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Abstract

Road traffic is a major contributor to air pollution which is a serious problem in many large cities. Experience in London, Milan, and Stockholm indicates that road pricing can be useful in reducing vehicle emissions as well as congestion. This study uses a dynamic traffic network simulator that models choices of mode, departure time, and route to investigate the effectiveness of tolls to target emissions and congestion externalities on a stylized urban road network during a morning commuting period. The spatial distribution of four pollutants is calculated using a Gaussian dispersion model that accounts for wind speed and direction. Single and double cordon tolls are evaluated, as well as flat tolls that do not change during the simulation period and step tolls that change at half-hourly intervals. The presence of emissions externalities raises optimal toll levels, and substantially increases the welfare gains from tolling, although the proportional advantage of step tolls over flat tolls is lower than if congestion is the only externality. The individual welfare-distributional effects of tolling vary strongly with residential and workplace locations relative to the cordon, and also differ for the upwind and downwind sides of the city.

Keywords: congestion; dynamic traffic simulation; emissions; pollution dispersion; tolls

JEL: R4, K 32

1 INTRODUCTION

Air pollution is a severe problem in many countries. Over 90% of the world's population is exposed to air pollution that exceeds World Health Organization standards (WHO, webpage a), and ambient air pollution is responsible for an estimated 4.2 million premature deaths worldwide. Particulate matter (PM) is especially harmful to health. The total health costs of PM_{10} in Mumbai and Delhi alone are estimated to be around one percent of India's GDP (Maji et al., 2017). Ambient levels of PM are several times the maximum recommended levels by the WHO (2005) in Beijing (Yin et al., 2017a), Tehran (Heger and Sarraf, 2018), and other major cities. According to an analysis of 38 cities in China, a 10 $\mu g/m^3$ rise in PM_{10} concentration increases the daily number of deaths by 0.44% (Yin et al., 2017b). Worldwide, one sixth of deaths related to Lower Respiratory Infections is attributed to $PM_{2.5}$, amounting to ~400,000 deaths per year (GBD, 2017). Recent studies have determined that air pollution increases the rate of influenza hospitalizations (Zivin et al., 2020), the risk of pre-existing conditions that make COVID-19 more harmful (Centre for Research on Energy and Clean Air, 2020), and COVID-19 deaths (Isphording et al., 2020).

Road transportation is a major source of emissions of most major air pollutants. It is estimated to contribute up to 50% of PM emissions in OECD countries, and 30% in European cities (WHO, webpage b). During the COVID-19 pandemic, a reduction in commuting trips in South Korea led to a measurable decrease in levels of $PM_{2.5}$, PM_{10}, CO, and NO_2 (Lee and Finerman, 2021), demonstrating how road transportation contributes to air pollution. Vehicular pollution tends to be more damaging to human health than pollution from other sources because people are often near to (or traveling in) vehicles, and thus exposed to the pollution at close quarters (McCubbin and Delucchi, 2003). Road transportation is also a significant contributor to climate change. In the European Union (EU), it is responsible for 20.4% of total greenhouse gas emissions (European Commission, 2021b). In July 2021, the EU adopted legislative proposals to achieve climate neutrality by 2050, including an intermediate target of reducing emissions by at least 55% relative to 1990 levels by 2030 (European Commission, 2021a). The proposed legislation includes measures directed at transportation, including more stringent emissions standards for new vehicles and extension of the Emissions Trading System to transportation.

It is true that new internal-combustion-engine vehicles are becoming more fuel-efficient and less polluting, and electric vehicles are entering the market. However, the stock of existing vehicles will remain in operation for many years. Electric vehicles contribute to emissions indirectly if the electricity they use is generated by carbon-based primary fuels. Road abrasion and wear and tear on tires and brakes occur regardless of the power source, and their contribution is increasing as a fraction of total PM emissions (EEA, 2019). Furthermore, vehicle ownership and usage are still growing in a number of developing countries. Thus, vehicle pollution will remain a problem for many years — especially in low- and middle-income countries.

Many cities have taken steps to reduce pollution; sometimes with congestion relief as an additional goal. In 1989, Mexico City introduced an odd-even license plate rationing scheme, and other countries have since adopted similar schemes. Following the 2008 Olympics, Beijing implemented driving restrictions based on license plate numbers (Viard and Fu, 2015). In 2013, a smog alert system was added that features more stringent restrictions when air quality is particularly bad. Around 30 Chinese cities now have license-plate-based vehicle driving restrictions (Chen et al., 2020). Studies have come to widely varying conclusions on whether these policies succeed in improving air quality. For example, Viard and Fu (2015) conclude that Beijing's was successful, whereas negative assessments have been made for Mexico City (Davis, 2008), São Paulo and Bogotá (Lin et al., 2011), and a sample of 11 cities in China (Chen et al., 2020).

Rather than imposing blanket restrictions on vehicles, some cities have chosen to target polluting vehicles. As of 2019, about 250 low-emission or zero-emission zones have been established in Europe.[1] Some low-emission zones allow entry to non-conforming vehicles if they pay a fee. An example is the Ultra Low Emission Zone in London, which comprises the same area as the London Congestion Charge (Transportation for London, 2020).

In general, license-plate and other quantity-based regulations are imperfect policies at best. They can induce behavioral adaptations that undercut their efficiency, and even result in outright welfare losses. Both microeconomic theory applied to transportation (e.g., Small and Verhoef, 2007) and experience with existing road pricing schemes indicate that well-designed price-based policies can be more effective at internalizing transportation-related externalities. Several cities have adopted tolling schemes that are motivated, at least in part, by environmental concerns. In 2008, Milan introduced EcoPass: a cordon scheme that imposed a charge on weekdays to enter a restricted zone in the city center.[2] The London Congestion Charge (2003) and the Stockholm Congestion Tax (2007) were designed to reduce congestion, rather than pollution. Nevertheless, certain categories of low-emission or zero-emission vehicles were initially granted discounts or exemptions from payment.

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[1] See https://urbanaccessregulations.eu/. Low-emission zones restrict access to vehicles that meet minimum emission control standards, whereas zero-emission zones permit entry only to vehicles with no emissions.

[2] In 2012, EcoPass was replaced by Plan C which shifted emphasis from emissions reduction to congestion relief (Beria, 2015).

Several studies have assessed the environmental effects of the London, Stockholm, and Milan schemes.[3] All three schemes are estimated to have reduced emissions of NOx, particulate matter, CO_2, and other air-borne pollutants. As a percentage of total benefits, the estimated benefits from pollution reductions were the largest in Stockholm, partly due to high population densities in the inner city. However, in London reductions of emissions in the charging zone were partly offset by increases on the perimeter. Overall, the benefits to drivers from travel time savings and reliability improvements were found to dominate environmental improvements. In part, this can be attributed to technological constraints on toll differentiation, and in the case of London and Stockholm, the priority given to tackling congestion rather than pollution. The potential for more effective control of emissions has been improving. Knowledge of the physics and chemistry of pollution has been advancing. Road-pricing technology has been progressing as well, and the literature on emissions pricing has been growing rapidly.

The goal of this paper is to assess the potential of cordon tolls to reduce traffic congestion and emissions. For this purpose, we use a dynamic traffic network simulator that treats endogenously the trip-timing, mode, and route-choice decisions of travelers. As outputs, the simulator generates traffic flows, emissions, and an often-forgotten impact of road pricing: health effects disaggregated by location within an urban area. Tradeoffs between traveler welfare gains or losses, toll revenue, health costs, and overall welfare are also examined.

The paper is organized as follows. Section 2 sets the stage by reviewing the literature on environmental pricing of roads. Section 3 describes the basic elements of the simulator and the stylized urban area to which it is applied. Section 4 summarizes the effects of the various cordon tolling schemes on aggregate traveler utility and air pollution health costs. Section 5 examines at a more disaggregated level the effects of the tolls on individual welfare gains and losses. It also examines the tradeoffs between total welfare, toll revenues, and pollution costs. Section 6 summarizes the results, and identifies possible extensions.

2 LITERATURE REVIEW

There is an extensive literature in atmospheric and health sciences on vehicular emissions, pollution dispersion and decay, and the health effects of exposure to pollutants of various types.[4] This study belongs to a largely separate literature stream on the potential to reduce road traffic pollution using tolls.[5] Table 1 provides a partial list of studies that consider pricing of road-

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[3] See Beevers and Carslaw (2005) and Tonne et al. (2008) for London, Gibson and Carnovale (2015) for Milan, and Johansson et al. (2009) for Stockholm.

[4] See, for example, Khillare et al. (2004), Billionnet et al. (2012), Anenberg et al. (2017), and Requia and Koutrakis (2018).

[5] For reviews, see Santos et al. (2010), Anas and Lindsey (2011), Szeto et al. (2012), and Wang et al. (2018).

traffic emissions. Most of the studies also address pricing of traffic congestion.[6] A majority consider pricing in the form of tolls on individual links or roads. The rest consider either toll cordons or area charges. Vehicles pay a cordon toll if they cross into the charging area, out of it, or possibly in both directions. With an area charge, they pay either if they cross the boundary in either direction or if they travel wholly within the area.

Link tolls, cordons, and area charges all entail second-best pricing since they cover only part of the road network. A few studies have analyzed comprehensive marginal-cost-based tolls that support a system optimum — although this is not yet practical for large urban areas. A majority of studies examine flat tolls that do not vary by time of day. Most that do feature time-variation consider step tolls that change at discrete times (e.g., on the hour or half-hour). A few, such as Coria and Zhang (2017), assume that tolls vary continuously in order to track externalities precisely.

As far as dimensions of traveler behavior, nearly all studies include route choice and about half include mode choice. Relatively few incorporate choice of departure time. In terms of emissions, a few studies deal with an abstract pollutant, but most consider specific pollutants, with CO, CO_2, NOx, and particulate matter being the most common. Most environmental pricing and other types of studies compute pollutant emission rates using speed-emission functions. The effect of wind on the concentration and spatial dispersion of pollution is often disregarded. Most studies that do consider it employ Gaussian dispersion models.

Several lessons can be drawn from the literature. First, emissions vary with speed. For most pollutants, emissions per kilometer are a U-shaped function with a minimum at an intermediate speed. Second, the concentration of pollution declines relatively rapidly with distance from a source, and is negligible upwind of the source when a wind is blowing. Third, pricing schemes such as cordons that apply over broad areas tend to be more effective at curbing emissions than small schemes that can be avoided by rerouting, which can increase distance traveled and total emissions. Fourth, trip-timing decisions matter since they determine the evolution of traffic flows over time and space, as well as speeds and variations in speed, that all affect pollution emissions. Finally, vehicle emissions vary with fuel type, engine displacement and maintenance, and emissions control technology.

[6] Congestion pricing methodologies and technologies are reviewed in Tsekeris and Voß (2008), de Palma and Lindsey (2011), and Clements et al. (2020). Lehe (2019) describes the practice of congestion pricing.

Table 1: Selected studies of emissions pricing

Study			Type of tolls			Traveler Choices				Pollutant(s)	
	Congestion	Emissions	Links	Cordon/Area	Time varying	Route	Mode	Departure time	Other		Wind effects
Daniel and Bekka, 2000	x	x	x			x			No. of trips	CO, NO_x, HC	
Santos, 2004	x	x		x		x			No. of trips	CO, CO_2, CH_3, CH_4, NO_x, N_2O, PM, VOC	
Johansson-Stenman, 2006	x	x	x						No. of trips	Abstract	
Yin and Lawphongpanich, 2006	x	x	x			x				CO	
Li et al., 2007	x	x	x		x	x	x		Land use	Abstract	
Safirova et al., 2007	x	x	x	x	x	x	x		Location	CO, NO_x, VOC	
Namdeo, 2008	x	x		x		x			No. of trips	CO, CO_2, NO_x, PM_{10}, SO_2, VOC	
Jaber and O'mahony, 2009	x	x	x			x				Abstract	
Dimitriou et al., 2009	x	x	x			x			Residential/work location	CO_2	
Jakkula and Asakura, 2009	x	x	x			x				NO_x	
Guo and Hsu, 2010	x	x	First-best			x				Abstract	x
Yang et al., 2010	x	x	x			x				Abstract	
Sharma and Mishra, 2011	x	x	x			x				CO_2	
Li et al., 2012	x	x	x			x				CO	
Chen and Yang, 2012	x	x	x			x				Abstract	
Mishra and Welch, 2012	x	x	x			x	x		Destination, no. of trips	CO_2, NO_x, VOC	
Zhong et al., 2012	x	x	x		x	x		x		Abstract	
Friesz et al., 2013	x	x	x		x	x		x		Abstract	
Yang et al., 2014		x	x	x		x				CO, CO_2, NO_x	
Li et al., 2014	x	x		x					No. of trips	CO	
Wang et al., 2014a	x	x	x			x	x			CO_2	
Wang et al., 2014b	x	x	x			x				CO	x
Coria et al., 2015	x	x		x	x	x	x	x	No. of trips	NO_2, PM_{10},	
Kickhöfer and Kern, 2015		x	x		x	x	x			CO_2, NO_x, PM, SO_2, NMHC	
Dai et al., 2015	x	x	x			x	x			CO_2	
Kickhöfer and Nagel, 2016		x	First-best		x	x				CO_2, NO_x, PM, SO_2, NMHC	
Wen and Eglese, 2016	x	x	x		x	x		x		CO_2e	
Poorzahedy et al, 2016	x	x		x		x	x			CO	x
Ma et al., 2017	x	x	x		x	x				CO	
Rodriguez-Roman and Ritchie, 2017	x	x	x			x				CO, $PM_{2.5}$	x
Coria and Zhang, 2017	x	x	x		x		x	x	No. of trips	Abstract	
Kaddoura et al., 2017	x	x	First-best		x	x				CO_2, NO_x, $PM_{2.5}$, SO_2, NMHC	
Wu et al., 2017	x	x		x		x	x			CO, HC, NO_x	
Agarwal & Kickhöfer 2018	x	x	x		x	x	x			CO_2, NO_x, PM, SO_2, NMHC	
Xu and Sun, 2018	x	x	x			x	x			CO	
Rodriguez-Roman and Ritchie, 2019	x	x		x		x	x		Destination	NO_2	x
Rodriguez-Roman and Allahviranloo, 2019	x	x		x		x	x	x	No. of trips, destination	NO_2	x
Lv et al., 2019	x	x	x			x				CO	
Zhang et al., 2019	x	x	x	x		x					
Vosough et al., 2020	x	x		x		x	x		Destination	CO	x
This paper	x	x		x	x	x	x	x		CO, CO_2, NO_x, $PM_{2.5}$	x

