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Pricing vehicle emissions and congestion using a dynamic traffic network simulator

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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 the dynamic traffic network simulator METROPOLIS to investigate the effectiveness of tolls to target emissions and congestion externalities on a stylized urban road network during a morning commuting period. The concentration and spatial distribution of four pollutants are 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 emission externalities raises optimal toll levels, and substantially increases the welfare gains from tolling although the 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 windward and leeward sides of the city.

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

1 INTRODUCTION

Air pollution is a severe problem in many countries. Over 90 percent 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 percent (Yin et al., 2017b). Worldwide, one sixth of deaths related to Lower Respiratory Infections are 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 significant contributor to 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). While diesel fuel combustion is the largest source of PM emissions, tire and brake wear and road abrasion are a growing fraction of the total (EEA, 2019). 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). Although new internal-combustion-engine vehicles are becoming greener, and electric vehicles are entering the market, 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. Economy theory suggests 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 green vehicles were initially granted discounts or exemptions from payment. Several studies have assessed the environmental benefits from the London, Stockholm, and Milan schemes.[3] Overall, they conclude that the benefits are moderate to modest. 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 equilibrium 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. While we apply the simulator to a stylized (i.e., symmetric circular city) network, we believe that our approach can be used on large, real-world city networks.

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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).

[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.

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 equilibria for various cordon tolling schemes and their aggregate effects on traveler utility and air pollution health costs. Section 5 examines at a more disaggregated level the effects of the tolls on traffic flows, trip distances, trip durations, departure times, and 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-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 feature 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

[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).

[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.

wind on the concentration and spatial dispersion of pollution is often disregarded. Most studies that do consider it employ Gaussian dispersion models.

Table 1: Selected studies of emissions pricing

Study	Congestion	Emissions	Type of tolls			Traveler Choices				Pollutant(s)	Wind effects
			Links	Cordon/Area	Time varying?	Route	Mode	Departure. time	Other		
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., 2007b	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	
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

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, the dynamics of traffic flow matter since flows determine the density of vehicles at a given location and time of day, 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 technology.

As noted in Table 1, relatively few studies treat endogenously travelers' trip-timing decisions. Moreover, some of those that do, such as Rodriguez Roman and Allahviranloo (2019), treat 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 resolution 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 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 automobile trips (Arnott et al., 1990) as well as smooth variations in travel speed that contribute to vehicle emissions. Static models lack the time resolution to capture these phenomena, too. 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, in this paper we use the dynamic traffic network simulator METROPOLIS. METROPOLIS treats endogenously individual departure-time, travel mode, and route-choice decisions. Individuals differ in their idiosyncratic preferences for departure time and mode.[7] 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

[7] However, the vehicles they drive are assumed to be homogeneous in fuel type, emissions technology, and operating costs.

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 large are the optimal cordons, and how high are the tolls? How much do the optimal cordons differ from cordons designed to target congestion alone? How large are the benefits from reducing emissions compared to congestion relief? How does wind speed affect pollution levels across the study area? How much is gained by levying step tolls rather than flat tolls? 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 in which the concentration of pollution is uniform within a cubic volume enclosing the city.

The stylized urban road network, origin-destination matrix, and travel demand preferences we use for our application 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.[8]

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. May et al. (2002)

[8] As explained in Section 3, our study also differs in terms of computation methods and the timing of the step tolls.

evaluated 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 percent. Similar results were obtained by Yang and Huang (2005) for the Shanghai road network, and by Safirova et al. (2007b) for the Washington, DC metropolitan area. Santos (2004) assessed cordon pricing for eight English towns, and concluded that double cordons yield on average nearly double the benefits of a single cordon.[9] 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. Hence, eliminating congestion increases CO_2 emissions per veh-km. 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 automobile to transit 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. [10] It employs a two-stage nested logit framework. In the outer nest, travelers choose between driving (hereafter referred to as "auto") and taking public transport. Those who choose auto select a departure time in the inner nest. Route choice is

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

[10] de Palma et al. (1997) and de Palma and Marchal (2002) describe the architecture of METROPOLIS.

governed by a heuristic based on minimization of travel time. The generalized systematic cost of an auto 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 applied here to peak-period morning trips during the time window 6:00 - 11:00 am.[11] 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.[12] 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 and free-flow travel speeds are listed in Table A2 of the appendix. Congestion takes the form of queuing.[13] Traffic signals are not modeled, so no additional delays occur due to conflicting traffic movements at intersections. The generalized systematic cost of a public transit trip is exogenous and independent of time of day. 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. The number of trips between each pair of zones is an exponentially decreasing function of the free-flow auto travel time between the zones.

[11] In the simulations, almost all trips are completed by 9:30 am. To reduce execution time, computation of emissions, discussed in Section 3.2, is limited to the interval 6:00 - 9:30 am.

[12] METROPOLIS has been applied to large road networks, including Paris with approximately 20,000 links (de Palma and Lindsey, 2006). For the purpose of this paper, the simple network in Figure 1 has some advantages. First, due to its symmetry results can be quickly checked for veracity and consistency because traffic flows should be approximately equal on all links of the same type. Second, deriving basic insights and understanding differences in the performance of alternative tolling schemes are easier than on a complicated, irregular network. Third, calculating pollution levels using the Gaussian dispersion model, described in Section 3.2, is computationally demanding, and would be impractical on a large network given the number of iterations of METROPOLIS required to reach a steady state and identify near-optimal toll levels.

[13] Queuing is implemented in the form of vertical queues. With horizontal queuing, queues can spill back onto upstream links if the number of vehicles on a link exceeds its storage capacity. Spillback can be practically important in some settings (e.g., Szeto et al., 2012). However, the links on the circular-city network are relatively

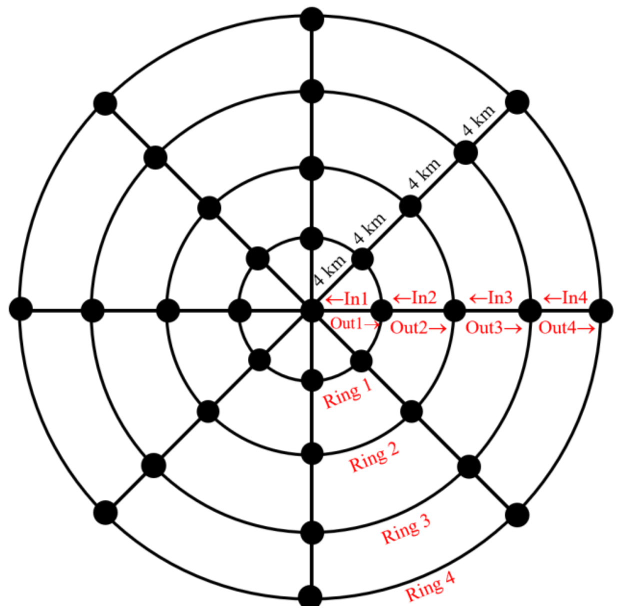

Figure 1: The circular city road network

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.[14] 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 veh-km of CO_2 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. Thus, 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

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long (i.e., π km or longer). If links are assumed to accommodate 250 vehicles per km per lane, spillback would occur only on the *In1* links, and intermittently during the peak of the travel period.

[14] 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.

reduce total vehicle-km on heavily congested links where the population density is high. Hence, tolling has the potential to reduce the costs of emissions substantially.

