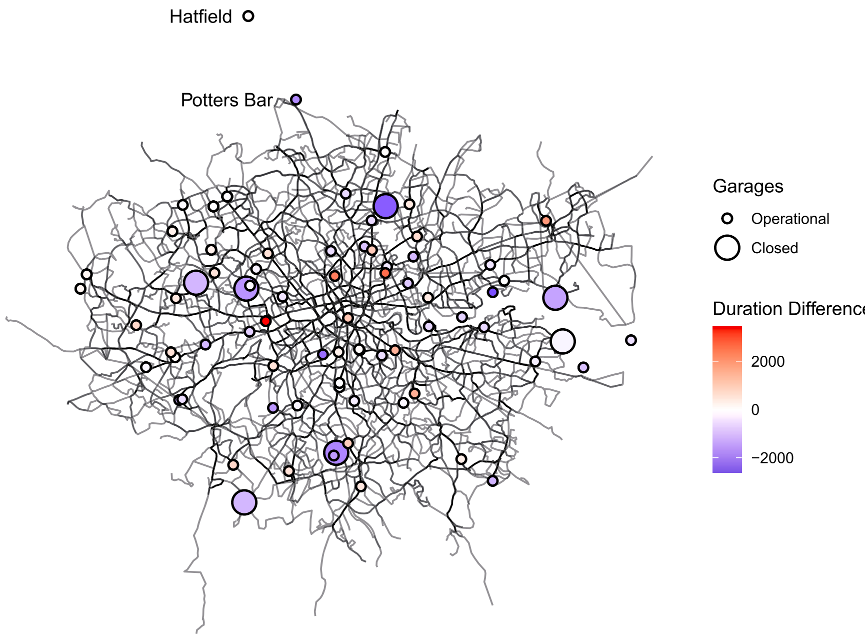


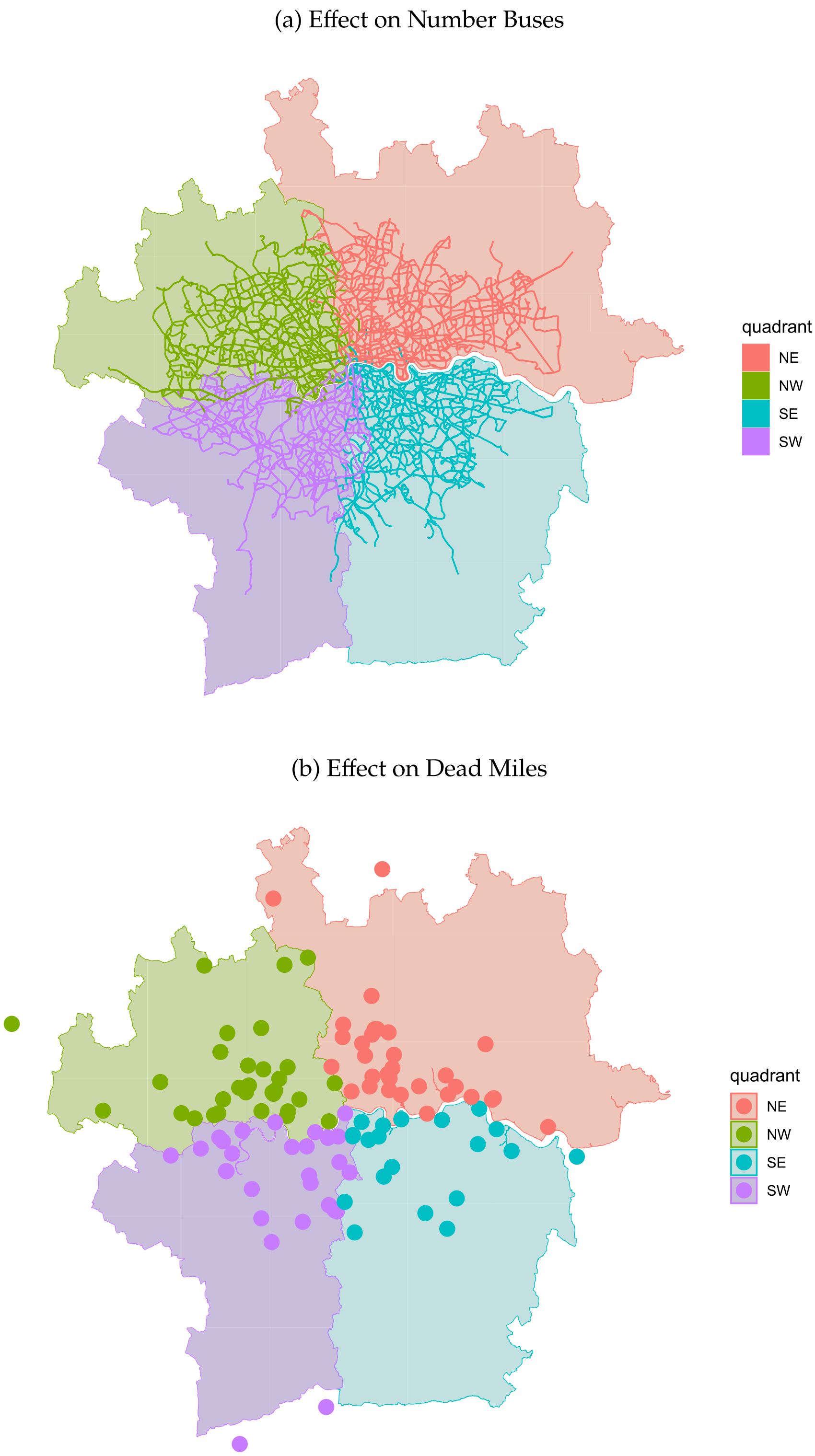
Fig. 6. Allocation of Routes and garages to quadrants.