As noted in Table 1, relatively few studies treat endogenously travelers' trip-timing decisions. Moreover, some of those that do so, such as Rodriguez-Roman and Allahviranloo (2019), consider distinct travel periods such as the morning peak hour, afternoon peak hour, and non-peak hours, and use static traffic assignment methods to compute equilibrium. Neither static models nor dynamic models with discrete (and broad) time periods can capture the evolution of traffic flows and variations in speeds over time scales short enough to adequately track variations in congestion delays and pollution emission rates. Such models also lack the time dimension to account for the fact that step tolls can induce delays or surges in vehicle departures when tolls rise or drop. In addition, static models exclude trip-timing preferences and the resulting schedule delay costs that arise when individuals travel earlier or later than desired. Schedule delay costs can contribute as much to the generalized cost of travel as do travel delays that are the only time-related cost included in static models. Suitably chosen time-varying tolls can alter favorably the trade-off between travel time delays and the numbers of car trips (Vickrey, 1969; Arnott et al., 1990) as well as smooth variations in travel speed that contribute to vehicle emissions. Static models cannot capture these phenomena. Indeed, Lo and Szeto (2005) have shown that static models can seriously misrepresent the effects of tolls, and even lead to choices of tolling schemes that exacerbate congestion.

To treat faithfully the dynamic aspects of travel demand and supply, we use the dynamic traffic network simulator METROPOLIS. It treats endogenously individual departure-time, travel mode, and route-choice decisions. Individuals differ in their idiosyncratic preferences for departure time and mode. Traffic flows are modeled at a mesoscopic scale, and congestion is assumed to take the form of queuing delays on links. METROPOLIS is supplemented by an air-quality module that features multiple pollution sources and receptors, and a Gaussian dispersion model that accounts for wind speed and direction. We apply the combined model to a morning peak travel period on a stylized urban road network featuring arterial links and ring roads, and assess the potential for single and double cordon tolls to redress emissions and congestion externalities. The levels of the cordon tolls are chosen to maximize welfare as measured by traveler utility plus toll revenues minus air pollution health costs. Among the questions we address are: How much do optimal cordon toll levels and locations differ from cordons designed to target congestion alone? How large are the benefits from reducing emissions compared to congestion relief? How much is gained by levying step tolls rather than flat tolls? How does wind speed affect optimal tolls and pollution levels across a study area? Who gains and who loses from tolling, and how do the welfare effects vary with location?

Our analysis differs from that of recent studies in some important respects. Similar to Coria and Zhang (2017), our model features endogenous departure times and pollution dispersion that varies by time of day. However, individual drivers in their model travel at a constant speed throughout their trips. Their model also features only one origin and destination, and there is no route choice except for brief consideration of a toy network with one origin and one destination connected by two routes. Rodriguez-Roman and Allahviranloo (2019) go further than we do in tracking the movements of individuals in order to measure their cumulative exposure to pollution. Yet, as noted above, they employ only three time periods per day and solve for equilibrium using static traffic assignment. Vosough et al. (2020) study a predictive pricing regime in which the level of a flat cordon toll is adjusted daily in response to rolling forecasts of wind speed. Their model excludes departure-time decisions. Moreover, instead of using a Gaussian dispersion model to describe the evolution of air quality, they employ a Box model (EPA, 2021a) in which the concentration of pollution is uniform within a rectangular prism enclosing the city.

The stylized urban road network, origin-destination matrix, and travel demand preferences, in this paper, are the same as those used by de Palma et al. (2005) to study congestion pricing. Our analysis builds on theirs by including vehicular emissions of CO, CO_2, NOx, and particulate matter, and studying the use of tolls to simultaneously address congestion and pollution externalities. Their analysis of tolling schemes goes further than ours in considering area tolls and comprehensive tolls that support an approximate system optimum. However, they limit attention to a cordon toll on one particular ring road, whereas we evaluate three alternative single cordons as well as double cordons. As explained in Section 3, our study also differs from de Palma et al. (2005) in terms of computation methods and the timing of the step tolls.

Double cordons have not yet been implemented anywhere. Proposals were made for Edinburgh and Manchester, but turned down by referendums in 2008. Nevertheless, several studies have assessed the pros and cons of double cordons vis à vis single cordons. As discussed in Section 4, they find that a double cordon can yield substantially higher benefits than a single cordon. By contrast, on our stylized network, double cordons do not add greatly to efficiency although they do reduce spatial disparities in individual gains and losses.

Before turning to the model, it is worth explaining why the analysis is restricted to cordon tolls. As noted earlier, pricing schemes that encompass broad areas have more potential to reduce emissions than link-based schemes that may displace, rather than suppress, pollution. Cordon tolls have been implemented in Singapore, Stockholm, Milan, and Gothenburg. The technology is reliable, and it is relatively easy for drivers to pay the toll (Maruyama and Harata, 2006). Area schemes are more complex to set up since vehicle movements have to be monitored within the charging area as well as at entrances and exits. The London Congestion Charge is the only existing area scheme, and it suffers from a high ratio of operating costs to toll revenues collected. de Palma et al. (2005) found that area tolls yield somewhat higher welfare gains for pricing congestion than the corresponding cordon tolls, but also much higher toll revenues and less favorable welfare-distributional effects. de Palma et al. (2005) also computed an approximate system optimum by levying step tolls on each link of the network in order to eliminate queuing without reducing traffic flows below link capacity. For two reasons, such a strategy is not optimal when pollution is present. First, on all the links in our study network, CO_2 emissions increase with speed at free-flow speeds so that eliminating queuing delays comes at a cost of greater pollution. The same is true of NO_x emissions on most of the arterial links of the network. Second, and more important, even if there is no congestion, it is desirable to shift some trips from cars to public transport in order to reduce emissions of all the pollutants.

3 THE MODEL

3.1 Travel demand and supply

The dynamic traffic network simulator METROPOLIS treats endogenously individual mode, departure-time, and route-choice decisions.[7] Travelers choose between driving (hereafter sometimes referred to as the car) and taking public transport. Those who choose car select a departure time. Route choice is governed by a heuristic based on minimization of travel time. The generalized systematic cost of a car trip departing at time t is given by the equation

$$C_A(t) = \alpha T(t) + \beta Max\left(t^* - \Delta - t - T(t), 0\right) + \gamma Max\left(t + T(t) - t^* - \Delta, 0\right),$$

where $T(t)$ is travel time, α is the unit cost of travel time, t^* is desired arrival time, Δ is the half-width of an on-time arrival window, β is the unit cost of arriving early, and γ is the unit cost of arriving late. Following convention, the costs of arriving early or late are called *schedule delay costs*. Travelers differ in their desired arrival times and idiosyncratic preferences for mode and departure time.

The model is exclusively applied here to peak-period morning trips during the time window 6:00 - 11:00 am. The mean desired arrival time is set to 8:00 am, and the standard deviation to 20 minutes. These and other parameter values are listed in Table A1 of the appendix. They are the same as in de Palma et al. (2005), except converted from dollars to euros to roughly account for inflation.

Trips are made on a stylized urban road network, shown in Figure 1, used by de Palma et al. (2005) to study congestion pricing. The road network consists of four ring roads and eight arterial roads. Links running inwards from Ring i to Ring i-1 are labeled *Ini*, and links running outwards adjacent to them are labeled *Outi*, i=1,2,3,4. The CBD is called Ring 0. Link capacities

[7] de Palma and Marchal (2002) describe the architecture of the traffic simulator we used.

and free-flow travel speeds are listed in Table A2 of the appendix. Congestion takes the form of vertical queuing, as in Vickrey (1969). Traffic signals are not modeled, so no additional delays occur due to conflicting traffic movements at intersections. The generalized systematic cost of a trip by public transport is exogenous and independent of time of day, which is reasonable if service frequency is high and public transport is free of crowding. Residences and workplaces are located at zones, each joined to one of the 33 intersection nodes by congestion-free connectors. Each zone houses 8,000 commuters so that the total number of travelers is 264,000. As explained in the appendix, the number of trips between each pair of zones is a decreasing function of the free-flow car travel time between the zones.

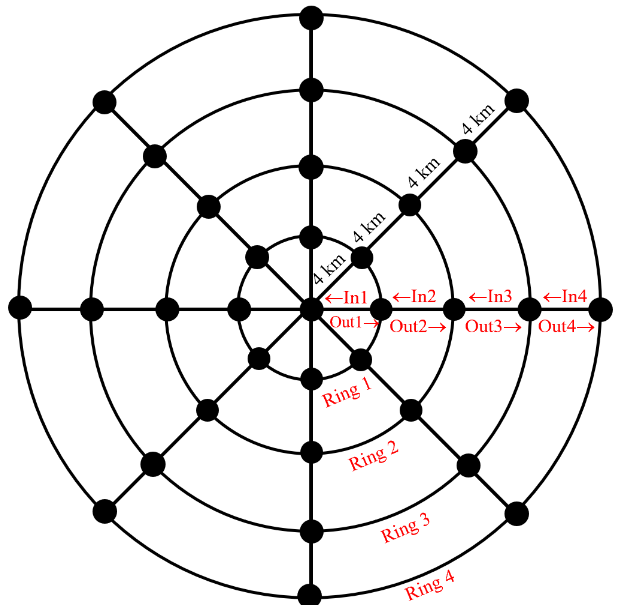

Figure 1: The circular city road network

3.2 Emissions

Vehicle emissions on each road link are calculated for CO, NO_x, $PM_{2.5}$, and CO_2. CO, NO_x, and $PM_{2.5}$ are treated as pollutants with adverse health effects. CO_2 is treated as a gas with adverse environmental effects due to its contribution to global warming. For brevity, it is referred to as a pollutant as well.[8] The external unit costs of each pollutant are listed in the appendix. Except for $PM_{2.5}$, emissions per km depend on travel speed. The functional relationships are listed in the appendix. As shown in Figure 2, emission rates per vehicle kilometer traveled (veh-km) of CO_2

[8] In 2009, the US Environmental Protection Agency declared CO_2 to be a pollutant that poses danger to human health. It is modeled here as a negative externality, but excluded from the calculation of local health effects.

and NO_x are U-shaped functions of speed with respective minima at 42 km/h and 61 km/h. CO emissions per km also reach a minimum, but at a much higher speed. As reported in Table A2, speed limits are set to 50 km/h on the ring roads, *In1* links, and *Out1* links; and 70 km/h on the other arterial links. Thus, travel speeds can be above or below the minimum-emission levels of CO_2 and NO_x. As reported in later sections, without tolls average travel speed on the network is about 41 km/h. Depending on the tolling scheme, tolls increase average speeds by up to 8 km/h. Therefore, tolling tends to increase CO_2 emissions per veh-km, and reduce NO_x and CO emissions per veh-km. However, tolling also induces some travelers to stop driving and switch to public transport. It also tends to reduce total veh-km on heavily congested links near the city centre where population density is high. Hence, tolling has the potential to reduce the costs of emissions substantially.

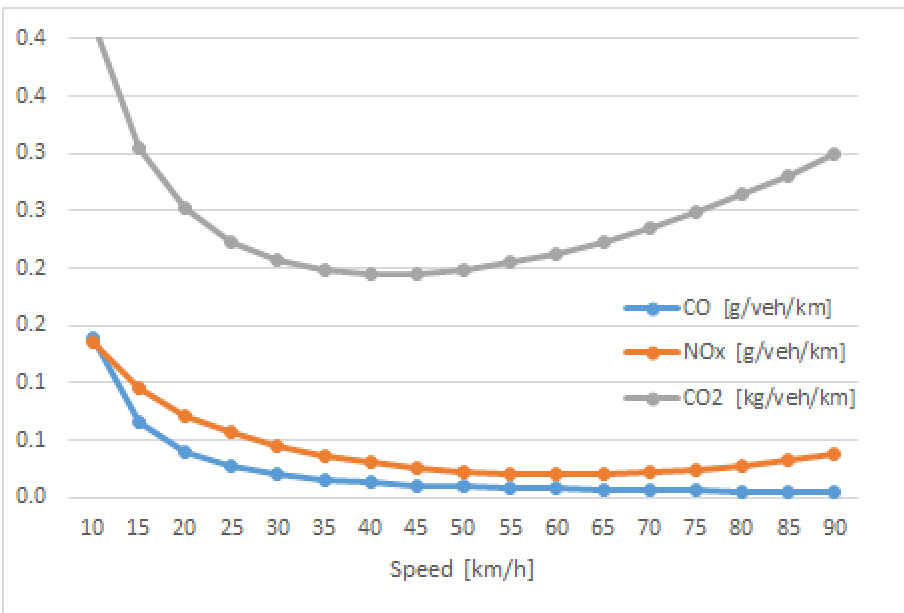

Figure 2: Emissions-speed curves for CO, NO_x, and CO_2

The four pollutants are assumed to be emitted at 1,536 point sources located every 500 meters along each link. Exposure to pollution is calculated at 1,536 receptors, distributed with increasing concentration toward the city center, representing a city of 1,002,760 individuals.