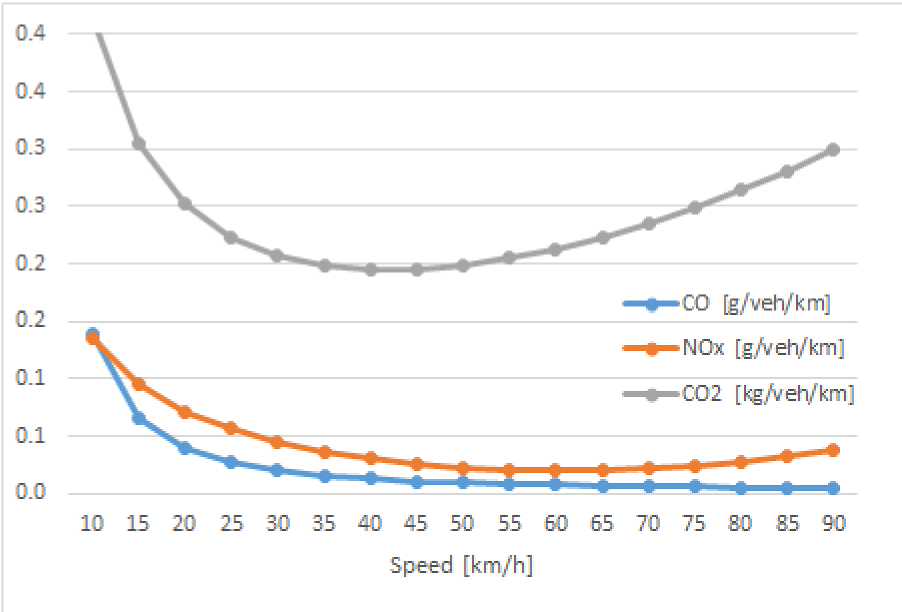

Figure 2: Emissions-speed curves for CO, NO_x, and CO_2

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.[15] Consider a source at the origin, and a receptor with Cartesian coordinates (x, y, z) where the x-axis points in the direction of the wind. The concentration 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

[15] The Gaussian plume model is a standard approach for studying the transport of airborne contaminants due to turbulent diffusion and advection by the wind. See, for example, Lin and Ge (2006), Sahlodin et al. (2007), Zhang et al. (2010) and Rehimi and Landolsi (2013).

on weather conditions. A neutral stability class or Pasquill category D is assumed, for which a = 0.0787, b = 0.0014, c = 0.1350, d = 0.0475, and e = 0.465.

According to the equation for $E(x,y,z)$, the concentration of pollution is inversely proportional to wind speed. Concentration diminishes rapidly with distance downwind from a source, and is negligible except for a narrow plume on either side. Nevertheless, since emissions are generated throughout the road network, air is polluted at a majority of the receptors. 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. [16]

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. Several assumptions are made to simplify calculations. First, all emissions occur at an elevation of $H = 0.5$ m, and all receptors are at an elevation of $z = 1.5$ m. Second, 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. Third, pollution does not affect travel decisions except insofar as pollution levels influence the choice of toll levels. Fourth, the health effects of emissions are proportional to pollution concentration.[17] The last 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.[18] 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. 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

[16] 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.

[17] Linear exposure-response functions are widely used in the literature; see, for example, McCubbin and Delucchi (2003) and Rodriguez-Roman and Ritchie (2017).

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

made. Toll levels are optimized jointly in each of the five intervals.[19] Optimal flat and step tolls are derived for the single cordons, whereas only flat tolls are derived for the double cordons.[20] Toll levels are chosen to maximize welfare as measured by traveler utility (i.e., consumers' surplus) plus toll revenues minus air pollution health costs.

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.[21] 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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[19] An alternative procedure would be to fix the toll levels, and optimize the time intervals. Optimizing the levels was chosen for three reasons. First, finding an optimum turns out to be quicker and more reliable numerically. Second, changing tolls on the hour or half hour makes it easier for motorists to remember when they change. Third, electronic tolling technology makes it easy for motorists to pay tolls in small increments (e.g., multiples of $0.05). 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).

[20] One reason is that motorists might find it difficult to make optimal departure-time decisions with time-varying tolls on two cordons. Another is that jointly optimizing toll schedules on two cordons would be computationally quite burdensome.

[21] See, for example, Verhoef et al. (1996), Liu and McDonald (1998), Safirova et al. (2004, 2007a), and 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.[22]

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 static component, which depends on the instantaneous congestion level, but also a dynamic component that is positive if congestion is increasing, and negative if it is decreasing. Coria et al. (2015) extend their analysis to dynamic pricing of congestion and emissions together on a single link.[23] 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.[24] 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[25] 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 automobile. As measured by the congestion index, trips take a little over 40% longer on the route chosen than under free-flow conditions. Because arriving late is quite costly, most drivers arrive either early or on time. Average consumer's surplus is

[22] In principle, the toll should also account for the exposure of other drivers to pollution, which increases with traffic density. As noted above, this effect is disregarded in the simulations here.

[23] See equation (A5) in their paper.

[24] Tolls are optimized using a response surface procedure employed in de Palma et al. (2005). An initial set of simulations are performed for a relatively wide range of tolls. A quadratic surface is then fitted to the set of (toll, welfare) points, and used to identify another set of toll values. Iterations continue until the absolute changes in toll levels and welfare between successive iterations drop below a threshold level. The simulations were performed using a laptop with an Intel® Core™ i5-7300U CPU @ 2.6 GHz 2.71GHz processor and 8 GB RAM.

[25] For three reasons the results are not identical. First, METROPOLIS assigns idiosyncratic preferences randomly and the random draws here differ from the earlier simulations. Second, to speed up calculations de Palma et al. (2005) scaled down the origin-destination demand matrix and capacities of all road links to 10% of their nominal values. This reduced the time to run a simulation by nearly 90 percent, while having minor effects on congestion delays, social surplus, and other summary statistics of interest. Third, iterations of METROPOLIS do not converge fully to an equilibrium, but oscillate about a stationary state. The end result of the simulation depends on random fluctuations and how many iterations are performed.

negative because travelers have to make a trip by auto or public transit, 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 3 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 half of the city than the west.[26] The highest costs are at receptors near the city center that are close to heavily-used roads.

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

Statistic	Value	Definition
Auto share	0.698	Fraction of trips made by automobile
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 auto travel speed
Trip duration	22.3 min	Mean auto travel time
Trip distance	14.9 km	Mean auto 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 auto free-flow travel time cost
Schedule delay cost	€1.46	Mean auto schedule delay cost
Consumer's surplus	€-4.40	Mean user surplus (log sum for auto and public transportation 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	2.75×10^6	Total kilometers traveled by auto
CO cost	€1,760	Carbon monoxide health cost
NO_x cost	€132,739	Health cost of nitrogen oxide emissions
$PM_{2.5}$ cost	€128,068	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

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 are referred to as *combined tolls*. To identify how emissions affect optimal toll levels and welfare gains, tolls that internalize only congestion externalities are also computed. These tolls are referred to as *congestion tolls*, and their welfare gains are computed without accounting for the costs of pollution.

[26] 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 3 indicates.

Table 3 lists summary statistics for the flat congestion tolls. All three single cordon tolls reduce the auto share of trips, the congestion index, total vehicle km traveled (vkt), and average travel time per trip. However, except for Cordon 3, average trip distance increases which partially offsets the effect of a shift toward transit in reducing vkt. Average speed rises, but despite reductions in travel time, average consumer's surplus falls by €0.31 to €0.64 per trip. The annual welfare gain is calculated assuming 250 days of travel per year; it includes all costs borne by travelers, 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 (0.24).