$$\min_{\mathbf{x}(g,r)\in\{0,\mathbb{N}\}^{G\times R}} \sum_{g=1}^{G}\sum_{r=1}^{R}\mathbf{x}(g,r)\times DM(g,r) \tag{4}$$

$$s.t.$$

$$\sum_{g=1}^{G}\mathbf{x}(g,r) = PVR(r), \quad \forall r \tag{5}$$

$$q(g) = q(r) \tag{6}$$



Notes. The same notes as in Fig. 5 apply but with quadrant restriction in expression (6).

Fig. 7. Mapping Results from the Unbundling Policy with quadrant restriction.

Table 11
Summary Results from Unbundling Policy with quadrants.

	Sum	Mean	Median	Min	Max
Current Dead Miles (min. per garage)	86771.45	1205.16	1097.95	23.85	2923.60
Optimal Dead Miles (min. per garage)	74691.80	1037.39	910.95	0.00	4365.20
Difference Dead Miles (min. per garage)	12079.65	167.77	126.60	−3438.70	2619.30
Difference Dead Miles (km per garage)	7062.72	98.09	81.43	−1678.65	1815.80
Difference Buses (num. per garage)	0.00	0.00	−2.00	−265.00	166.00
Garages closed down	7				
Annual Cost Savings (m£)	[4.2, 9.4]				
NOx saved: Euro-3 Diesel Engine standard (kg)	3.53				
NOx saved: Euro-3 Petrol Engine standard (kg)	1.06				

Notes. Same as Table 9, but with quandrant restriction in expression (6).

Table 12
Baseline Unbundling Policy without quadrants and without capacity constraint.

	Sum	Mean	Median	Min	Max
Current Dead Miles (min. per garage)	86771.45	1205.16	1097.95	23.85	2923.60
Optimal Dead Miles (min. per garage)	72569.80	1007.91	770.85	0.00	4854.00
Difference Dead Miles (min. per garage)	14201.65	197.25	167.70	−4653.75	2619.30
Difference Dead Miles (km per garage)	8251.52	114.60	111.28	−2340.55	1815.80
Difference Buses (num. per garage)	0.00	0.00	−0.50	−319.00	166.00
Garages closed down	8				
Annual Cost Savings (m£)	[4.9, 11.1]				
NOx saved: Euro-3 Diesel Engine standard (kg)	4.13				
NOx saved: Euro-3 Petrol Engine standard (kg)	1.24				

Notes. The same notes as in Table 9 apply, but without the capacity constraint (3). This is to facilitate a better comparison with Table 11.