Propagation of emissions is described by a three-dimensional Gaussian plume dispersion model.[9] Consider a source at the origin, and a receptor with Cartesian coordinates (x, y, z) where the x-

[9] The Gaussian plume model is a standard approach for studying the transport of airborne contaminants (Zannetti, 1990). The model can account for wind speed and direction, atmospheric turbulence, air temperature, and other meteorological conditions. It is used for the design of control strategies by the US Environmental Protection

axis points in the direction of the wind, y is perpendicular to the wind direction, and z is the elevation of the receptor. The concentration, E, of any pollutant at the receptor is given by the equation:

$$E(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)\right),$$

where Q is the emission rate at the source [*kg/sec*], u is wind speed [*m/sec*], σ_y (resp. σ_z) is the standard deviation of concentration in the y (resp. z) direction [m], and H is the height of the emission source [m]. Parameters σ_y and σ_z depend on x according to the formulas $\sigma_y = ax/(1+bx)^c$ and $\sigma_z = dx/(1+bx)^e$. Parameters a, b, c, d, and e are coefficients that depend on weather conditions. A neutral stability class or Pasquill category D is assumed, for which a = 0.0787, b = 0.0014 [m^{-1}], c = 0.1350, d = 0.0475, and e = 0.465. Parameters a, c, d, and e are dimensionless. Parameter values are taken from Green et al. (1980); they are also used in Hsu and Guo (2005).

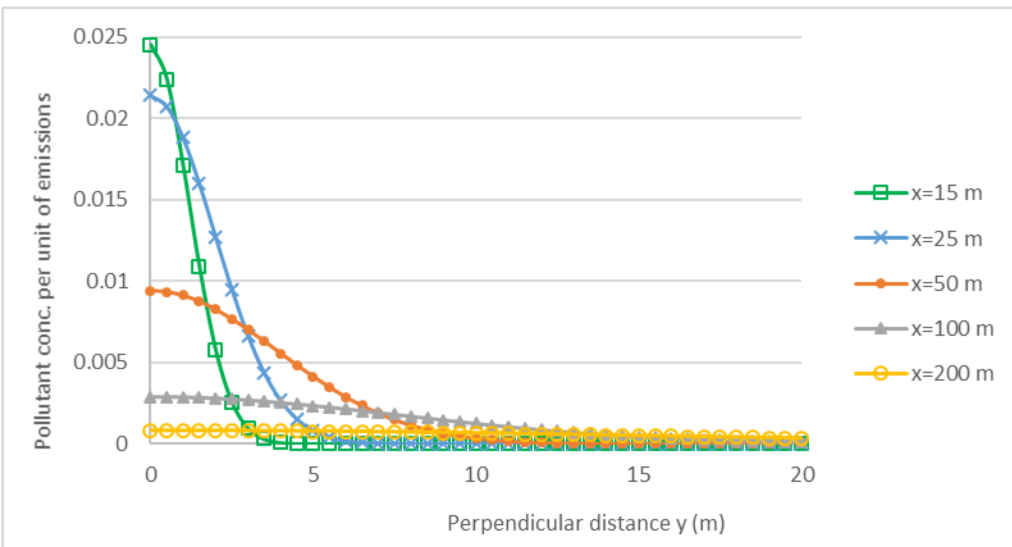

Figure 3: Pollutant concentration as a function of distance downwind (x) and perpendicular distance from wind direction (y)

The formula for $E(x,y,z)$ is applicable when wind speed and direction are constant over an interval of time. The formula is an approximation that is accurate only for speeds above about 0.5 m/s. For the base case of the simulations, a wind speed of 3 m/s is assumed. [10] All emissions

Agency. It has also been applied in many studies of road traffic pollution; see, for example, Lin and Ge (2006), Sahlodin et al. (2007), Zhang et al. (2010), and Rehimi and Landolsi (2013).

[10] Average wind speeds vary seasonally. For London, Stockholm, and Milan, the range is 1.65-5.14 m/s (https://weatherspark.com). The base-case value of 3 m/s adopted here is within this range.

are assumed to occur at an elevation of $H = 0.5$ m (the approximate height of a vehicle tailpipe), and all receptors are at an elevation of $z = 1.5$ m (the approximate height of a person's head when standing at ground level). Because the source and receptor are at different heights, maximum concentration does not occur at the origin (x,y) = (0,0), but downwind at (x,y) = (16.76,0), when wind speed is 3 m/s. Concentration directly downwind drops to one tenth of its maximum value at (x,y) = (108.4,0). As shown in Figure 3, concentration falls rapidly with perpendicular distance from the downwind direction, dropping to one tenth of its highest value at $y = 8.4$ m for $x = 50$ m, at $y = 16.6$ m for $x = 100$ m, and at $y = 32.7$ m for $x = 200$ m. Nevertheless, despite the rapid reduction in concentration with perpendicular distance from a source, since emissions are generated throughout the road network, air is polluted at a majority of the receptors.

Due to the number of iterations of METROPOLIS required to reach a steady state, and the large number of source-receptor pairs, solving for the spatial distribution of pollution is time-intensive. Three assumptions are made to simplify calculations. First, the population exposed to pollution does not change during the simulation period. Thus, population movements are ignored, and so is the exposure of drivers to pollution during their trips. Second, pollution does not affect travel decisions except insofar as pollution levels influence the choice of toll levels. Third, the health effects of emissions are proportional to pollution concentration. Linear exposure-response functions are widely used in the literature; see, for example, McCubbin and Delucchi (2003), Muller and Mendelsohn (2007), Rabl et al. (2014), and Rodriguez-Roman and Ritchie (2017). The US Environmental Protection Agency also supports the use of linear exposure-response functions for the effects of particulate matter on humans (EPA, 2013; EPA, 2021b). These three assumptions reduce computation time because the effect of a unit of emissions from any source on any receptor is independent of all other emissions, and needs to be calculated only once for a given wind speed.

3.3 Optimal tolling

In METROPOLIS, vehicles pay tolls when they enter links. The tolling schemes analyzed here are single or double cordons located on Ring Roads 1, 2, or 3.[11] Drivers pay a cordon toll on Ring Road *i* if they drive inwards across it on one of the eight arterial links labeled *Ini* in Figure 1. They do not pay the toll if they drive around the ring road. Tolls are chosen to maximize welfare (W) as measured by consumers' surplus (CS) plus toll revenues (TR) minus air pollution health costs (HC):

$$W = CS + TR - HC .$$

[11] Cordon tolls on Ring Road 4 were found to be relatively ineffective, and hence excluded from consideration.

The welfare gain (TG) from tolling relative to no-toll equilibrium is the change in welfare:

$$TG = \Delta W = \Delta CS + \Delta TR - \Delta HC \,.$$

Two types of tolls are considered: *flat tolls* that do not depend on time of day, and *step tolls* that change in discrete steps. Step tolls are assumed to vary in half-hour intervals over the period 6:00 am - 8:30 am when most trips are made.[12] Toll levels in the five intervals are optimized jointly. Optimal flat and step tolls are derived for the single cordons, whereas only flat tolls are derived for the double cordons. One reason for omitting step tolls for double cordons is that motorists might find it difficult to make optimal departure-time decisions with time-varying tolls on two cordons. Another reason is that jointly optimizing toll schedules on two cordons would be computationally quite burdensome.

Deriving optimal tolls analytically is straightforward in static models when all links are tolled, and congestion is the only externality. It is intractable in the model here which features tolling of only some links, pollution as a second externality, departure-time decisions, and traffic dynamics. It is instructive to briefly review the implications of each complication.

Second-best pricing on part of a road network: The complexities of second-best pricing on subsets of links are well known.[13] The main lessons can be framed in terms of substitutes and complements. If two links or routes are alternatives, and only one is tolled, some traffic will be diverted to the un-tolled link and exacerbate congestion (and possibly other externalities) on it. Second-best pricing, therefore, calls for setting lower tolls than under first-best pricing when all links are tolled. For example, imposing a cordon toll on Ring Road 2 will induce some motorists to avoid the cordon, and drive around Ring Road 2. If, instead, two links are complements in the sense that both are traversed on a given trip, then tolling one link will reduce congestion on the other. Second-best pricing then calls for a higher toll than under first-best pricing. For example, a toll cordon on Ring Road 2 will tend to alleviate congestion on links of type *In3* and *In4* which feed traffic through the cordon into the city center. A priori, it is unclear whether this benefit outweighs the disadvantage of increasing congestion on Ring Road 2.

Pricing congestion and emissions: Setting tolls to reduce emissions as well as congestion is complicated by the fact that emissions depend on speed, which depends on congestion. As Johansson-Stenman (2006) explains, the optimal toll includes not only a standard congestion

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[12] Most existing systems that employ time-of-day pricing follow this practice. See, for example, Singapore (https://www.onemotoring.com.sg/content/onemotoring/home.html), Stockholm and Gothenburg (https://transportstyrelsen.se/en/road/Congestion-taxes-in-Stockholm-and-Goteborg/congestion-tax-in-stockholm/hours-and-amounts-in-stockholm/), State Route 91 in California (https://www.octa.net/91-Express-Lanes/Toll-Schedules/), and Highway 407 in Canada (https://on407.ca/en/tolls/rate-charts/highway-407-toll-rates.html).

[13] See Small and Verhoef (2007, Section 4.2).

charge and a standard pollution charge, but also a term that accounts for how the congestion delay caused by a vehicle affects the pollution emitted by other vehicles.

Dynamic pricing: Carey and Srinivasan (1993) derive optimal dynamic congestion tolls on a general network. They show that the optimal toll includes not only a contemporaneous component, which depends on the instantaneous congestion level, but also an intertemporal component that is positive if congestion is increasing, and negative if it is decreasing. Coria et al. (2015) extend the analysis of Carey and Srinivasan (1993) to dynamic pricing of congestion and emissions together on a single link. The optimal toll and corresponding flow are determined by a differential equation that cannot be solved analytically even for a single link, let alone a network with tolls on some links but not others.

In summary, optimal tolls cannot be derived analytically in the setting adopted here. However, all the complications listed above are implicitly accounted for in the process of identifying tolls numerically through repeated simulations.[14] The next section successively describes the equilibria obtained with no tolls, optimal flat tolls, and optimal step tolls.

4 TOLLING REGIMES

4.1 No tolls

Summary statistics for the equilibrium with no tolls are listed in Table 2. The statistics are similar to those reported in de Palma et al. (2005) except for pollution which is not in their model. About 70% of trips are made by car. As measured by the congestion index, trips take a little over 40% longer on the route chosen than under free-flow conditions. Flows are generally heaviest on the inbound arterials, intermediate on the outbound arterials, and lowest on the ring roads. Because arriving late is quite costly, most drivers arrive either early or on time. The average consumer's surplus is negative because travelers have to make a trip by car or public transport, and the benefits of travel are not quantified. Daily pollution costs of €299,578 are dominated by NO_x and $PM_{2.5}$ emissions. Figure 4 shows a two-dimensional heat map of annual per-capita health costs, assuming 250 trips per year. With a wind blowing at 3 m/s from the west, the costs are much higher in the eastern (i.e., downwind) half of the city than the western (i.e., upwind) half.[15] The highest costs are at receptors near the city center that are close to heavily-

[14] Tolls are optimized using a response surface procedure employed in de Palma et al. (2005). The simulations were performed using a laptop with an Intel® Core™ i5-7300U CPU with a rated speed of 2.60 GHz, a maximum operating frequency of 2.71GHz, and 8 GB RAM. A simulation comprising 75 iterations takes about seven minutes. Post-processing the output to calculate emission costs takes another two to three minutes.

[15] Since the predominant wind direction varies by time of year (https://weatherspark.com), the annual incidence of health costs would be less imbalanced than Figure 4 indicates.

used roads. Costs are also high near sections of Ring Roads 1, 2, and 3, and near sections of the radial roads.