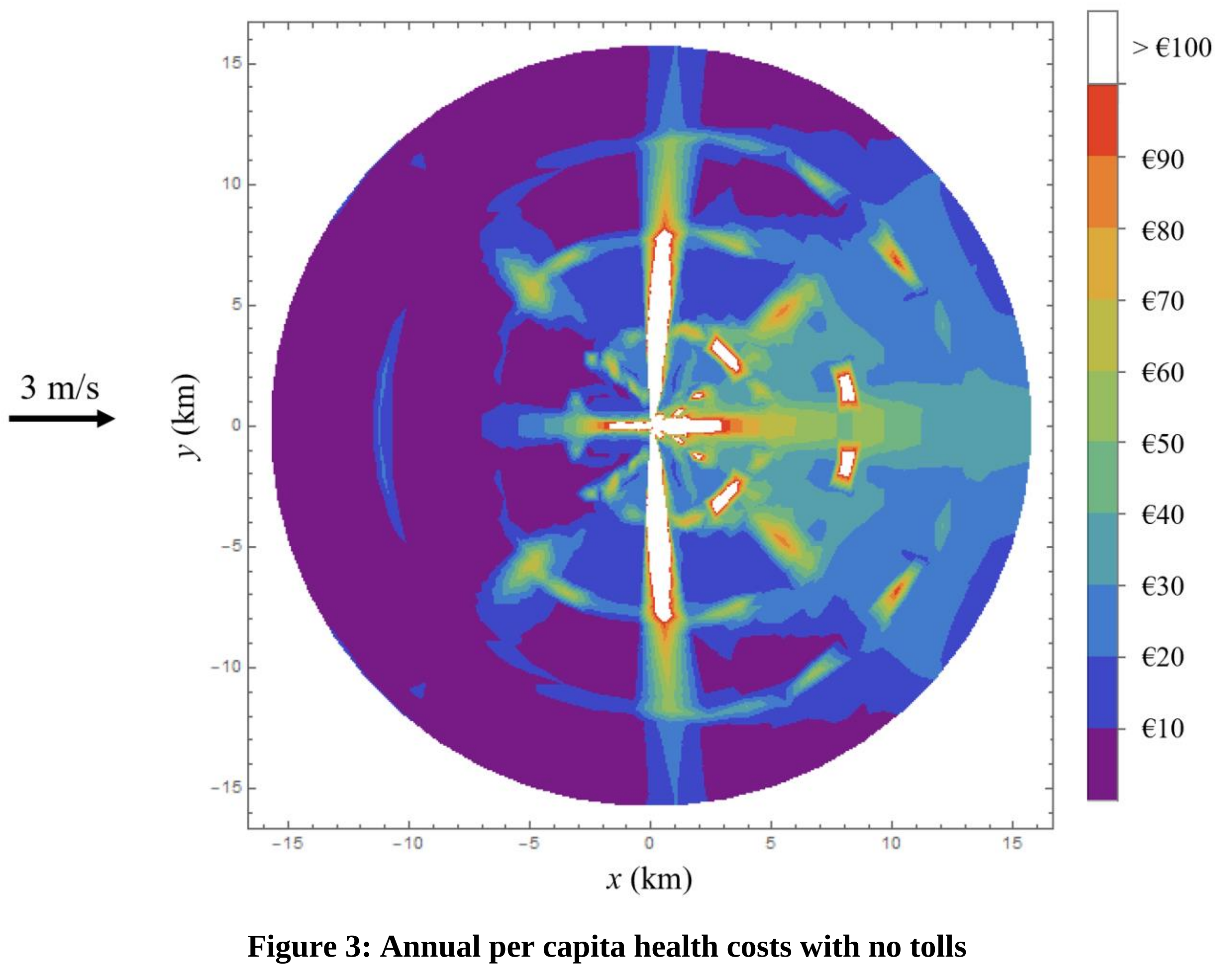

Figure 3: Annual per capita health costs with no tolls

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.[27]

Table 3: Summary statistics for flat congestion 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
Auto 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 [€]		-4.40	-4.71	-4.91	-4.93	-4.86	-5.04	-5.03
Total vehicle km [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	41.10	30.58	42.09	34.81	46.96
Revenue/capita-yr (R) [€]		-	94.92	169.38	162.76	157.46	194.13	209.27
G/R		-	0.19	0.24	0.19	0.27	0.18	0.23
Rank by G		-	6	3	5	2	4	1

Table 4 provides the same summary statistics as in Table 3 for the combined tolls. As expected, all tolls are higher than the corresponding congestion tolls. Consequently, reductions in the auto share of trips, congestion, travel times, and vkt are larger, although the relative changes are similar to those for the congestion tolls. Total welfare gains and welfare gains per unit of revenue collected are both much higher than for the congestion tolls. The rankings also change, with

[27] Safirova et al. (2007b) 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 corresponding index of efficacy is 0.530 for their congestion tolls, and 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 larger values is that their Downtown cordon encloses a very small area compared to the Beltway cordon.

Cordon 1 now outperforming Cordon 3, and Cordon 1&3 outperforming Cordon 2&3. This is 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 3. 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.

Table 4: Summary statistics for flat combined tolls

		No toll	Cordon 1	Cordon 2	Cordon 3	Cordon 1&2	Cordon 1&3	Cordon 2&3
	Ring 1	-	4.07	-	-	1.60	3.31	-
Toll levels	Ring 2	-	-	8.41	-	5.26	-	6.93
	Ring 3	-	-	-	6.63	-	3.95	2.24
Auto 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 [€]		-4.40	-4.72	-5.09	-5.11	-5.07	-5.15	-5.23
Total vehicle km [10^6]		2.75	2.70	2.50	2.43	2.56	2.51	2.43
Welfare gain/capita-yr (G) [€]		-	126.44	137.91	68.59	141.52	154.57	145.31
Revenue/capita-yr (R) [€]		-	108.23	203.21	199.46	199.30	230.09	242.18
G/R		-	1.17	0.68	0.34	0.71	0.67	0.60
Rank by G		-	5	4	6	3	1	2
Reduction in pollution costs [€]		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. Yet, vkt drop by less than 9 percent. The reduction in pollution costs is disproportionately large because, as shown in Section 5, traffic flows drop sharply on the inner arterial links where population is concentrated. This is evident in Figure 4 where the annual per capita health costs decline most strongly near the city center. The costs also decline moderately in most of the eastern hemisphere of the city. However, costs rise slightly on a few segments of Ring Roads 2 and 3 as travelers avoid the toll by driving around the ring road rather than crossing it inwards. Costs also rise slightly in much of the western hemisphere as travelers take advantage of the reduction in congestion elsewhere by driving more.[28] As explained in Section 3.3, these two effects can be understood as the (unintended) effects 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 vkt. This demonstrates that distance driven can be a poor indicator 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 higher 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.

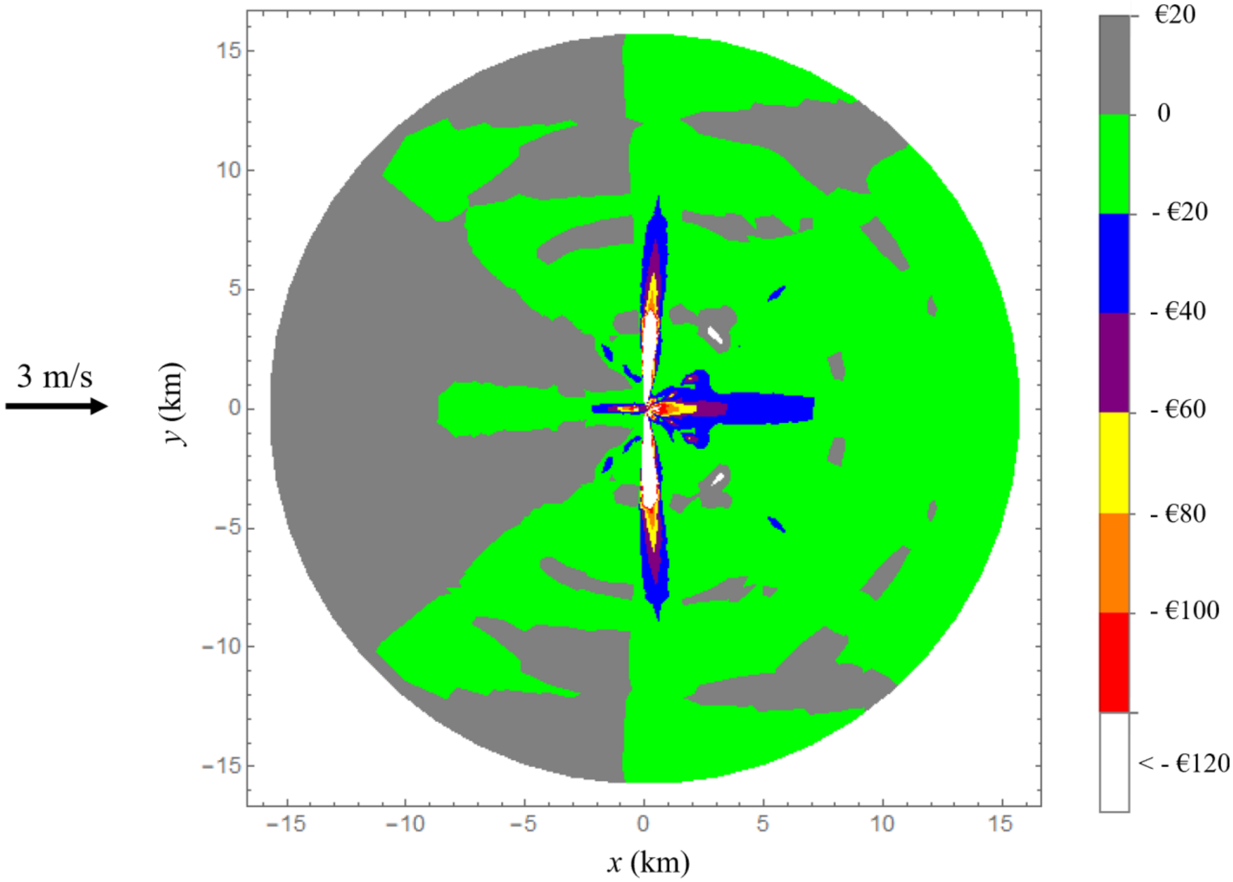

Figure 4: Change in annual per capita health costs with combined flat Cordon 1&3 toll