Table 13
Allocation of London Boroughs into Quadrants.

Quadrant	Boroughs
NE	Islington, Haringey, Enfield, Broxbourne, Welwyn Hatfield, Tower Hamlets, Hackney, Waltham Forest, Epping Forest, Newham, Redbridge, Barking and Dagenham, Havering, Thurrock, Brentwood, City of London
SE	Southwark, Croydon, Tandridge, Sevenoaks, Bromley, Lewisham, Greenwich, Dartford, Bexley
SW	Lambeth, Sutton, Merton, Wandsworth, Kingston upon Thames, Richmond upon Thames, Epsom and Ewell, Hounslow, Spelthorne, Reigate and Banstead, Mole Valley, Runnymede, Elmbridge
NW	Hillingdon, Ealing, Hammersmith and Fulham, Kensington and Chelsea, Westminster, Camden, Barnet, Brent, Harrow, Slough, Hertsmere, Watford, South Bucks, Three Rivers

where the function $q(\cdot)$ returns the quadrant of either garage or route. We have to relax the garage capacity constraint, because the problem becomes infeasible otherwise – limited capacity of garages within a quadrant may be part of the reason why we observe garages outside of the quadrant of a given route. This optimization program still respects the operational constraints on the number of buses for each route via (5), but it forces garages and routes to lie in the same quadrant as per (6).

We first present the allocation of routes and garages to quadrants. This is show in Fig. 6. Panel (a) of the figure illustrates the way the route network was designed seemed to be already closely aligned with the quadrant layout – most routes do not traverse the quadrant boundaries. This may have to do with the layout of the underground network, or a desire to provide bus lines that predominantly lead towards the city center. Panel (b) shows the resulting classification of garages to quadrants.

In Fig. 7, then, we perform the experiment defined in equation (4). We see immediately that more garages will be shut down than under the city-wide policy, partly as a result of our need to abandon the capacity constraint on the program. Because garages lie in a certain area now, only routes in the same quadrant than the garage can be serviced. As illustrated further in Table 11, this leads to a slightly stronger reduction in dead miles than in the single dispatcher case. The difference in dead mile reduction is similar to the universal dispatcher case presented in section 6 (a dead mile reduction of 6745 vs. 7062 km. across all garages, respectively). While the latter result is obtained from a stylized example with a spatial split of the market into quadrants, it highlights that the uniform dispatcher scenario is not necessary to obtain cost savings. This is especially useful to counter the concern that cost savings can only be obtained by some form of monopoly provision of garage space, especially if this is left to the market rather than the government-provided central dispatcher that we have in mind. In this respect, we underline that a model of route bidding is needed to provide more precise insights on changes in actual dead miles and bids after strategic responses of operators to the imposed constraints in both scenario's.

The comparison to the baseline experiment is imperfect, however, because of the omission of the garage capacity constraint. In order to facilitate a better comparison, we repeat the baseline experiment from section 6, but this time we omit the capacity

Table 14
Operators sharing garages in section 6.