Table 2: Summary statistics for the no-toll equilibrium (wind speed 3 m/s)

Statistic	Value	Definition
Car share	0.698	Fraction of trips made by car
Peak period duration	1.3 h	Starting when 10% of drivers have reached their destination, and ending when 90% have reached their destination
Speed	40.1 km/h	Mean car travel speed
Trip duration	22.3 min	Mean car travel time
Trip distance	14.9 km	Mean car trip distance
Congestion index	40.6%	Congestion delay as percentage of free-flow travel time on same route
Free-flow travel cost	€2.65	Mean free-flow travel time cost by car
Schedule delay cost	€1.46	Mean auto schedule delay cost
Consumer's surplus	€-4.40	Mean user surplus (for car and public transport trips)
Early arrivals	59.3%	Percentage of drivers arriving early
On-time arrivals	29.0%	Percentage of drivers arriving within desired arrival-time window
Late arrivals	11.7%	Percentage of drivers arriving late
Total vehicle km	$2.75x10^6$	Total kilometers traveled by car
CO cost	€1,760	Total health cost of carbon monoxide
NO_x cost	€132,739	Total health cost of nitrogen oxide emissions
$PM_{2.5}$ cost	€128,068	Total health cost of particulate matter with diameter less than 2.5 μm
CO_2 cost	€37,011	Global cost of carbon dioxide emissions
Total	€299,578	Total pollution cost

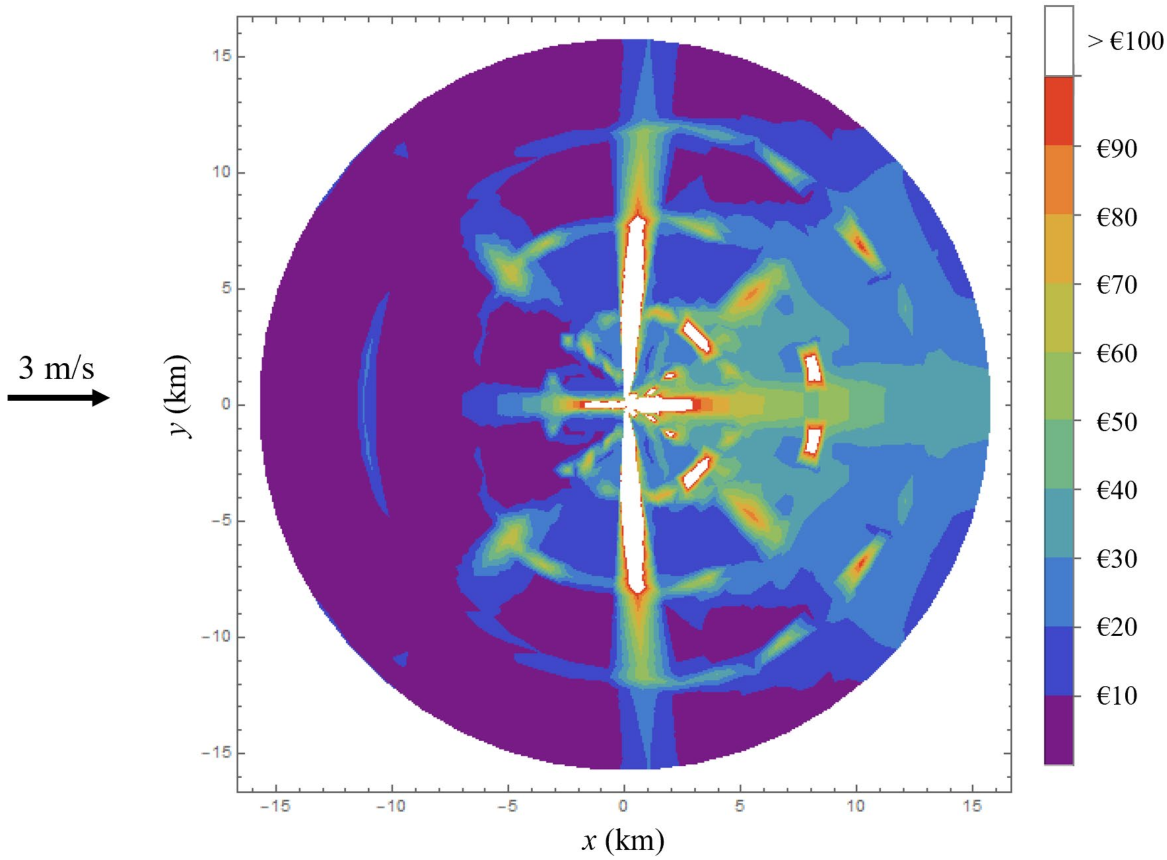

Figure 4: Annual per-capita health costs with no tolls

4.2 Flat tolls

Flat tolls are levied on Ring Roads 1, 2, and/or 3 to form single or double cordons. A cordon toll around Ring Road *i* is called *Cordon i*, and a double cordon on Ring Roads *i* and *j* is called *Cordon i&j*. Tolls that account for both congestion and emissions will be called *combined tolls*. To identify how emissions affect optimal toll levels and welfare gains, tolls that internalize only congestion externalities are also computed. These tolls will be called *congestion tolls*.

Table 3 lists summary statistics for the congestion flat tolls. All three single cordon tolls reduce the car share of trips, the congestion index, total veh-km, and average travel time per trip. However, except for Cordon 3, average trip distance increases, which partially offsets the effect of a shift toward public transport in reducing veh-km. Average speed rises, but despite reductions in travel time, average consumer's surplus falls by €0.31 to €0.64 per trip.[16] The annual welfare

[16] The standard errors for per-capita consumer's surplus, per-capita toll revenue, per-capita welfare gain, and ratio of welfare gain to revenue, *G*/*R*, are computed using the same general procedure as in de Palma et al. (2005). This entails recording each statistic for the last 25 iterations of a simulation, computing the standard deviation, and assuming serial independence between iterations so that the standard deviation can be divided by $\sqrt{25}$.

gain per-capita, G, is calculated assuming 250 days of travel per year. The gain accounts for the costs borne by travelers net of toll revenue, but excludes the costs of pollution. Cordon 2 has the highest toll (€5.34), and yields both the highest annual per-capita welfare gain (€41.10) and the highest ratio of welfare gain to revenue collected, G/R (0.24). The annual per-capita welfare gain from Cordon 1 of €18.00 is quite small. The total daily welfare gain from reduced pollution is tallied at the bottom of Table 3. In contrast to the results for traveler costs, the gain in reduced pollution from Cordon 1 is the highest of the three single cordons.

Table 3: Summary statistics for congestion flat tolls

		No toll	Cordon 1	Cordon 2	Cordon 3	Cordon 1&2	Cordon 1&3	Cordon 2&3
Toll levels [€]	Ring 1	-	3.29	-	-	0.94	2.07	-
	Ring 2	-	-	5.34	-	3.67	-	4.19
	Ring 3	-	-	-	4.42	-	3.51	1.81
Car share		0.698	0.676	0.653	0.654	0.658	0.648	0.644
Speed [km/h]		40.12	42.41	44.62	42.88	43.74	44.44	44.64
Trip duration [min]		22.31	21.52	20.29	20.55	20.65	20.18	20.00
Trip distance [km]		14.92	15.21	15.09	14.69	15.06	14.95	14.88
Congestion index [%]		40.58	31.68	23.79	30.33	26.48	25.14	23.77
Consumer's surplus/day [€]		-4.40 $\pm$0.015	-4.71 $\pm$0.005	-4.91 $\pm$0.022	-4.93 $\pm$0.026	-4.86 $\pm$0.018	-5.04 $\pm$0.017	-5.03 $\pm$0.021
Total vehicle km/day [10^6]		2.75	2.72	2.60	2.54	2.62	2.56	2.53
Welfare gain/capita-yr (G) [€] (excludes health costs)		-	18.00 $\pm$1.496	41.10 $\pm$7.764	30.58 $\pm$7.654	42.09 $\pm$5.971	34.81 $\pm$5.474	46.96 $\pm$7.039
Revenue/capita-yr (R) [€]		-	94.92 $\pm$0.504	169.38 $\pm$2.241	162.76 $\pm$1.144	157.46 $\pm$1.515	194.13 $\pm$1.262	204.27 $\pm$1.822
G/R		-	0.19 $\pm$0.016	0.24 $\pm$0.041	0.19 $\pm$0.045	0.27 $\pm$0.035	0.18 $\pm$0.027	0.23 $\pm$0.031
Rank by G		-	6	3	5	2	4	1
Drop in total pollution cost/day [€]		-	87,891	79,110	33,418	84,957	91,770	77,233

Turning to the double cordons, Table 3 reveals that Cordon 2&3 yields the highest welfare gain of all six schemes. However, the welfare gain from each double cordon is much less than the sum of the welfare gains from the constituent cordons in isolation. One way to measure the efficacy of a double cordon comprising cordons A and B is the index $R_{AB} \equiv \left(G_{A+B} - G_A\right)/G_B$, where A can be the smaller cordon, the larger cordon, or the cordon with the larger welfare gain. If the welfare gains from the two cordons are additive, then $G_{A+B} = G_A + G_B$, and $R_{AB} = 1$ regardless of the choice of A. If the welfare gains are subadditive, $R_{AB} < 1$, and if they are superadditive, $R_{AB} > 1$. If A is the cordon with the larger welfare gain, the index works out to $R_{12} = 0.055$, $R_{13} = 0.235$, and $R_{23} = 0.192$. These small values indicate that the incremental benefits from the double cordons are rather small. Not surprisingly, R_{13} is the largest because cordons 1 and 3 are the furthest apart, and intercept the most disjoint sets of trips.

These results contrast with those of some earlier studies that examined the effects of tolling schemes on real-city networks rather than stylized networks such as the one used here. May et al. (2002) evaluate a cordon around Central London, and a second cordon in Inner London. They find that adding the second cordon increases the economic benefits by about 50%. Yang and Huang (2005) obtain similar results for the Shanghai road network. Santos (2004) assesses cordon pricing for eight English towns and concludes that double cordons yield on average nearly double the benefits of a single cordon.[17] Safirova et al. (2007) calculate the welfare gains from a downtown cordon for Washington D.C., a larger cordon located on the Beltway (defined by I-495 and I-95), and a double cordon comprising both. The index of efficacy that we adopt works out to 0.530 for their congestion tolls, and to 0.521 for their combined tolls, which are set to internalize not only congestion, air pollution, and climate change externalities, but also accidents, oil dependency, and noise. One reason for the large efficiency values that Safirova et al. (2007) obtain is that their downtown cordon encloses a very small area compared to the Beltway cordon.

Table 4 provides summary statistics for the combined tolls. As expected, all tolls are higher than the corresponding congestion tolls. Consequently, reductions in the car share of trips, congestion, travel times, and veh-km are larger, although the relative changes are similar to those for the congestion tolls. Including the gains from reduced pollution, total welfare gains and welfare gains per unit of revenue collected are both much higher than for the congestion tolls. Depending on the cordon scheme, the gains from reduced pollution range from 20% to 50% higher than for the congestion tolls. The rankings of the schemes change, with Cordon 1 now outperforming Cordon 3, and Cordon 1&3 outperforming Cordon 2&3. These rankings change because Cordon 1 discourages motorists from driving in the city center where emissions and population are concentrated, and the health costs of pollution are highest as shown in Figure 4. The indexes of efficacy for the combined double cordon tolls are $R_{12} = 0.029$, $R_{13} = 0.410$, and $R_{23} = 0.108$. The values of R_{12} and R_{23} are even smaller than for the congestion tolls, while the value of R_{13} is larger.

[17] However, Santos concludes that when the costs of additional charging points are accounted for, adding a second cordon might not be cost-effective.

Table 4: Summary statistics for combined flat tolls

		No toll	Cordon 1	Cordon 2	Cordon 3	Cordon 1&2	Cordon 1&3	Cordon 2&3
Toll levels [€]	Ring 1	-	4.07	-	-	1.60	3.31	-
	Ring 2	-	-	8.41	-	5.26	-	6.93
	Ring 3	-	-	-	6.63	-	3.95	2.24
Car share		0.698	0.672	0.628	0.631	0.639	0.638	0.618
Speed [km/h]		40.12	42.98	47.45	44.27	44.94	45.38	47.90
Trip duration [min]		22.31	21.28	19.10	19.76	20.26	19.73	18.68
Trip distance [km]		14.92	15.24	15.10	14.58	15.17	14.92	14.92
Congestion index [%]		40.58	29.74	16.02	25.86	23.73	22.34	14.81
Consumer's surplus/day [€]		-4.40 ±0.015	-4.72 ±0.006	-5.09 ±0.004	-5.11 ±0.026	-5.07 ±0.006	-5.15 ±.001	-5.23 ±0.003
Total vehicle km/day [10^6]		2.75	2.70	2.50	2.43	2.56	2.51	2.43
Welfare gain/capita-yr (G) [€]		-	126.44 ±1.904	137.91 ±1.182	68.59 ±8.168	141.52 ±1.658	154.57 ±0.666	145.31 ±0.775
Revenue/capita-yr (R) [€]		-	108.23 ±0.618	203.21 ±0.126	199.46 ±1.639	199.30 ±0.435	230.09 ±0.449	242.18 ±0.161
G/R		-	1.17 ±0.013	0.68 ±0.006	0.34 ±0.037	0.71 ±0.007	0.67 ±0.002	0.60 ±0.003
Rank by G		-	5	4	6	3	1	2
Drop in total pollution cost/day [€]		0	105,413	114,107	48,754	117,970	117,769	116,280

The most beneficial combined toll, Cordon 1&3, reduces the total costs of pollution by €117,769: a 39.3% reduction from the costs with no toll of €299,578. Yet, veh-km drop by less than 9%. The reduction in pollution costs is disproportionately large because traffic flows drop sharply on the inner arterial links where population density is high. This is evident in Figure 5, where the annual per-capita health costs decline most strongly near the city center. The costs also decline moderately in most of the eastern downwind half disk of the city. However, costs rise slightly on a few segments of Ring Roads 1, 2, and 3 as travelers avoid the tolls by driving around the ring roads rather than crossing them inwards. Costs also rise slightly in much of the western upwind half disk. This is because the tolls on Ring Roads 1 and 3 deter some travelers from driving inwards across their boundaries. Some of these travelers switch to transit. Other travelers who do not cross the ring roads take advantage of the reduction in traffic by driving more. At some locations in the western half disk, the net increase in traffic is positive, causing emissions to rise.[18] As explained in Section 3.3, these two effects can be understood as the

[18] Similarly, Rodriguez-Roman and Ritchie (2019) and Rodriguez-Roman and Allahviranloo (2019) find that an area charge induces local increases in pollution. Zhang et al. (2019) study a variety of tolling schemes, and

unintended consequences of second-best pricing on substitutes and complements, respectively. Yet, despite the slight increase in costs in parts of the city, the overall reduction is large and several times greater than the decline in veh-km. This demonstrates that distance driven can be a poor indicator of the health effects of vehicle emissions.