[28] Similarly, 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 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: Flat combined 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 percent 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
Auto 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 [€]		-4.40	-4.44	-4.45	-4.62
Total vehicle km [10^6]		2.75	2.76	2.75	2.73
Welfare gain/capita-yr (G) [€]		-	56.09	99.45	87.88
Revenue/capita-yr (R) [€]		-	67.89	111.87	143.28
G/R		-	0.83	0.89	0.61
Rank by G		-	3	1	2

Summary statistics for optimal congestion step tolls are listed in Table 6, and optimal combined step tolls in Table 7. All the combined tolls are higher than their congestion-toll counterparts, although the differences are relatively modest. Consequently, the revenues collected and the 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 flat combined tolls in Table 4, the step combined tolls are more effective in targeting congestion without significantly reducing auto travel. These differences mirror the differences between flat and step congestion tolls in Tables 3 and 6.[29]

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
Auto 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 [€]		-4.40	-4.49	-4.51	-4.70
Total vehicle km [10^6]		2.75	2.75	2.73	2.72
Welfare gain/capita-yr (G) [€]		-	143.40	169.29	133.36
Revenue/capita-yr (R) [€]		-	92.73	126.94	166.50
G/R		-	1.55	1.33	0.80
Rank by G		-	2	1	3
Reduction in pollution costs [€]		0	78,934	74,573	44,726

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 5, is similar to the pattern for the flat combined Cordon 1&3 toll in Figure 4, although costs decline in a smaller fraction of the city area.

[29] The reductions in delays are broadly similar to those achieved by the Stockholm Congestion tax. According to Eliasson et al. (2009), delays on arterials fell by a third during the morning peak, and one half during the evening peak. The congestion index in Table 7 falls by more than one half with the Cordon 2 toll, and by somewhat less than one half with the Cordon 1 and Cordon 3 tolls. Insofar as the METROPOLIS simulations feature queuing congestion, whereas both queuing and flow congestion occur in practice, the model-based reductions are expected to be larger unless hypercongestion was prevalent on the Stockholm network before the congestion charge was imposed.

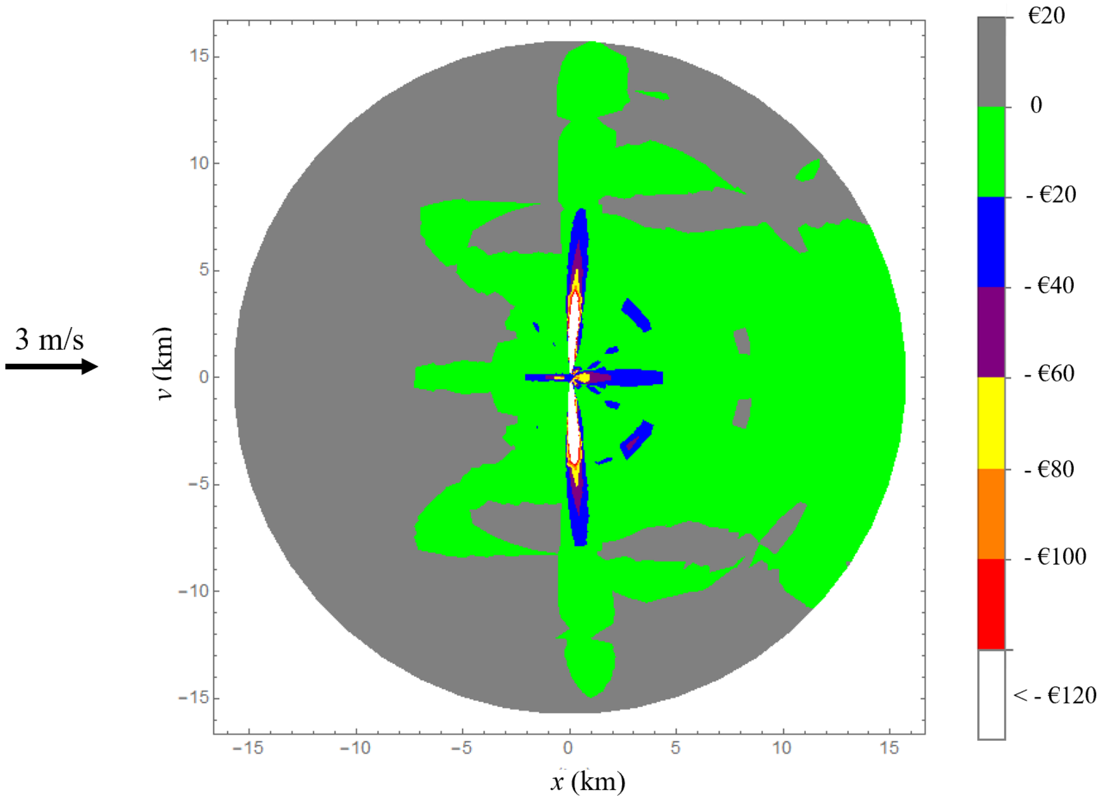

Figure 5: Change in annual per capita health costs with combined step Cordon 2 toll

5 EFFECTS OF TOLLING

Section 4 provides an initial look at how tolling affects travel decisions and welfare. This section undertakes a more detailed examination for the three best-performing or "leading" combined tolling schemes: the flat Cordon 2, the flat Cordon 1&3, and the step Cordon 2. It concludes with a summary of the aggregate welfare gains and toll revenues generated for all nine tolling schemes.

5.1 Traffic flows

Traffic flows for the no-toll and three leading combined tolling schemes are presented in Figure 6. These flows are aggregated over the period 6:00-9:30, and averaged over the links of each type.[30] In the no-toll equilibrium, flows are generally heaviest on the inbound arterials,

[30] Flows on the ring road links running in the clockwise and counter-clockwise directions are added, and then divided by two.

intermediate on the outbound arterials, and lowest on the ring roads. The flat combined Cordon 2 toll reduces flows on all link types except for Ring Roads 2 and 3. As noted earlier, increased flows on these links reflect traffic diversion to avoid the toll. The flat Cordon 1&3 toll has similar effects to the Cordon 2 toll except that, as expected, it reduces usage of the *In2* links by less because these links are not tolled. The step combined Cordon 2 toll has qualitatively similar, but smaller, impacts than the flat tolls.