Garage Code	Operators
HK	London Central, London General, Arriva London North, Metroline
RR	Blue Triangle, Docklands Buses, Arriva London North, Stagecoach East London, Tower Transit
RM	Arriva London North, Stagecoach East London, Arriva Kent Thameside, Blue Triangle
WH	Docklands Buses, Stagecoach East London, Blue Triangle, CT Plus, Tower Transit
BT	Metroline, Arriva London North, London Sovereign, Arriva The Shires Ltd
AV	London United, Metroline West, Metroline, Abellio West London
ON	Metroline West, Metroline, London Sovereign, London United, London General
HH	London United, Abellio West London, Metroline
AH	Metroline, Abellio London West, London United
AL	London General, Arriva London South, Abellio London, Quality Line
SG	Metroline West, London United, Metroline, Abellio West London
E	Arriva London North, Metroline, London General
KB	Stagecoach Selkent, Arriva London South, Metrobus, Abellio London
TL	Stagecoach Selkent, Arriva Kent Thameside, Metrobus
TB	Metrobus, Stagecoach Selkent
C	Metrobus, London General, Arriva London South, Quality Line
MG	London Central, Stagecoach Selkent
TH	Abellio London, Arriva London South, Metrobus, London Central
PL	London General, Abellio London, Arriva London South
BW	Docklands Buses, CT Plus, Tower Transit, Stagecoach East London
NX	Stagecoach Selkent, London Central, Arriva London North
WN	Arriva London North, London General, Metroline
HD	London Sovereign, Metroline
HT	Metroline, London General, CT Plus
W	Metroline, London Sovereign
AD	Arriva London North, London General, Metroline
DX	Stagecoach East London, Blue Triangle, Arriva London North
MB	Stagecoach Selkent, Metrobus, Abellio London
NS	Arriva London North, Stagecoach East London, Blue Triangle
A	London General, Abellio London, Quality Line, London United, Arriva London South
KC	London General, Arriva London North
BC	London General
QB	Abellio London, London General, Arriva London South
BK	Stagecoach East London, Blue Triangle, Arriva London North
RA	Metroline, London United, London Central, London General, Abellio London
PM	London Central
PD	Stagecoach Selkent, London General, Arriva Kent Thameside, London Central
WL	London Central
AC	Metroline West, Metroline, Tower Transit
V	Metroline, London United
NP	Arriva London North, London General
BN	Abellio London, Arriva London South, London General, Metrobus, London Central
AW	CT Plus, Stagecoach East London, London General
S	London United, Travel London, Abellio London
TF	London United
WJ	Tower Transit, Metroline
FW	Metroline, Abellio West London, Quality Line
CT	Tower Transit, CT Plus, Stagecoach East London
T	Stagecoach East London, Tower Transit, CT Plus
SI	Tower Transit, Arriva London North, Stagecoach East London, CT Plus
TV	London United, Quality Line, Abellio West London
BX	Arriva London North, Stagecoach Selkent, London Central, Arriva Kent Thameside
X	Metroline, Tower Transit, London United
G	Metroline West, Metroline Travel, London United
TC	Arriva London South, Metrobus, Quality Line, Abellio London‘
LI	Tower Transit, CT Plus
N	London General, Arriva London South
UX	Metroline West, London United, First London West, Abellio West London
SW	Arriva London South, Abellio London, London Central, London General
AF	London General, London United

(*continued on next page*)

Table 14 (*continued*)

Garage Code	Operators
SO	Arriva the Shires, London Sovereign, Metroline Travel, Metroline West
WS	Abellio West London, London United, Metroline West, First London West
GY	Arriva London North, Stagecoach East London, Blue Triangle
HF	Uno, Metroline
PB	Metroline, London General
DT	Arriva London North, Arriva Kent Thameside, Stagecoach Selkent
MR	Arriva Kent Thameside
AR	London General, Tower Transit, Arriva London North
Q	Abellio London
PA	Metroline West

Table 15
Operators sharing garages under quadrant restriction in Appendix A.