The results in Table 4 are obtained with a wind speed of 3 m/s. Table 5 shows optimal combined toll levels for wind speeds of 1 m/s and 6 m/s. Health costs are greater at lower wind speeds because pollution concentrations vary inversely with wind speed. Consequently, as wind speed drops, the optimal combined tolls increase and diverge progressively from the optimal congestion tolls.

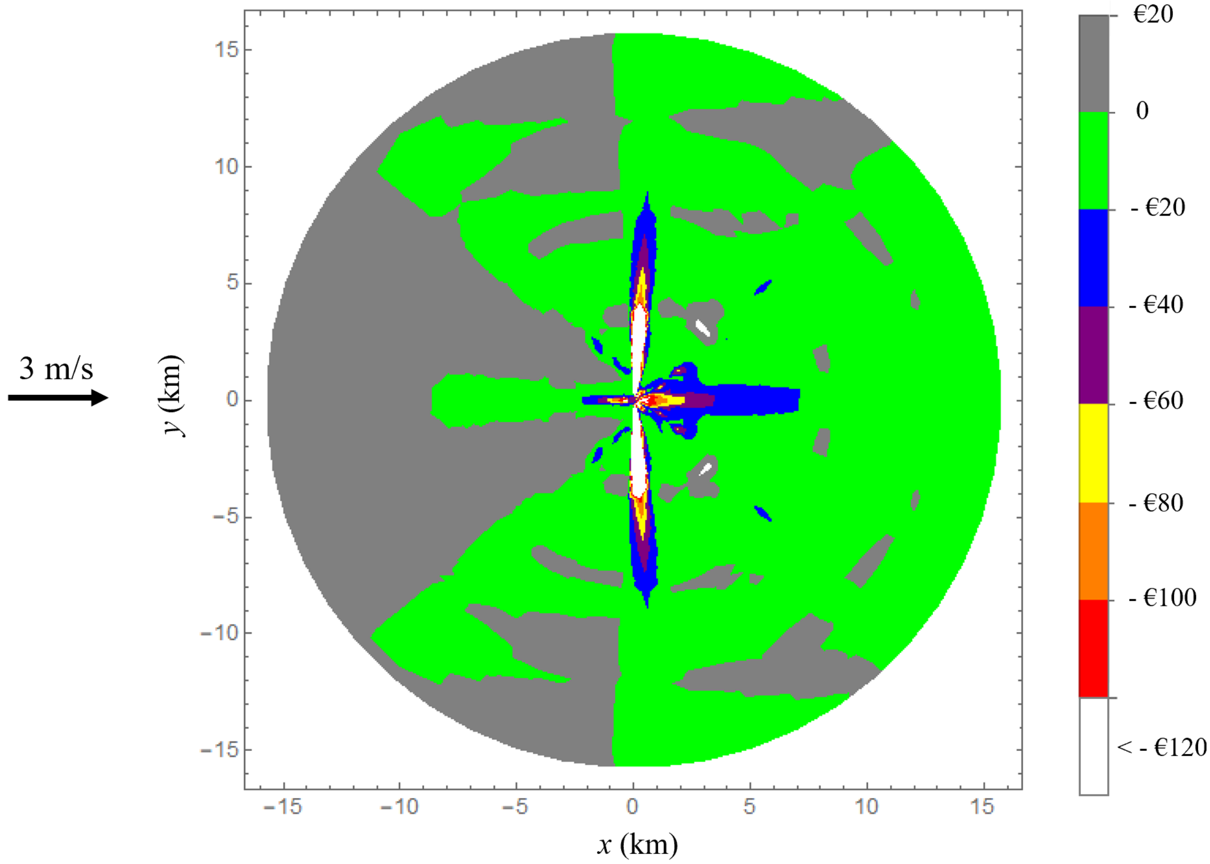

Figure 5: Change in annual per-capita health costs with combined flat Cordon 1&3 toll

determine that while most of them reduce emissions within the congestion zone, they increase emissions outside the zone as well as total emissions.

Table 5: Combined flat tolls for different wind speeds

Toll [€]	Cordon 1	Cordon 2	Cordon 3	Cordon 1&2	Cordon 1&3	Cordon 2&3
Congestion	3.29	5.34	4.42	0.94 & 3.67	2.07 & 3.51	4.19 & 1.81
Combined 6 m/s	3.70	6.96	5.50	1.56 & 4.37	2.75 & 3.74	5.74 & 1.88
Combined 3 m/s	4.07	8.41	6.63	1.60 & 5.26	3.31 & 3.95	6.93 & 2.24
Combined 1 m/s	5.53	10.56	11.40	3.46 & 5.92	4.72 & 5.05	8.10 & 5.00

4.3 Step tolls

As noted above, step tolls were computed only for the single cordons. The congestion step tolls are limited to the 6:30 – 8:30 period since there is almost no congestion on any links before 6:30 or after 8:30. There is also little traffic after 8:30. However, over 3% of link flows during the simulation period occur before 6:30, and all vehicle travel contributes to emissions. Consequently, the combined tolls are levied between 6:00 and 6:30 as well as from 6:30 to 8:30.

Table 6: Summary statistics for congestion step tolls

	Time period	No toll	Cordon 1	Cordon 2	Cordon 3
Toll levels [€]	6:00 – 6:30	-	-	-	-
	6:30 – 7:00	-	0.29	0.58	1.45
	7:00 – 7:30	-	3.99	6.03	9.32
	7:30 – 8:00	-	3.31	4.05	5.29
	8:00 – 8:30	-	0.54	1.87	3.51
Car share		0.698	0.696	0.688	0.675
Speed [km/h]		40.12	45.64	46.28	45.38
Trip duration [min]		22.31	19.78	19.64	20.25
Trip distance [km]		14.92	15.05	15.15	15.31
Congestion index [%]		40.58	23.38	20.95	23.31
Consumer's surplus/day [€]		-4.40 $\pm$0.015	-4.44 $\pm$0.007	-4.45 $\pm$0.012	-4.62 $\pm$0.020
Total vehicle km/day [10^6]		2.75	2.76	2.75	2.73
Welfare gain/capita-yr (G) [€] (excluding health costs)		-	56.09 $\pm$1.616	99.45 $\pm$3.746	87.88 $\pm$3.737
Revenue/capita-yr (R) [€]		-	67.89 $\pm$0.518	111.87 $\pm$1.834	143.28 $\pm$2.369
G/R		-	0.83 $\pm$0.024	0.89 $\pm$0.027	0.61 $\pm$0.031
Rank by G		-	3	1	2
Drop in total pollution cost/day [€]		-	62,279	59,067	34,518

Summary statistics for optimal congestion step tolls are listed in Table 6, and optimal combined step tolls in Table 7. Except for the Cordon 3 toll between 7:00 and 8:00, the combined tolls are higher than their congestion-toll counterparts. However, the differences are relatively modest and the revenues collected and effects on traffic are similar. Only the welfare gains when accounting for health benefits are significantly larger, with differences of 156%, 70%, and 52% for Cordons 1, 2, and 3, respectively. Compared to the combined flat tolls in Table 4, the combined step tolls are more effective in targeting congestion without significantly reducing car travel. These differences mirror the differences between congestion flat and congestion step tolls in Tables 3 and 6. Nevertheless, the step tolls yield lower gains from pollution reduction than the corresponding flat tolls because, on average, travelers pay lower tolls and reduce driving by less.

Table 7: Summary statistics for combined step tolls

	Time period	No toll	Cordon 1	Cordon 2	Cordon 3
Toll levels [€]	6:00 – 6:30	-	0.59	0.39	1.16
	6:30 – 7:00	-	0.57	1.04	2.32
	7:00 – 7:30	-	4.08	6.70	9.10
	7:30 – 8:00	-	4.49	4.84	5.21
	8:00 – 8:30	-	1.42	1.89	3.60
	8:30–11:00	-	0	0	0
Car share		0.698	0.690	0.682	0.666
Speed [km/h]		40.12	45.61	48.12	45.61
Trip duration [min]		22.31	19.86	18.87	20.35
Trip distance [km]		14.92	15.10	15.13	15.47
Congestion index [%]		40.58	23.12	16.03	22.30
Consumer's surplus/day [€]		-4.40 ±0.015	-4.49 ±0.009	-4.51 ±0.023	-4.70 ±0.016
Total vehicle km/day [10^6]		2.75	2.75	2.73	2.72
Welfare gain/capita-yr (G) [€]		-	143.40 ±2.265	169.29 ±6.253	133.36 ±4.051
Revenue/capita-yr (R) [€]		-	92.73 ±0.849	126.94 ±1.552	166.50 ±1.655
G/R		-	1.55 ±0.028	1.33 ±0.044	0.80 ±0.024
Rank by G		-	2	1	3
Drop in total pollution cost/day [€]		0	78,934	74,573	44,726

The three tolling schemes differ somewhat in their effects on departure times. The flat Cordon 2 toll induces a sharp reduction in departures from 6:30 to 7:00, followed by a more gradual increase between 7:00 and 8:00. Travelers postpone departures because, with less congestion, they can leave later and still arrive on time.[19] By contrast, the flat Cordon 1&3 and step Cordon 2 tolls prompt an increase in departures between 6:00 and 6:30 before the toll begins.

[19] Such a shift was observed when the Stockholm Congestion Tax was introduced in 2007, although the shift was small (Karlström and Franklin, 2009).

Consequently, these tolls spread departures out both before and after the 6:30 - 7:30 peak period, rather than only afterwards.

Naturally, the welfare gains from combined step tolls are higher than for combined flat tolls, but the percentage differences are much smaller than for the congestion tolls. The reason is that emissions do not vary greatly over the range of speeds experienced on the network. Thus, there is less to gain from using time-varying tolls to target pollution than to target congestion. The most beneficial cordon, Cordon 2, reduces the total daily costs of pollution by €74,573 (a 24.9% reduction). The spatial pattern of changes, shown in Figure 6, is similar to the pattern for the combined flat Cordon 1&3 toll in Figure 5, although costs decline in a smaller fraction of the city area.

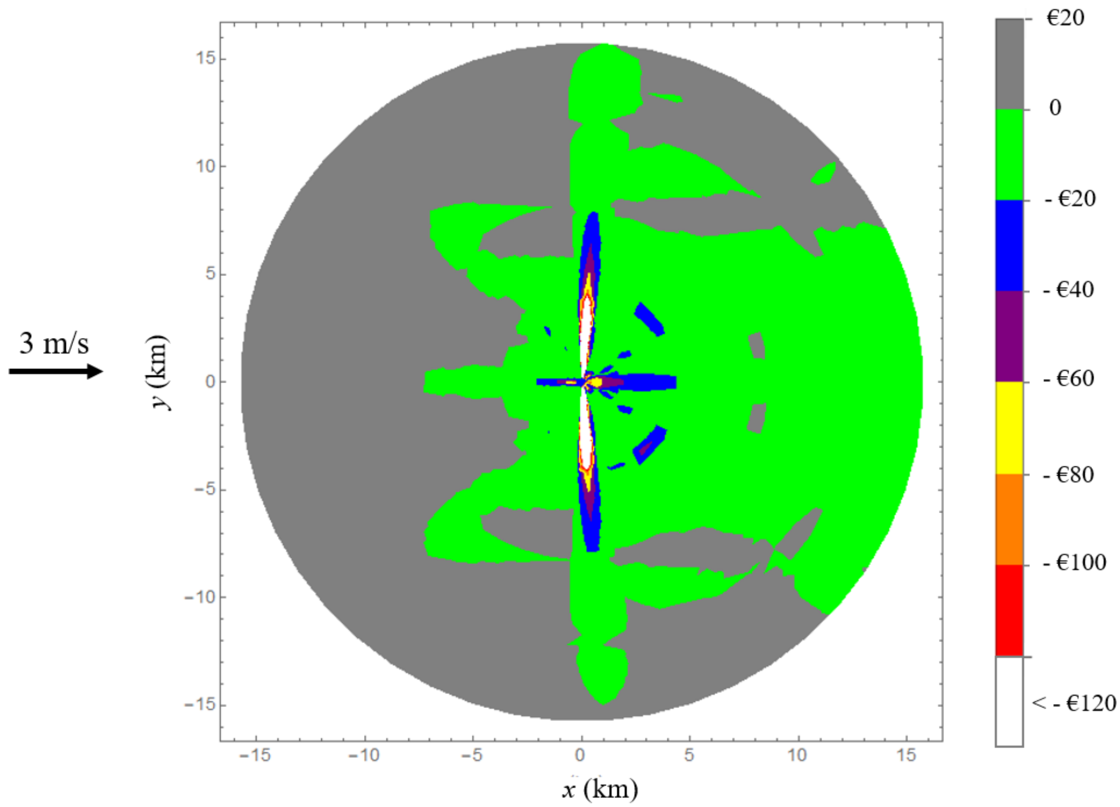

Figure 6: Change in annual per-capita health costs with combined step Cordon 2 toll

5 WELFARE DISTRIBUTIONAL EFFECTS OF TOLLING

Section 4 examined the effects of tolling on travel decisions and welfare. This section focuses on welfare-distributional effects. Section 5.1 looks at individual gains and losses from the three best-performing or "leading" combined tolling schemes: the flat Cordon 2, the flat Cordon 1&3,

and the step Cordon 2. Section 5.2 analyzes the tradeoffs between welfare gains, toll revenues, and pollution costs for all nine tolling schemes.