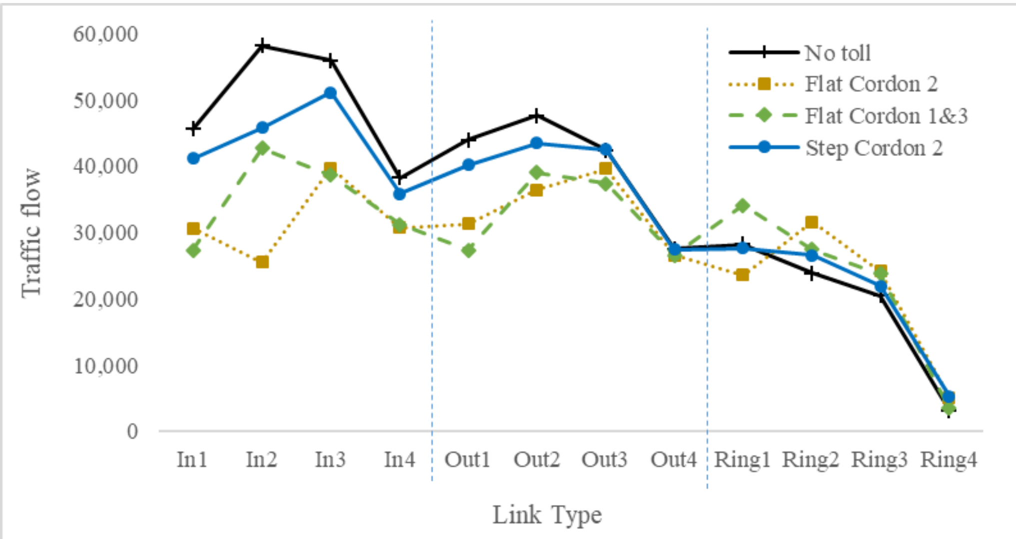

Figure 6: Link flows with no toll and with leading combined tolls

5.2 Trip distances

The overall effect of a cordon toll on mean trip distance is ambiguous, a priori. Several forces are at work. First, regardless of their trip distance, travelers can stop driving and take public transport. Second, travelers taking short trips are less likely to encounter the toll because their preferred route is less likely to cross the cordon. Third, because the toll reduces congestion, it can make trips along the shortest-distance-path more attractive compared to longer, circuitous routes. However, the toll can also induce rerouting to a longer path in order to avoid the toll. The shortest path runs through the charging zone for trips destined either to the other side (i.e., along a diameter) or to a destination on an arterial at an angle of 135° or 225° to the originating arterial.[31] Travelers taking these trips who choose to avoid the toll by skirting around the cordon have to travel a greater distance.

[31] See the appendix for a proof.

Average trip distances for the combined flat and step tolls are reported in Tables 4 and 7, respectively. Changes in the frequency distribution of distance for the leading toll schemes are shown in Figure 7. In all three cases, short and long trips become more prevalent at the expense of trips of intermediate distance. Similar to traffic flows, the step toll has a less pronounced effect on the distribution. These results can be compared with those obtained by Namdeo (2008) in a study of tolling on the road network of Leeds in the UK. He finds that a single £3 cordon charge increases mean trip length by 4-5%. He also finds that the increase in mean trip distance is less marked for a double cordon. Here, the flat Cordon 1&3 toll has no effect on average trip distance (see Table 4), and it affects the distribution less than the flat Cordon 2 toll (Figure 7).

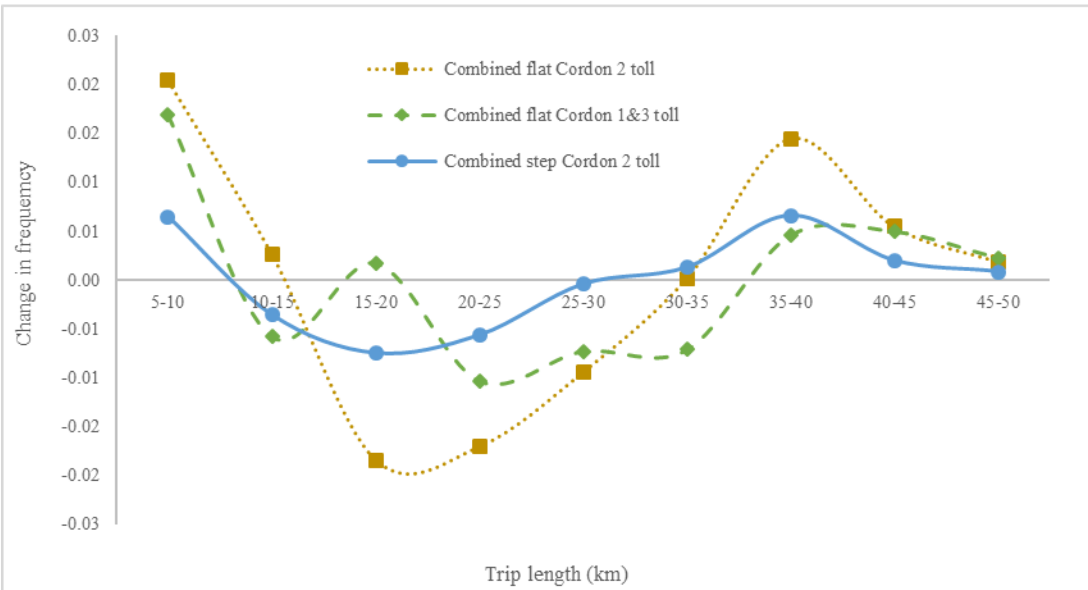

Figure 7: Effects of leading combined tolls on trip distances

5.3 Trip durations

As reported in Tables 4 and 7, all nine tolling schemes reduce average trip duration. This is a natural consequence of the increase in average speeds. For the three leading schemes, average trip durations decrease by 11.5 to 15.4 percent. Changes in the frequency distribution of durations, shown in Figure 8, are proportionally larger than the changes in trip distance shown in Figure 7. In all cases, there is a shift from medium to shorter durations. Yang and Huang (2005, pp. 304-5) report a similar pattern in a study, using a static model, of simulated single and double cordon tolls on the Shanghai network. They attribute the increase in quicker trips to two of the forces identified above: higher speeds, and the fact that most short trips do not have to re-route to avoid paying a toll.

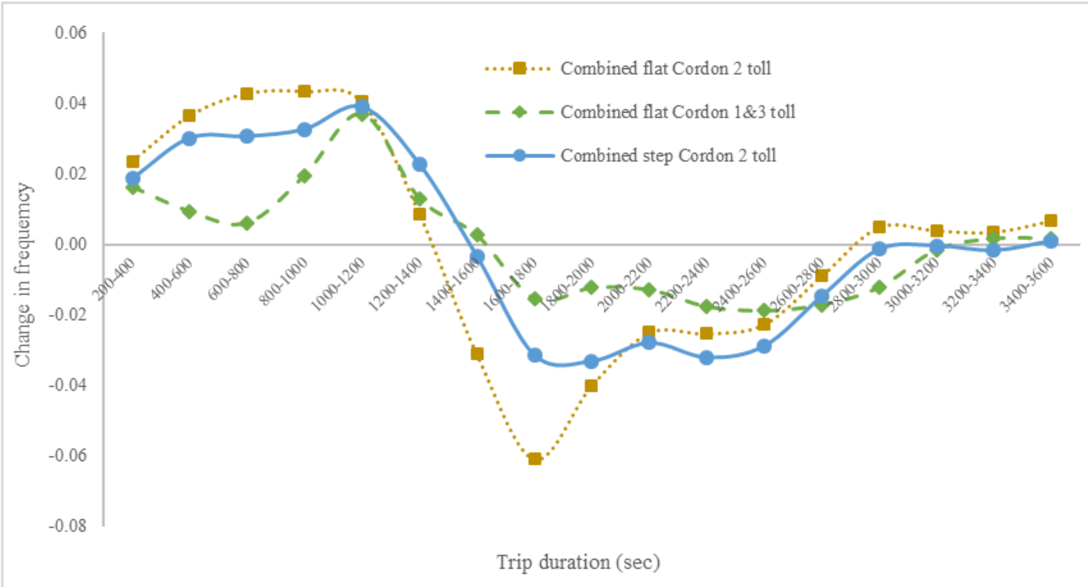

Figure 8: Effects of leading combined tolls on trip durations

5.4 Departure times

Figure 9 shows the effects of tolling on departure times.[32] 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.[33] 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. Consequently, these tolls spread departures out both before and after the 6:30 - 7:30 peak period, rather than only afterwards.

[32] Unlike Figures 7 and 8, Figure 9 shows changes to the cumulative distribution rather than the frequency distribution.