Garage Code	Operators
HK	London Central, London General, Arriva London North, Metroline, CT Plus
RR	Blue Triangle, Stagecoach East London
NS	Arriva London North, Stagecoach East London, Blue Triangle, Arriva Kent Thameside
WH	Docklands Buses, Blue Triangle, Stagecoach East London, Tower Transit
BT	Metroline, London Sovereign, Arriva London North, Arriva The Shires Ltd, Arriva the Shires, Uno
AV	London United, Abellio West London, Metroline
ON	Metroline West, Metroline, London Sovereign, London United
SG	Metroline, London United, Abellio West London
SW	London General, Abellio London, Arriva London South
WS	Metroline West, Abellio West London, London United, Metroline
E	Arriva London North, Metroline, London General
TL	Stagecoach Selkent, Arriva Kent Thameside, Metrobus
TB	Metrobus, Stagecoach Selkent, Abellio London
C	Metrobus, Quality Line
MG	London Central, Stagecoach Selkent
TH	Abellio London, Arriva London South, Metrobus
PL	London General
BW	Docklands Buses, CT Plus, Stagecoach East London
NX	Stagecoach Selkent, London Central, Abellio London, Arriva London North
WN	Arriva London North, London General, Metroline
W	Metroline, Metroline West, London General, London Sovereign
AD	Arriva London North
DX	Stagecoach East London, Blue Triangle, Arriva London North, Docklands Buses
A	London General, Arriva London South, Quality Line, London United
N	Arriva London South, Abellio London, London General
AL	London General
AW	Stagecoach East London, CT Plus, London General, Tower Transit, Blue Triangle
KC	Metroline, London General
BK	Stagecoach East London, Arriva London North, Blue Triangle
AF	London General, London United, Abellio London, Metrobus
PD	London General, Arriva Kent Thameside, London Central, Stagecoach Selkent
HD	Metroline, London Sovereign
WL	London Central, Abellio London
AC	Metroline West, Metroline, Tower Transit
V	Metroline
AR	Arriva London North, London General
KB	Arriva London South
PM	Metrobus, London Central
BN	Abellio London, Arriva London South, Metrobus, London General
S	London United, London Central, Travel London, London General, Tower Transit, Abellio London
TF	London United
UX	Metroline West, London United, First London West, Abellio West London
WJ	Tower Transit, Metroline, Metroline West
MB	Metrobus, Stagecoach Selkent
FW	Metroline, Abellio West London, Quality Line

Table 15 (*continued*)

Garage Code	Operators
CT	Tower Transit, CT Plus
T	Stagecoach East London, Tower Transit, CT Plus
BX	Arriva London North, Stagecoach Selkent, London Central, Arriva Kent Thameside
HT	Metroline, CT Plus
G	Metroline West, Metroline Travel, Metroline, London United
TC	Arriva London South, Metrobus, Quality Line, Abellio London, Abellio London'
TV	Quality Line, London United, Abellio West London
HF	Arriva London North
QB	Arriva London South
SI	Arriva London North, Tower Transit, CT Plus
LI	Tower Transit, Stagecoach East London, CT Plus
GY	Arriva London North, Stagecoach East London, Blue Triangle
PB	Metroline
SO	London Sovereign, Metroline West
DT	Arriva London North, Arriva Kent Thameside, Stagecoach Selkent
AH	Abellio London West
RA	Arriva London South, London Central
HH	Abellio West London
Q	Abellio London

constraint also from the there, i.e. we delete constraint (3). This provides a closer benchmark to the quadrants restriction, where the capacity constraint is absent as well. The results in Table 12 confirm indeed that if the dispatcher could dispose of the entire city, and not just the four restricted areas, the reduction in dead miles would be even larger – 197 minutes on average reduced vs 167 minutes in the quadrant scenario (Table 11). Table 15 documents the resulting allocation of operators to garages.

References

Andreyanov, Pasha, Decarolis, Francesco, Pacini, Riccardo, Spagnolo, Giancarlo, 2023. Past Performance and Procurement Outcomes. NBER Working Paper No. 22814.

Bajari, Patrick, Tadelis, Steven, 2001. Incentives versus transaction costs: a theory of procurement contracts. Rand J. Econ., 387–407.

Balboni, Clare Alexandra, 2019. In harm's way? Infrastructure investments and the persistence of coastal cities. PhD diss. London School of Economics and Political Science.

Brancaccio, Giulia, Kalouptsidi, Myrto, Papageorgiou, Theodore, Rosaia, Nicola, 2020. Search frictions and efficiency in decentralized transportation markets. Natl. Bur. Econ. Res.

Brueckner, Jan K., Spiller, Pablo T., 1994. Economies of traffic density in the deregulated airline industry. J. Law Econ. 37 (2), 379–415.

Cantillon, Estelle, Pesendorfer, Martin, 2006. Auctioning bus routes: the London experience. In: Cramton, Peter, Shoham, Yoav, Steinberg, Richard (Eds.), Combinatorial Auctions. The MIT Press, Cambridge, Massachusetts, pp. 573–592. Chapter 22.

Cantillon, Estelle, Pesendorfer, Martin, 2007. Combination bidding in multi-unit auctions. CEPR Discussion Paper No. 6083.

Davis, Peter, 2006. Spatial competition in retail markets: movie theaters. Rand J. Econ. 37 (4), 964–982.