5.1 Individual welfare gains and losses

In addition to the aggregate effects of tolling schemes, it is useful to consider their welfare-distributional impacts on individuals which are likely to affect their attitudes towards road pricing (Levinson, 2002; Rietveld, 2003). Assessing these impacts is challenging since they depend not only on utility (or disutility) from travel, but also on how toll revenues are used and on the incidence of pollution costs. Neither of these additional factors is easy to assess. Toll revenues can be spent on road capacity expansion and maintenance, improving public transport service, or other public goods and services. Revenues can also be rebated in a lump-sum fashion to travelers, or used to replace other user charges and taxes in order to maintain revenue-neutrality.

The burden of pollution costs depends on where individuals are located when the air is polluted. The simulations involve about a quarter of a million travelers in a city of 1 million people. About three-quarters of the population are thus excluded from the consumers' surplus calculations for travelers. Those who do travel begin the simulation period at their respective origins, travel by car or public transport to their destinations, and remain at their destinations for the rest of the period. Trip origins and destinations are assumed to be joined to nodes by 1 km connectors, and their precise locations are not specified. Hence, travelers are not identified with particular receptors either before or after making their trips. At the end of the subsection, we offer a brief and rough assessment of the spatial incidence of pollution costs.

The fractions of travelers who pay the leading combined tolls are reported in Table 8. The fraction ranges from 9.7% for the flat Cordon 2 toll to 22.1% for the flat Cordon 1&3 toll.

Table 8: Fractions of travelers who pay the leading combined tolls

Flat Cordon 2		Flat Cordon 1&3		Step Cordon 2	
Toll	Fraction	Toll	Fraction	Toll	Fraction
€8.41	9.67%	Cordon 1 €3.31	7.49%	before 6:30 €0.39	1.73%
		Cordon 3 €3.95	11.77%	6:30-7:00 €1.04	4.63%
		Both €7.26	2.86%	7:00-7:30 €6.70	2.68%
				7:30-8:00 €4.84	4.01%
				8:00-8:30 €1.89	4.19%
Total	**9.67%**	**Total**	**22.12%**	**Total**	**17.25%**

Aggregate changes in consumer's surplus due to combined tolling can be deduced from Tables 4 and 7. For ease of reference, they are collected for the three leading tolling schemes in the last row of Table 9. All three schemes reduce mean consumer's surplus, although the reduction is quite small for the step Cordon 2 toll. In part, this is because the step toll is more efficient at reducing queuing, and in part, because travelers can reduce or avoid paying a toll by retiming their trips. Despite imposing average losses, all three schemes leave significant numbers of individuals better off. The fraction who gain ranges from 17% for the flat Cordon 1&3 toll to 38% for the other two tolls.

Table 9: Welfare-distributional impacts of combined tolls on the *Tolled* and *Untolled*

Group	Flat Cordon 2		Flat Cordon 1&3		Step Cordon 2	
	Mean ΔCS	Gainers	Mean ΔCS	Gainers	Mean ΔCS	Gainers
Tolled	- €3.27	0.0%	- €1.61	1.0%	- €0.78	16.6%
Untolled	- €0.42	42.1%	- €0.50	21.6%	€0.03	42.0%
All	- €0.69	38.0%	- €0.75	17.0%	- €0.11	37.6%

The first two rows of Table 9 break out results for travelers who pay a toll, and those who do not pay. For ease of reference, the two groups will be called the *Tolled* and *Untolled*, respectively. As expected, the *Tolled* fare worse than the *Untolled*. Most of the *Tolled* suffer because any gains the *Tolled* enjoy from reductions in congestion and pollution are not enough to compensate for their out-of-pocket costs. A larger fraction of the *Untolled* gain, but a majority still lose because they either switch from driving to transit or change to a longer route in order to avoid paying tolls. The difference in the welfare effects for the *Tolled* and *Untolled* is largest for the flat Cordon 2 toll, and least for the step Cordon 2 toll. None of the *Tolled* gain from the flat Cordon 2 toll, and only 1% gain from the flat Cordon 1&3 toll. By contrast, nearly 17% of the *Tolled* gain from the step Cordon 2 toll.

Figures 7-9 show the frequency distribution of gains and losses for the *Tolled* and *Untolled*. For the flat Cordon 2 toll (Figure 7), the overall distribution is bimodal. The distribution for the flat Cordon 1&3 toll (Figure 8) is also bimodal, but narrower since the tolls for the two cordons, €3.31 and €3.95, are much smaller than the Cordon 2 toll of €8.41. For the step Cordon 2 toll (Figure 9), the distribution is unimodal, and there is a greater overlap between the distributions for the *Tolled* and *Untolled*.

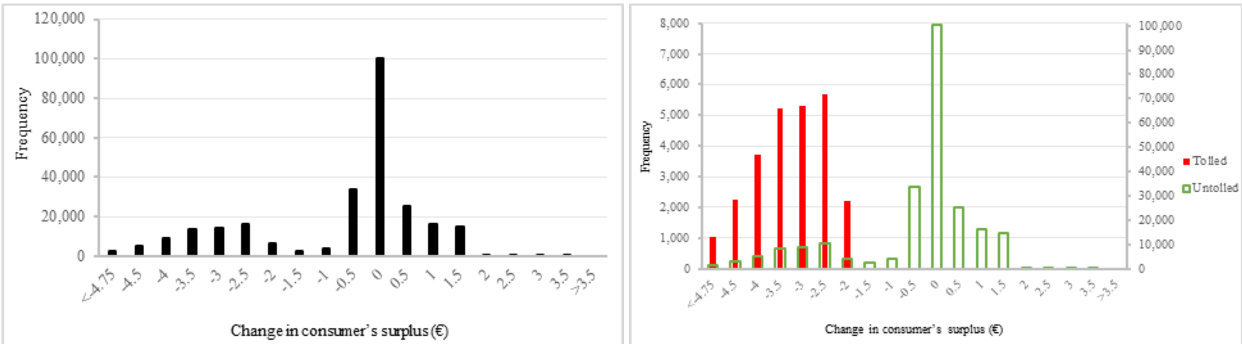

Figure 7: Change in daily consumers' surplus for combined flat Cordon 2 toll
Left panel: all travelers. Right panel: *Tolled* (left axis) and *Untolled* (right axis)

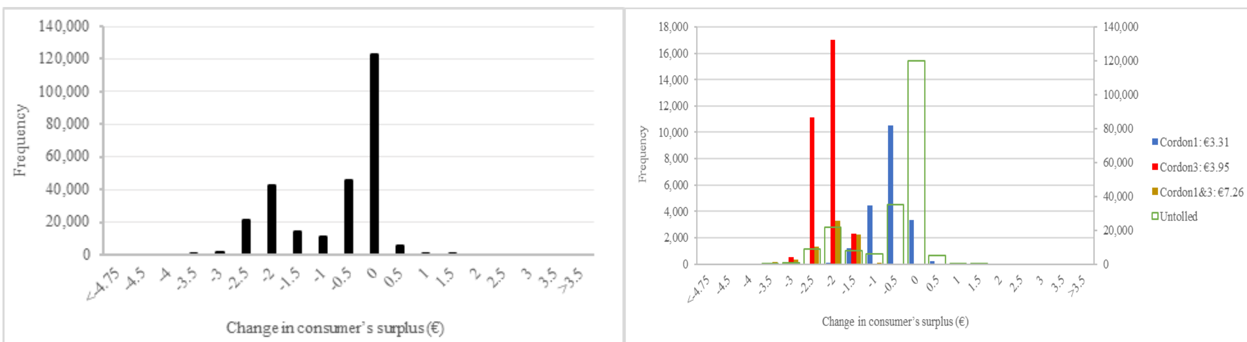

Figure 8: Change in daily consumers' surplus for combined flat Cordon 1&3 toll
Left panel: all travelers. Right panel: *Tolled* (left axis) and *Untolled* (right axis)

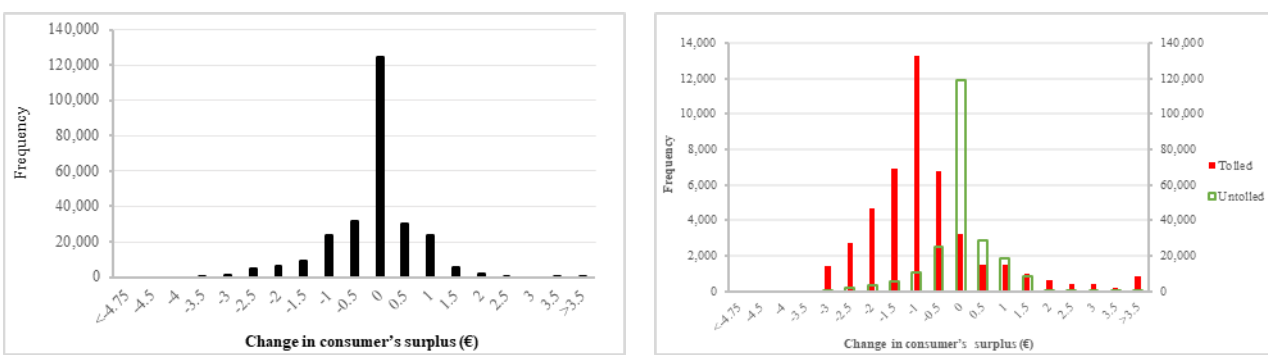

Figure 9: Change in daily consumers' surplus for combined step Cordon 2 toll
Left panel: all travelers. Right panel: *Tolled* (left axis) and *Untolled* (right axis)

Further insights can be derived by disaggregating gains and losses by trip origin, as is done in Table 10. For the flat Cordon 2 toll, travelers who begin their trips on Rings 0 and 1 are exempt from paying the toll and tend to benefit from reductions in travel by residents living outside.

Almost none of them end up worse off, and no one switches to public transport (PT). By contrast, travelers who begin their trips on Ring 2 pay the toll if they travel inwards — as most do if they take a direct route to their destination. Nearly 95% of them are worse off, and 13% switch to public transport. Smaller majorities of those starting on Rings 3 or 4 are also worse off. The dichotomy between the gains of those starting trips on Rings 0 and 1, and the losses of those starting on the other three rings, is largely responsible for the bimodal distribution in Figure 7. These results are similar to those of Rodriguez-Roman and Allahviranloo (2019) who consider a cordon charge that is paid in both the inbound and outbound directions. In their simulations, individuals traveling into or out of the charge zone experience an increase in driving costs, and some shift to public transport. By contrast, individuals who travel either completely within the charging zone, or completely outside it, benefit from a drop in driving costs, and some individuals stop using public transport and start to drive.

With the flat Cordon 1&3 toll, only travelers beginning on Ring 0 are exempt. Similar to the flat Cordon 2 toll, almost none of them end up worse off, and none switch to public transport. Travelers beginning on Rings 1 and 3 pay one of the tolls if they travel inwards, and over 90% in each group end up worse off. Somewhat smaller fractions of those starting on Ring 2 or 4 are worse off, too. With both flat tolling schemes, most of those who chose to drive before the toll is imposed are worse off. Those who pay a toll tend to lose because the monetary cost outweighs the value of any reductions in travel time and schedule delay. Those who avoid the toll by switching to public transport are worse off because they chose not to take public transport when there was no toll. Those who avoid the toll by choosing a longer route are typically worse off as well because of the added travel time.

The distributional effects are rather different for the step Cordon 2 toll. Although travelers beginning on Ring 0 are exempt, over 70% end up worse off. The reason for this unexpected result can be traced to the large jump in the toll from €1.04 to €6.70 at 7:00 am (see Table 7). Travelers who choose to cross the cordon much prefer to do so before 7:00. Significant numbers cross it shortly before 7:00, and a few minutes later a large proportion of them enter the Out1 links. Those who start their trips on Ring 0 have no choice but to use the Out1 links, and this surge of traffic delays them. In total, 63% of those starting on Ring 0 experience higher travel times than with no toll.

Travelers starting on Ring 1 are also exempt from the toll, but unlike those on Ring 0, they can avoid the Out1 links. As Table 10 shows, only 11.2% of them are worse off. The welfare effects for those on Rings 2-4 are similar to those for flat Cordon 2, but the average losses are much smaller because the step toll is high only from 7:00 to 8:00, and can be avoided by crossing the cordon either earlier or later.