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

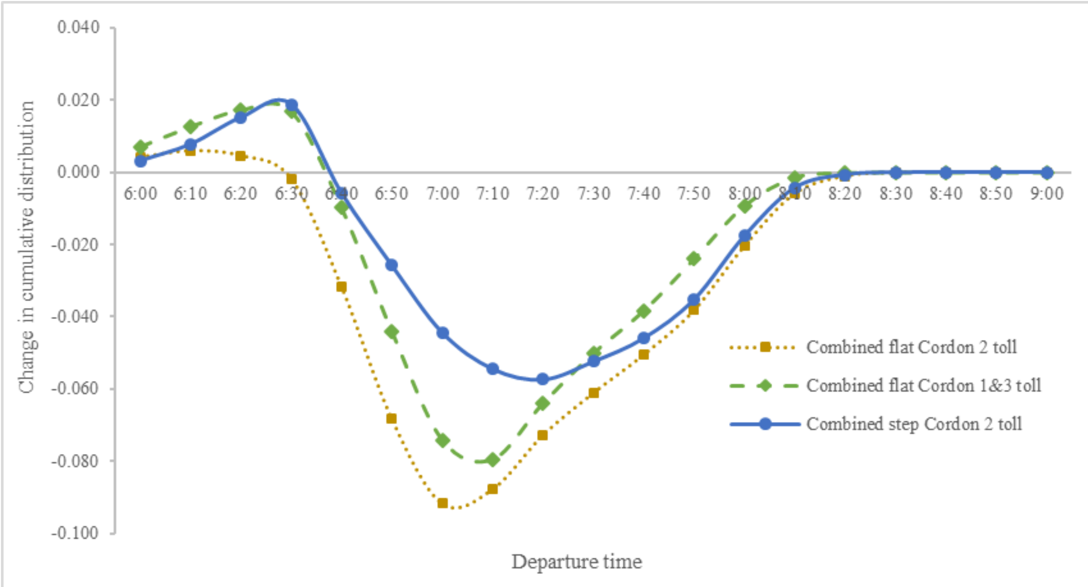

Figure 9: Effects of leading combined tolls on departure times

5.5 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 transit service, or other public goods and services. Revenues can also be rebated in some 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. Hence, about three-quarters of the population are excluded from the consumers' surplus calculations for travelers. Those who do travel begin the simulation period at their respective origins, travel by auto or public transit 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. Roughly speaking, the fraction who pay a toll decreases with its level.

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 toll payment 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 percent for the Flat Cordon 1&3 toll to 38 percent 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* fair worse than the *Untolled*. The difference 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 percent gain from the Flat Cordon 1&3 toll. By contrast, nearly 17 percent of the *Tolled* gain from the Step Cordon 2 toll.

Figures 10-12 show the frequency distribution of gains and losses for the *Tolled* and *Untolled*. For the flat Cordon 2 toll (Figure 10), the overall distribution is bimodal. Almost all the *Tolled* incur losses which range from €2.00 to €4.75. Many of the *Untolled* incur substantial losses as well. The distribution for the Flat Cordon 1&3 toll (Figure 11) 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 €7.45. For the Step Cordon 2 toll (Figure 12), the distribution is unimodal, and there is greater overlap between the *Tolled* and *Untolled*.

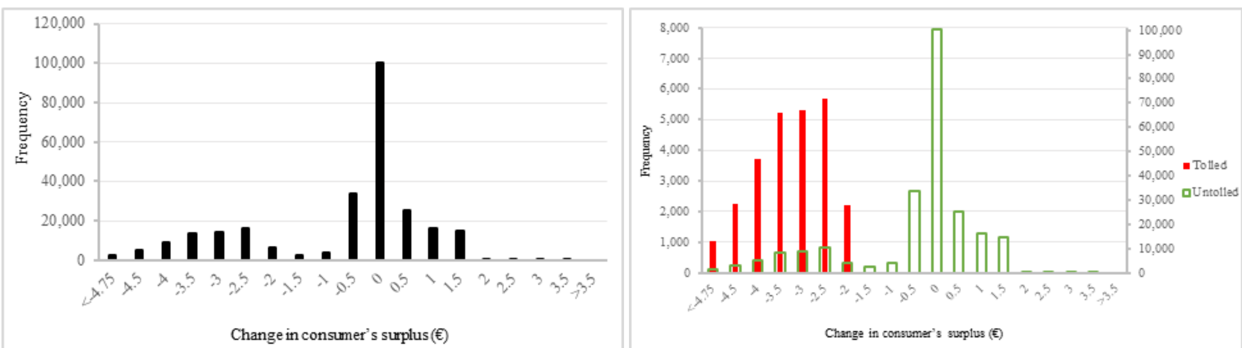

Figure 10: Change in daily consumers' surplus for combined Flat Cordon 2 toll
Left panel: all travelers. Right panel: Tolled (left axis) and Untolled (right axis)

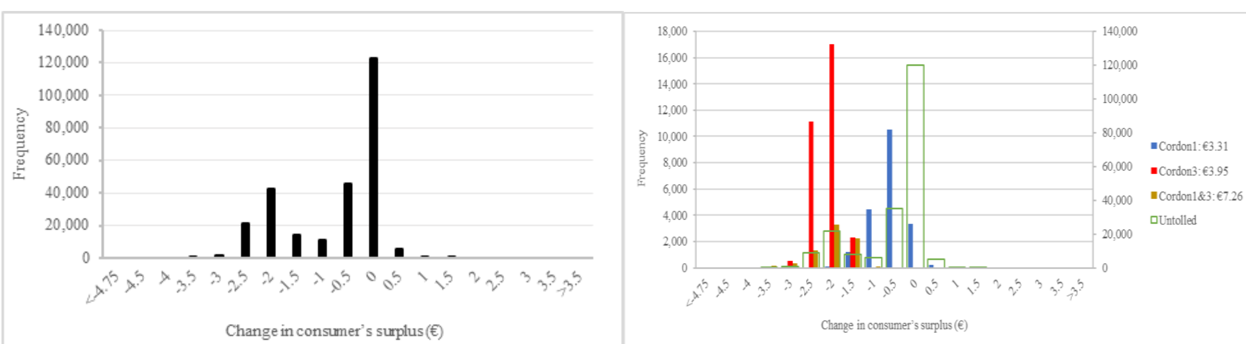

Figure 11: Change in daily consumers' surplus for combined Flat Cordon 1&3 toll
Left panel: all travelers. Right panel: Tolled (left axis) and Untolled (right axis)

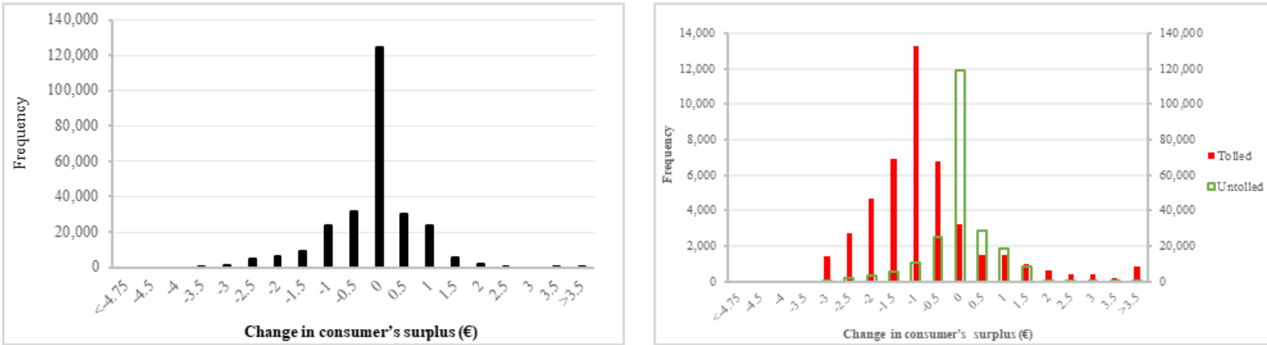

Figure 12: Change in daily consumers' surplus for combined Step Cordon 2 toll
Left panel: all travelers. Right panel: Tolled (left axis) and Untolled (right axis)

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 transit. 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 percent of them are worse off, and 13 percent switch to transit. 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 10.