Decarolis, Francesco, 2014. Awarding price, contract performance, and bids screening: evidence from procurement auctions. Am. Econ. J. Appl. Econ. 6 (1), 108–132.

Fajgelbaum, Pablo D., Schaal, Edouard, 2020. Optimal transport networks in spatial equilibrium. Econometrica 88 (4), 1411–1452.

Florio, Massimo, 2013. Network Industries and Social Welfare: The Experiment That Reshuffled European Utilities. OUP Oxford.

Frechette, Guillaume R., Lizzeri, Alessandro, Salz, Tobias, 2019. Frictions in a competitive, regulated market: evidence from taxis. Am. Econ. Rev. 109 (8), 2954–2992.

Gaduh, Arya, Graff, Tilman, Hanna, Rema, Kreindler, Gabriel, Olken, Benjamin A., 2022. Optimal Public Transportation Networks: Evidence from the World's Largest Bus Rapid Transit System in Jakarta. NBER Working Paper No. w31369.

Gagnepain, Philippe, Ivaldi, Marc, 2002. Incentive regulatory policies: the case of public transit systems in France. Rand J. Econ., 605–629.

Gagnepain, Philippe, Ivaldi, Marc, Vibes, Catherine, 2011. The industrial organization of competition in local bus services. In: De Palma, André, Lindsey, Robin, Quintet, Emile, Vickerman, Roger (Eds.), A Handbook of Transport Economics. Edward Elgar.

Gurobi Optimization, LLC, 2023. Gurobi Optimizer Reference Manual.

Holmes, Thomas J., 2011. The diffusion of Wal-Mart and economies of density. Econometrica 79 (1), 253–302.

Hotelling, H., 1929. Stability in competition. Econ. J. 39, 41–57.

Houde, Jean-François, 2012. Spatial differentiation and vertical mergers in retail markets for gasoline. Am. Econ. Rev. 102 (5), 2147–2182.

Iossa, Elisabetta, Waterson, Michael, 2019. Maintaining competition in recurrent procurement contracts: a case study on the London bus market. Transp. Policy 75 (February 2017), 141–149.

Jia, Panle, 2008. What happens when Wal-Mart comes to town: an empirical analysis of the discount retailing industry. Econometrica 76 (6), 1263–1316.

Laffont, Jean-Jacques, Tirole, Jean, 1986. Using cost observation to regulate firms. J. Polit. Econ. 94 (3, Part 1), 614–641.

Marra, Marleen, Oswald, Florian, 2023. Spatial rents, garage location, and competition in the London bus market. Working paper. https://floswald.github.io/pdf/garage-locations-main.pdf.

Miller, Nathan H., Osborne, Matthew, 2014. Spatial differentiation and price discrimination in the cement industry: evidence from a structural model. Rand J. Econ. 45 (2), 221–247.

Newbery, David M.G., 2004. Privatising network industries. Available at SSRN 518044.

Oberfield, Ezra, Rossi-Hansberg, Esteban, Sarte, Pierre-Daniel, Trachter, Nicholas, 2024. Plants in space. J. Polit. Econ.

Olivares, Marcelo, Weintraub, Gabriel Y., Epstein, Rafael, Yung, Daniel, 2012. Combinatorial auctions for procurement: an empirical study of the Chilean school meals auction. Manag. Sci. 58 (8), 1458–1481.

Porter, Robert H., Zona, J. Douglas, 1999. Ohio school milk markets: an analysis of bidding. Rand J. Econ. 30 (2), 263–288.

Salop, Steven C., 1979. Monopolistic competition with outside goods. Bell J. Econ., 141–156.

Seim, Katja, 2006. An empirical model of firm entry with endogenous product-type choices. Rand J. Econ. 37 (3), 619–640.
Waterson, Michael, Xie, Jian, 2019. Testing for collusion in bus contracting in London. Warwick Economics Research Papers No: 1196.
Wunsch, Pierre, 1996. Estimating Menus of Linear Contracts for Mass Transit Firms (in the Spirit of Laffont and Tirole). Université catholique de Louvain, Center for Operations Research and Econometrics.