Table 10: Welfare-distributional impacts of leading combined tolls by origin

Origin	Flat Cordon 2			Flat Cordon 1&3			Step Cordon 2		
	Mean ΔCS	Fraction who lose	Switch to PT	Mean ΔCS	Fraction who lose	Switch to PT	Mean ΔCS	Fraction who lose	Switch to PT
Ring 0	€0.14	0.2%	0.0%	€0.19	0.2%	0.0%	- €0.05	70.8%	0.3%
Ring 1	€0.83	0.4%	0.0%	- €0.42	93.7%	2.5%	€0.70	11.2%	0.0%
Ring 2	- €1.49	94.8%	13.0%	- €0.11	68.7%	1.2%	- €0.51	91.9%	4.7%
Ring 3	- €1.17	84.4%	11.2%	- €1.35	90.3%	10.9%	- €0.35	75.6%	3.9%
Ring 4	- €1.05	76.2%	10.7%	- €1.23	86.9%	11.0%	- €0.31	68.1%	3.7%
All	- €0.69	62.0%	8.5%	- €0.75	83.0%	6.2%	- €0.11	62.4%	3.0%

We conclude the analysis of individual welfare gains and losses with a brief assessment of the spatial incidence of pollution costs that complements the heat maps in Figures 5 and 6. To give a rough assessment of who gains and who loses, receptors are divided into eight groups according to whether they are located on the downwind or upwind side of the city, and between which pair of ring roads. The populations at each receptor are then aggregated, and the fractions of residents in each group that suffer an increase in pollution costs are calculated. The results are reported in Table 11. Consistent with Figures 5 and 6, the fraction that loses is lowest on the inner rings of the downwind side, and highest on the outer rings of the upwind side. The contrast between the two sides is conspicuous for each tolling scheme. Fewer than one fifth of residents of the downwind side experience higher costs, whereas over three fifths of residents of the upwind side do. Residents of the upwind side do not fare as well for two reasons. First, they are exposed to less pollution than residents downwind and therefore have less to gain from reductions in pollution from traffic upwind of where they live. Second, as explained regarding Figure 5, traffic may increase near where they live, causing pollution to increase. Naturally, the differences between the upwind and downwind sides of the city in both pollution levels and changes in pollution levels depend on wind speed and direction, which in practice vary diurnally, day by day, and seasonally.

Table 11: Fractions of residents that experience an increase in pollution costs

	Flat Cordon 2		Flat Cordon 1&3		Step Cordon 2	
Origin between	Downwind side	Upwind side	Downwind side	Upwind side	Downwind side	Upwind side
Rings 0-1	0.0%	7.6%	0.0%	41.1%	0.0%	5.9%
Rings 1-2	0.0%	64.7%	8.2%	51.1%	0.0%	63.7%
Rings 2-3	24.5%	80.8%	7.8%	71.9%	24.5%	84.9%
Rings 3-4	34.9%	89.6%	17.8%	89.5%	49.5%	100.0%
Whole side	15.5%	62.8%	8.8%	64.4%	19.3%	65.9%
Whole city	**39.1%**		**36.6%**		**42.6%**	

5.2 Aggregate welfare gains, toll revenues, and pollution costs

At the aggregate level, road pricing schemes are sometimes judged not only by their welfare gains but also by the amount of revenue collected. Large revenues are a drawback if they undermine the public acceptability of tolling. However, large revenues are advantageous from a fiscal perspective if other revenue sources are tapped out, and the marginal cost of public funds is correspondingly high. Thus, depending on the setting, large revenues may be beneficial or detrimental. Figure 10 shows the trade-off between welfare gains and revenues for all nine congestion tolling schemes. For the single cordons, the step tolls clearly dominate the flat tolls as far as welfare since the welfare gains are several times larger. The flat double cordons yield much less than the sum of the gains from the constituent flat single cordons, and except for Cordon 1&2 they generate larger revenues.

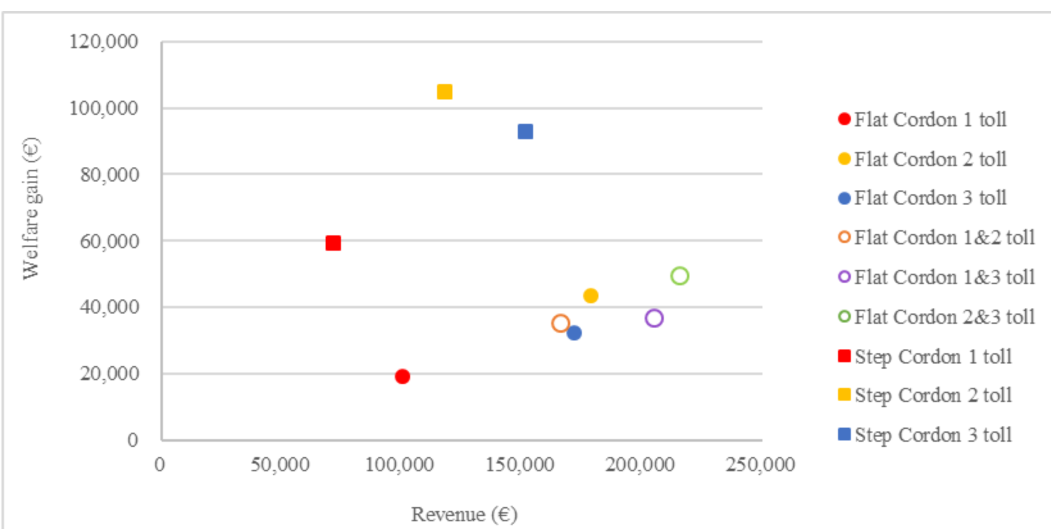

Figure 10: Total daily welfare gains vs revenues for congestion tolls

Figure 11 depicts the trade-offs for the combined tolls. As noted earlier, the percentage gains in benefits from time variation of tolls are much smaller than for the congestion tolls. Furthermore, the double cordons do little better than the corresponding single cordons. Indeed, except for the flat toll on Cordon 3, all schemes yield similar welfare gains. By contrast, the revenue generated ranges by a factor of nearly 3. A single cordon on Ring Road 1 or 2 appears attractive, and its merits relative to the double cordons might be enhanced if the costs of implementing and operating tolls are considered.

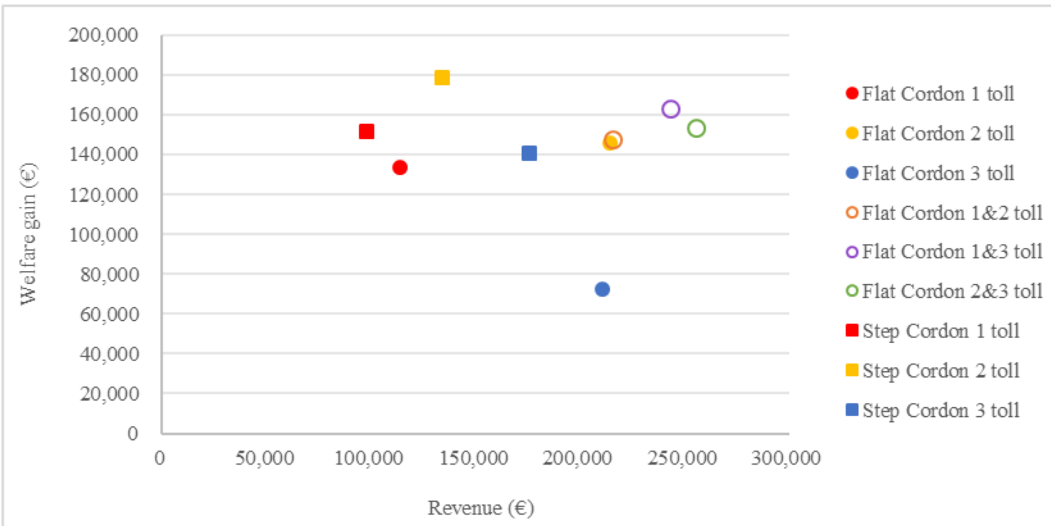

Figure 11: Total daily welfare gains vs revenues for combined tolls

In the model, welfare depends not only on travelers' consumers' surplus and toll revenue, but also on the health costs of pollution. A shift from congestion pricing to combined pricing calls for higher tolls, which benefits the environment at the expense of transportation. The combined tolls are derived here by maximizing social surplus which weights consumers' surplus, revenues, and health costs on the basis of their monetized values. For political or other reasons, alternative weights might be deemed appropriate. The trade-off between health benefits and transportation efficiency can be examined by varying toll levels parametrically. This is straightforward when the scheme involves only a single toll. Figure 12 illustrates this for the flat Cordon 2 toll.

Transportation benefits are maximized with the congestion toll of €5.34, and overall welfare is maximized with the combined toll of €8.41. Toll revenue is maximized at a toll of about €9, whereas health benefits increase monotonically with the toll over the range shown. On other networks, health benefits can decline at very high toll levels if traffic is diverted into heavily populated areas or onto roads with insufficient capacity, resulting in low speeds and heavy emissions per veh-km.

Figure 13 illustrates more sharply the trade-off between transportation benefits and health benefits by plotting the locus of points in a two-dimensional space. As the toll rises, transport benefits and health benefits both increase at first so that no trade-off exists. When the toll reaches €5.34, transportation benefits reach a maximum, while health benefits continue to increase. At this point, the implicit weight on health benefits is zero. If the toll is increased further to €8.41, transport benefits and health benefits are assigned equal weights. Welfare, as measured by the sum of transport and health benefits, is maximized, and the locus has a slope of -1. (Note the difference in scale on the horizontal and vertical axes.) To the north-west of this point, the locus becomes flatter, and health benefits are assigned a progressively higher relative weight.

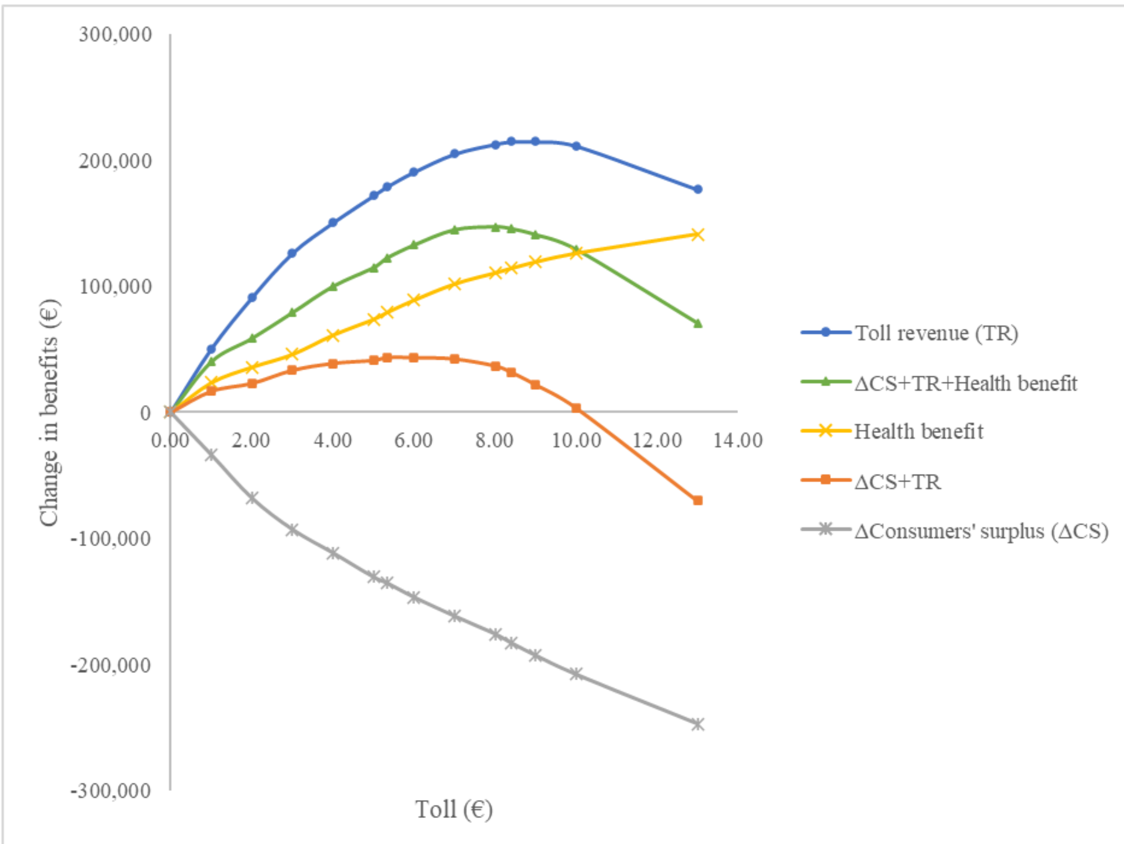

Figure 12: Changes in consumers' surplus, toll revenue, and health benefits as a function of the flat Cordon 2 toll

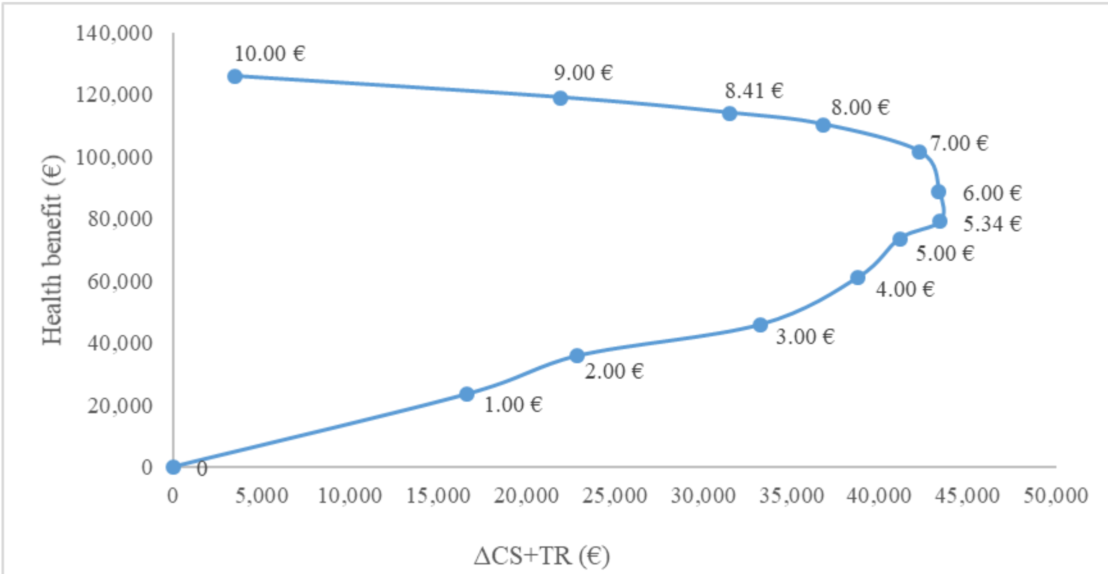

Figure 13: Trade-off between transport benefits and health benefits as a function of the flat Cordon 2 toll

6 CONCLUSIONS

Road pricing has long been advocated as a tool for reducing traffic congestion, but it also has a potential role to play in reducing vehicular emissions. This paper uses the dynamic traffic network simulator METROPOLIS to study the use of tolls to pursue these twin goals. To calculate the concentration and spatial distribution of pollution, METROPOLIS is supplemented with a Gaussian dispersion model that accounts for wind speed and direction. The combined model is applied to a stylized urban road network during a morning commuting period to evaluate the efficacy of single and double cordon tolls, as well as flat tolls and step tolls that change at half-hourly intervals. Emissions of CO, CO_2, NOx, and particulate matter (PM) are calculated, as well as the local health effects of CO, NOx, and PM on receptors distributed throughout the city.