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 transit. Travelers beginning on Rings 1 and 3 pay one of the tolls if they travel inwards, and over 90 percent 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 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 transit are worse off because they chose not to take transit in the equilibrium without tolls. 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 percent 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. 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 percent 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 never use 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	Losers	Switch to transit	Mean ΔCS	Losers	Switch to transit	Mean ΔCS	Losers	Switch to transit
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 4 and 5. To give a rough assessment of the gainers and losers, receptors are divided into eight groups according to whether they are located on the east side or west side of the city, and between which pair of ring roads. The populations at each receptor are then aggregated, and the fraction of residents in each group that suffer an increase in pollution costs are calculated. The results are reported in Table 11. Consistent with Figures 4 and 5, the fractions of losers are lowest on the inner rings of the east side, and highest on the outer rings of the west side. The contrast between east and west is marked for each tolling scheme, with less than one fifth of residents experiencing higher costs in the east, whereas over three fifths do in the west. Naturally, the difference depends on wind speeds and directions, which in practice vary diurnally, day by day, and with the season.

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

	Flat Cordon 2		Flat Cordon 1&3		Step Cordon 2	
Origin	East side	West side	East side	West side	East side	West 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%**	

5.6 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 13 shows the trade-off between welfare gains and revenues for the congestion tolls. For the single cordons, the step tolls clearly dominate the flat tolls as far as welfare since the welfare gains are several times as large. 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.

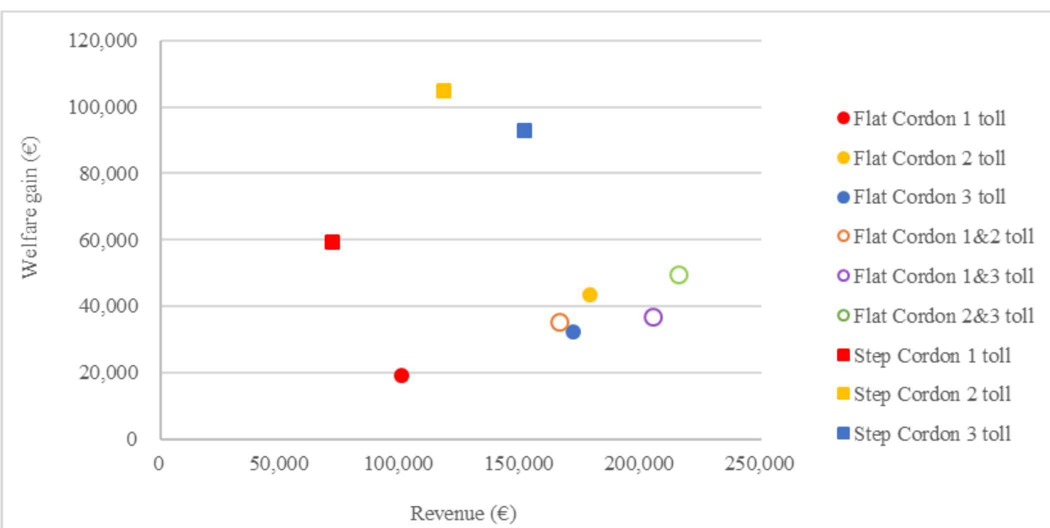

Figure 13: Total daily welfare gains vs revenues for congestion tolls

Figure 14 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.

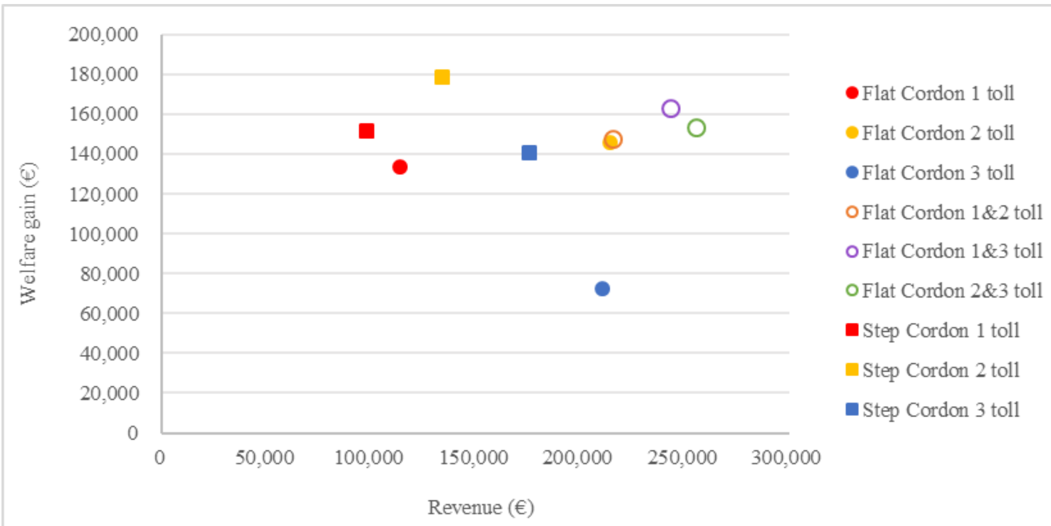

Figure 14: Total daily welfare gains vs revenues for combined tolls

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 15 illustrates for the Flat Cordon 2 toll.

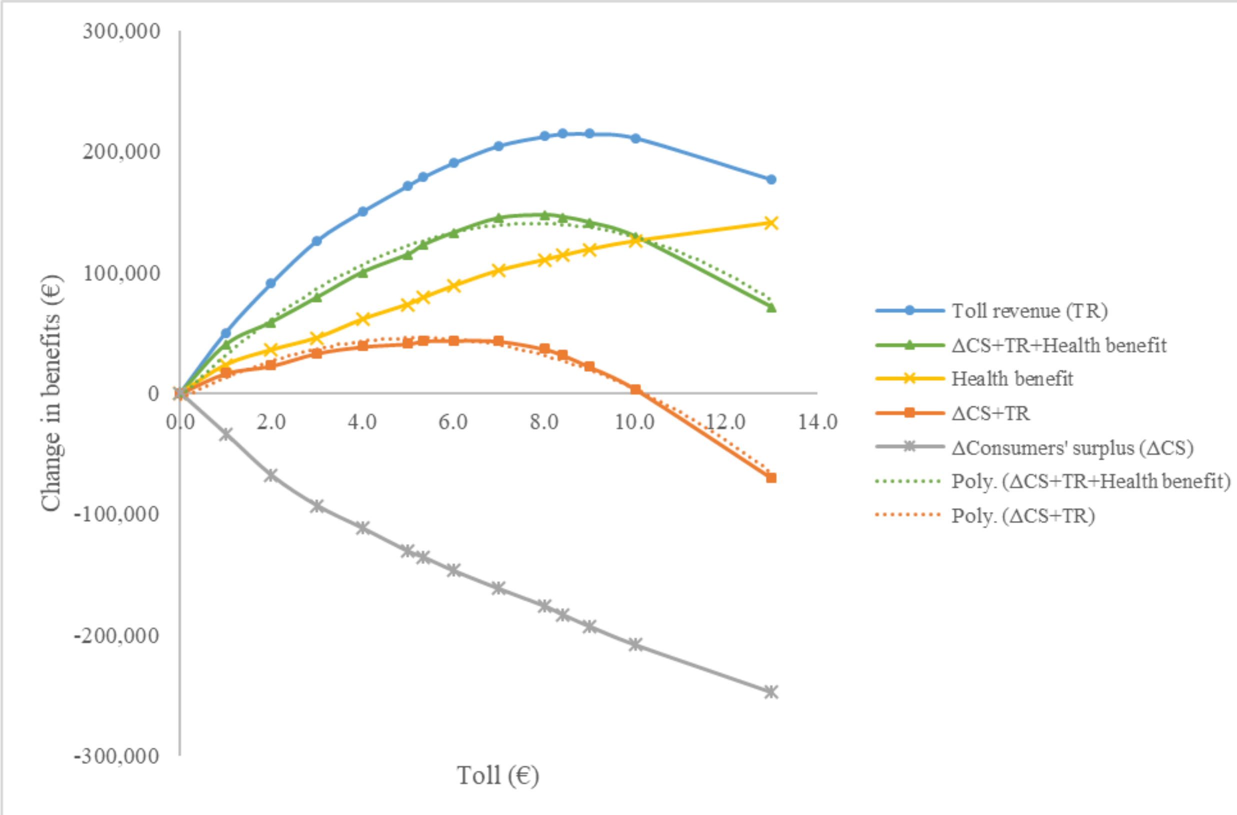

Figure 15: Changes in consumers' surplus, toll revenue, and health benefits as a function of the flat Cordon 2 toll

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.[34] Figure 16 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.[35] To the north-west of this point, the locus becomes flatter, and health benefits are assigned a progressively higher relative weight.