A number of results emerge that provide provisional answers to the five questions posed in Section 2.

1). How much do optimal cordon toll levels and locations differ from cordons designed to target congestion alone? Accounting for the health costs of pollution substantially raises the optimal levels of tolls, and alters the welfare rankings of the single and double cordon tolls. The ranking of the inner cordon toll (Cordon 1) improves because both emissions and population are concentrated toward the city center. Double cordons confer only a small advantage over single cordons.

2). How large are the benefits from reducing emissions compared to congestion relief?

Accounting for the health costs of pollution increases substantially the welfare gains from tolling relative to the gains from congestion relief alone. For example, as reported in Table 4 the best-performing combined flat Cordon 1&3 toll yields an annual per-capita welfare gain of €155. Total daily pollution costs decrease by €117,970. With 264,000 travelers and 250 trips per year, this translates to an annual per-capita welfare gain of approximately €112, or about 72% of the total gain. The corresponding fractions for the Cordon 1&2 and Cordon 2&3 tolls are slightly higher yet.

3). How much is gained by levying step tolls rather than flat tolls?

Step tolls are highly effective in reducing congestion without greatly increasing travelers' costs, but they have only a modest advantage over flat tolls for pricing emissions. Step tolls can also induce surges of traffic just before a large toll increase (or just after a steep drop), causing traffic delays that make certain groups of travelers worse off.

4). How does wind speed affect optimal tolls and pollution levels across a study area?

Pollution levels decrease with wind speed. Consequently, optimal toll levels and the welfare gains from tolling decrease with wind speed as well.

5). Who gains and who loses from tolling, and how do the welfare effects vary with location?

Although combined congestion and emissions pricing yields substantial welfare gains, a large fraction of travelers end up worse off unless the revenues from tolling are used to benefit them in some way. Those who lose tend to cluster in three groups: (a) those who live outside a cordon area, but near its boundary so many have to pay the toll if they drive, (b) those who cannot easily reroute around a cordon and do not consider public transport to be a good alternative, and (c) those who live on the upwind side of the city who are not exposed to severe pollution. Individuals in the last group are not exposed to much pollution generated by traffic further upwind. They can also suffer from an increase in car traffic in their neighborhoods, causing both congestion and pollution to increase. In addition, due to rerouting of traffic, residents living near roads can experience increases in pollution — as occurred in the simulations on some ring roads.

Overall, the results suggest that a single flat cordon toll on one of the inner rings might be a good compromise as far as the trade-off between welfare gains, revenue generated, and complexity of design and operation. Other things equal, the benefits from tolling will be higher in cities with low average wind speed, such as Milan where a cordon scheme designed to reduce pollution was introduced in 2008.

Some of our results are consistent with previous studies. Other results emerge from the use of a dynamic simulator, such as the fact that step tolls do not have a large advantage over flat tolls for pricing emissions. Still, other results contrast with those of earlier studies. In particular, some modeling studies that examined tolling schemes on real-city networks (e.g., May et al., 2002; Yang and Huang, 2005; Santos, 2004; Safirova et al., 2007) have determined that double cordons can yield substantially larger benefits than single cordons. Some studies (e.g., Daniel and Bekka, 2000; Santos, 2004) have also concluded that the environmental benefits from tolling are much smaller relative to the benefits from congestion relief than what we find.

The discrepancies between our results and those of earlier modeling studies are presumably partially due to differences in models, assumptions, and the numerical applications considered — whether they are stylized examples or real cities. Most previous studies have used static models. Some, such as Yang et al. (2014) and Rodriguez-Roman and Ritchie (2017), design tolls to meet maximum pollutant concentration constraints. Hence, they do not undertake unconstrained social welfare maximization as we do. Other studies, such as Wu et al. (2017), set tolls to achieve a target average speed (which is how tolls are set on arterials and expressways in Singapore). The discrepancies between our results and those of other studies may also be due to elements of our modeling procedure, such as choice of parameter values and spatial grid of sources and receptors, and imprecision in optimizing the tolling schemes.

The relative importance of controlling congestion and controlling emissions will vary from city to city. In most cities in developed countries, congestion externalities are larger. However, the opposite may be true in large cities in developing countries with high levels of pollution such as Mumbai and Delhi. The estimated costs of pollution and carbon emissions tend to increase over time as epidemiological and other evidence cause their unit costs to be revised upwards. Naturally, the costs of both congestion and emissions are generally greater in big cities because of their large populations and high population densities. In any case, marketing road pricing as a tool for reducing emissions as well as congestion could improve the public acceptability of tolling.

The analysis in this paper could be extended in several directions. Traveler decisions besides transport mode, departure time, and route could be added. The health effects of pollution could be measured more accurately by tracking exposure of travelers to pollution before, during, and after their trips. Other externalities such as noise and safety could also be considered, although tolls may not be the best policy instrument to address them.

Emissions modeling would be enhanced by accounting for differences between vehicles in fuel type, fuel efficiency, and emissions control technology; as well as emissions caused by cold starts and warm soaks. Tolls should then be differentiated according to vehicle characteristics. The welfare-distributional effects of tolling would be enriched by also allowing for traveler heterogeneity in income, values of travel time, and trip-timing preferences. Pollution and congestion externalities are anonymous in the sense that it does not matter who is responsible for creating them at a given time and place. Consequently, differences in personal characteristics do not, in themselves, call for discriminatory tolls. However, since cordons and other practical tolling schemes are second-best, discrimination on the basis of personal as well as vehicle characteristics could improve efficiency (Arnott and Kraus, 1998) although it would raise privacy and equity issues.

Finally, the simulations were carried out on a stylized city with a symmetric road network in which both trip destinations and population are concentrated toward the center. Cordon tolls located on ring roads tend to perform well with this configuration. Some cities do have ring roads that serve as natural cordon boundaries. For example, the inner ring road was chosen as the boundary for the London Congestion Charge. In Milan, both the original Ecopass scheme designed for pollution control and the Area C congestion charge that replaced Ecopass are delimited by the 'Cerchia dei Bastioni' sixteenth-century walls. Beijing has seven ring roads that are candidates for a cordon.[20] However, many cities are located on coastlines, traversed by rivers, or located in hilly terrain. Their road networks may be irregular, rather than radially symmetric or rectangular as in Manhattan. In cities with a dense road network, forming a cordon may require using a large number of checkpoints as is the case of Gothenburg (Börjesson and Kristoffersson, 2015). In some cases, it may be unclear where to place cordons. Yet, as May et al. (2002) show, the performance of a pricing scheme can be sensitive to cordon location. For some road networks, it may be helpful to divide cordons into cells or zones (as in the former Trondheim scheme) or supplement them with screenlines. If congestion is concentrated on a few bridges or other "hot spots", point or link-based tolling may also be useful.

Public transport accessibility and frequency can also vary greatly within cities. Areas with poor service offer little alternative to driving. Crowding and inability to board buses or trains that are full to capacity also limit the scope to reduce traffic congestion by inducing travelers to switch mode. On equity grounds, it has been suggested that tolls could be set at lower levels on roads or in neighborhoods far from public transport service (Becker et al., 2017). Another feature of many cities is that average incomes are lower on their east side. Heblich et al. (2021) provide convincing evidence that this pattern began to develop during the Industrial Revolution as prevailing winds blew pollution to the east, dissuading wealthier individuals from residing there. Residents living on the east sides of these cities have lower incomes and may suffer from poor health due to high pollution levels. Equity concerns would then call for lower tolls in the east. To the extent that values of travel time tend to be lower in lower-income areas, efficiency itself calls

[20] See https://en.wikipedia.org/wiki/Ring_roads_of_Beijing. Wu et al. (2017) study road pricing in Beijing using double cordons: one bounded by the 2nd ring road and the other by the 3rd ring road. Baranzini et al. (2021) have recently studied two candidate cordons for Geneva, Switzerland that are designed to reduce congestion while respecting the local topography and the nearby border with France. One cordon forms a perimeter around the urban center where public transport and non-motorized modes offer a reasonable alternative to driving. The other cordon forms a perimeter along, or close to, the Geneva highway ring that encompasses most of the city.

for lower tolls in the east, as well. Conversely, efficiency calls for higher tolls in the west if emissions there impose disproportionately high costs on the city overall. It is unclear whether differentiating tolls on these grounds would be politically tenable. An alternative might be to offer residents in the east some kind of compensation, such as subsidies for purchasing air conditioners or local investments in greenery.

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CONFLICT OF INTEREST

None of the authors has a conflict of interest.

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8 APPENDIX

8.1 Travel demand

Table A1: Travel demand parameter values

Parameter	Value
Car	
Unit cost of travel time by car (α_A)	€10/h
Desired arrival time (t^*)	Uniformly distributed with mean of 8:00, standard deviation of 20 mins.
Unit cost of early arrival (β)	€6/h
Unit cost of late arrival (γ)	€25/h
Width of on-time arrival window (Δ)	10 min
Logit scale parameter for car departure-time choice (μ_t)	€2
Mode choice and public transport	
Logit scale parameter for mode choice (μ_m)	€5
Unit cost of travel time by public transport (α_P)	€15/h
Fixed penalty for public transport (C_{P0})	€10

8.2 Road network parameter values

Table A2: Road network parameter values

Links	Flow capacity [veh/h]	Free-flow speed [km/h]
In*1*, Out*1*	3,000	50
In*i*, Out*i*, *i*=2,3,4	4,000	70
Ring*i*, *i*=1…4	2,000	50
All public transport	∞	40

8.3 Origin-destination matrix

The number of trips between each pair of nodes is computed as follows. Let P_r denote the number of commuters who start trips at zone *r*, N_{rs} denote the number who take trips from node *r* to node *s*, and t_{rs} denote free-flow travel time from node *r* to node *s*. Let λ be a positive parameter. Then

$$N_{rs} \equiv P_r \exp\left(-\lambda t_{rs}\right) / \sum_d \exp\left(-\lambda t_{rd}\right).$$

In the morning, the majority of trips are inbound because the density of destinations is higher in the city center. The average distance to destinations near the center is correspondingly shorter. Hence, demand in the morning is not symmetric between any pair of zones (r, s) and (s, r). If *s* is closer to the center than *r*, there are more trips from *r* to *s* than from *s* to *r*, and vice versa.

The commuters who traveled from *r* to *s* in the morning will make the reverse trip from *s* to *r* in the evening. Hence, in the evening there would be more outbound trips than inbound trips. This would be reflected in the results if METROPOLIS were applied to evening travel.

8.4 Pollutant emissions functions and unit health costs

CO: $0.2038 \cdot T \cdot \exp(0.7962 \cdot l / T)$ g/veh/h] *T*: travel time [min], *l*: link length [km] [1]
Health cost: 0.14 [\$/person/h/(mg/m^3)] [2]

NOx: $0.05113 + 1.019V^{-1} - 1.861 \times 10^{-3} V + 1.765 \times 10^{-5} V^2$ [g/veh/km] *V*: km/h [3]
Health cost: 26.34 [\$/person/h/(mg/m^3)] [4]

PM$_{2.5}$: $k(sL/2)^{0.65}(W/3)^{1.5} - C$ [g/veh/km] for paved roads. *sL*: road surface silt loading [g/m^2] *W*: average vehicle weight [ton], *C*: Emission factor for 1980's vehicle fleet exhaust, *k*: constant [5]
Health cost: 16.46 [\$/person/h/(mg/m^3)] [6]

CO$_2$: $72.73 + 33.98 \times 10^2 / V + 23.26 \times 10^{-3} V^2$ [g/veh/km] *V*: km/h [7]
Health cost: 70 [\$/ton] [8]

[1]: Chen and Yang (2012), Ma et al. (2017), Wang et al. (2018).
[2]: Bigazzi and Figliozzi (2013).
[3]: Yao and Song (2013).
[4]: Bigazzi and Figliozzi (2013).
[5]: EPA (2009).
[6]: Bigazzi and Figliozzi (2013).
[7]: Dimitriou et al. (2009).
[8]: Kickhöfer and Nagel (2016).

Note: Monetary costs in the original sources are stated in USD. For the simulations here, they were inflated to euros to be consistent with the values of the demand parameters.