[34] On other networks it is possible for health benefits to 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 vehicle-km.

[35] Note the difference in scale on the horizontal and vertical axes.

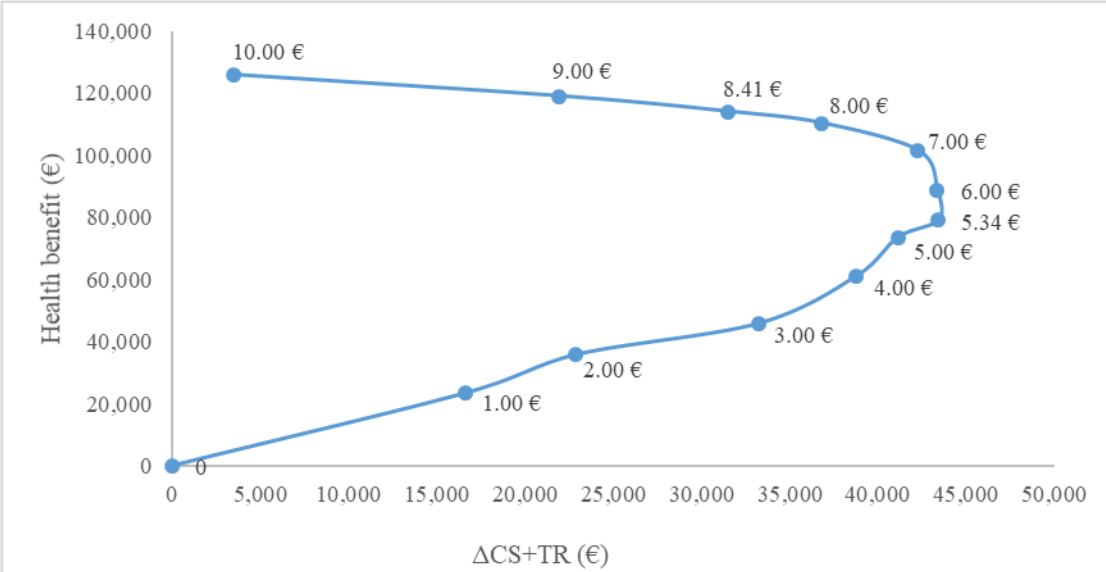

Figure 16: Trade-off between transport benefits and health benefits as a function of the flat Cordon 2 toll

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. In this paper, we use 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, we supplement METROPOLIS with a Gaussian dispersion model that accounts for wind speed and direction. We apply the combined model to a stylized urban road network during a morning commuting period, and 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. Tolling increases average travel speeds, reduces average travel times, shifts some trips from automobile to public transport, and reduces emissions. Accounting for the health costs of pollution raises the optimal levels of tolls, and increases substantially the welfare gains from tolling relative to the gains from congestion relief alone. Step tolls are highly effective in reducing congestion without greatly increasing travelers' costs, but have only a modest advantage over flat tolls for pricing emissions. Accounting for emissions 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. Overall, the results suggest that a single flat cordon toll on one of the inner rings might be a good choice as far as the trade-off between welfare gains, revenue generated, and complexity of design and operation. Marketing the cordon toll as a tool for reducing emissions as well as congestion could improve the public acceptability of tolling, and it would not require much additional infrastructure or accounting costs.

The analysis could be extended in several directions. Traveler decisions besides transport mode, departure time, and route could be added including vehicle ownership, choice of residential and workplace location, vehicle occupancy, trip destination, and parking location. Variations both within a day and from day to day in wind speed, wind direction, and precipitation affect the severity of pollution and hence the optimal levels of tolls. This creates a role for predictive pricing, as Vosough et al. (2020) study using a static model. 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 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).

Finally, the simulations were carried out on a stylized city with a symmetric road network in which trip destinations and population are both concentrated toward the center. Single cordon tolls tend to perform well with this configuration. Other, asymmetric city topologies as well as larger networks and real cities are worth investigating.

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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
Auto	
Unit cost of travel time by automobile (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 auto departure-time choice (μ_t)	€2
Mode choice and public transportation	
Logit scale parameter for mode choice (μ_m)	€5
Unit cost of travel time by public transportation (α_P)	€15/h
Fixed penalty for public transportation (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 transit	∞	40

8.3 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.

8.4 Extra distance traveled when rerouting around a cordon

Assume the cordon toll is imposed on Ring Road *i*. Consider a trip starting on ring road *j* and ending on ring road *k*, with an angle of $45n\,°$, $n \in \{1,2,3,4\}$, between the arterial running from the origin to the center, and the arterial running from the center to the destination. If $j < i$, the traveler begins the trip within the charging zone and does not have to pay the toll. If $j \geq i$ and $k < i$, the traveler has no choice but to pay the toll. Hence, one can assume $j \geq i$ and $k \geq i$.

An example with $i = 2$, $j = 3$, $k = 4$, and $n = 3$ is shown in Figure A1.

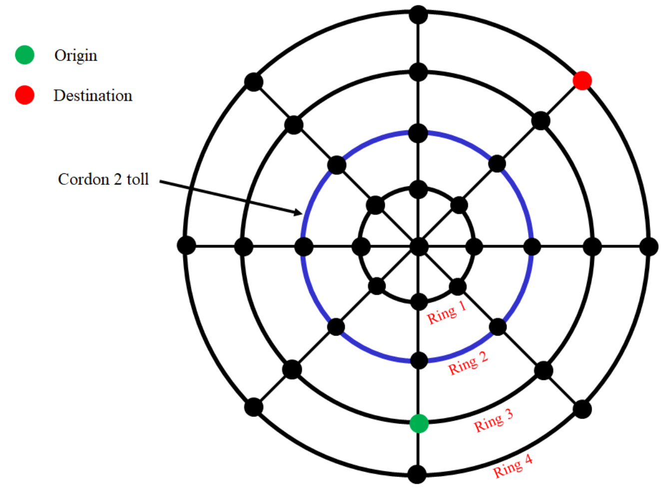

Figure A1: An example O-D pair

If the shortest path passes through the charging zone, it runs inwards on an arterial to the center and then outwards to the destination. Since arterial links are 4 km long, the distance traveled is $4(j+k)$. An alternative to traveling through the charging zone is to drive inbound along an arterial from ring road *j* to ring road *i*, drive around *n* links of ring road *i*, and finally go outwards along an arterial to ring road *k*. The distance traveled is $4(j-i)+n\frac{2\cdot\pi\cdot(4i)}{8}+4(k-i)=4(j+k-2i)+n\pi i$.

The extra distance traveled to avoid the toll is $(n\pi-8)i$, which is positive if $n=3$ or $n=4$.

If $j>i$ and $k>i$, a second alternative is to avoid Ring Road *i* and drive circumferentially around ring road *j* or *k*. If $j>k$, the best route is to drive inwards from ring road *j* to ring road *k*, and then drive circumferentially around ring road *k* to the destination. The distance traveled is $4(k-j)+n\pi k$, which differs from the first alternative by $(n\pi-8)(k-i)$. This is positive if $n=3$ or $n=4$. If $j<k$ (as in Figure A1), the best route is to drive circumferentially around ring road *j*, and then outwards to the destination on ring road *k*. The distance traveled is $4(j-k)+n\pi j$, which differs from the first alternative by $(n\pi-8)(j-i)$. Again, this is positive if $n=3$ or $n=4$.

Thus, avoiding the toll adds to the distance traveled for destinations at angles of 135°, 180° or 225° from the origin.