Green Vehicles’ Responses to an Expiring Congestion Toll Exemption: Findings from a Natural Experiment in Stockholm, Sweden

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Abstract

Stockholm established time-varying congestion pricing in 2007, and adopted a toll exemption as a temporary incentive for green vehicles (GVs) that ended in 2012. We examine the behavioral effects of phasing out the exemption by studying the change in cordon crossing events for GV morning commuters between May 2012 and May 2013, with a random sample of conventional vehicles (CVs) as control. The results suggest i) a significant drop in the total number of crossings; ii) a slight shift towards later journeys in the morning; and iii) a reduction in the ratio of peak-toll period crossings to other ones.

1 Introduction

Negative externalities from road transport are numerous. It accounts for a major part of global climate emissions and it causes noise and air pollution in the form of nitrogen oxides and particulate matter (Hugosson and Algers (2012)). In addition to these environmental impacts, it induces traffic safety risks and congestion leading to increased travel times for other travelers. Supply-side policies to mitigate these effects include transit investments, fuel standards, and emission regulations, while demand-side policies comprise purchase or driving restrictions, taxation of high-emission vehicles, as well as subsidies to alternative fuel vehicles (Hugosson and Algers (2012)), which we refer to as Green Vehicles (GVs) here. The current study is focused on another demand-side policy, congestion pricing, which in addition to reducing congestion is expected to reduce air pollution, time loss, and traffic accidents (Ge et al.)
Behavioral adjustments in response to a congestion toll can affect car ownership, route choice, mode choice, and departure time (see Karlström and Franklin (2009)). Congestion pricing schemes have been implemented in large cities such as London (2003), Stockholm (2006), Milan (2008), Rome (2001), Singapore (the late 1990s), and in smaller towns such as Durham in England, Znojmo (Czech Republic), Valletta (Malta, 2007). It is a topic of interest in other parts of the world, such as The Netherlands, Copenhagen, Budapest, Djakarta, San Francisco, and New York City, which are all considering congestion charges or planning to introduce them (Börjesson et al. (2012)). Gu et al. (2018) reviewed different area-based congestion pricing schemes in some of these cities and provided an analysis of public acceptance, which has been identified as the main barrier to congestion pricing implementation.

The policy has a relatively recent history in Stockholm. In 2006, the city introduced a seven-month trial of congestion charges and in August 2007, it reintroduced them on a permanent basis. The purpose was to decrease congestion in the city center, increase accessibility, and reduce environmental impacts (Karlström and Franklin (2009)).

The scheme consists of a cordon that surrounds the central city and car owners are charged a toll that varies by the time of the day. Previous studies have found that the charges have been effective in reducing traffic across the cordon, leading to substantial reductions in congestion within and around the city (Hamilton et al. (2014)). In a short period, GVs were exempt from charges to incentivize their purchase. However, the exemption was in effect up to and including July 2012 for vehicles that were entered in the Swedish Road Traffic Registry prior to 1 January 2009 (see Swedish Transport Agency (2010)). Since then, the congestion charging system in Stockholm has remained largely unchanged.

In this study, we revisit this topic with a unique, previously unpublished data set. Over an introductory period, green vehicles (GVs) were exempt from charges to incentivize their purchase, while conventional vehicles (CVs) were subject to the tolls. (Here, GVs are defined as vehicles following the description of “clean vehicles” in Hugosson and Algers (2012) regarding fuel type.) However, following a rapid increase in GV sales and a concern that the congestion reductions could be undermined, the exemption was phased out on 1st January 2009 for newly registered GVs, and on 1st July 2012 for GVs registered prior to 1st January 2009 (Swedish Transport Agency (2010)). Consequently, in 2012, older GVs faced a toll price increase while CVs and newer GVs saw no toll price change.
2 Literature review

The need for higher accessibility as the requirement of specialization of production and labor market and lifestyles as a source of well-being and economic development (Eliasson, 2021). As urbanization and transport volumes increase, other problems such as congestion, poor air quality, and noise pollution arise (Heyer et al., 2020; Qu and Wang, 2021).

Congestion pricing developed based on the idea that people tend to make socially beneficial decisions when considering the social costs and benefits of their actions (Lindsney and Verhoef, 2001). Reaching the balance between the costs and benefits of transportation, while increasing the efficiency of the transport system has been studied with various methods (Eliasson, 2021; Qu and Wang, 2021; Xu et al., 2021; Bie et al., 2020; Daganzo et al., 2020; Seki et al., 2018).

While different tools can be used for demand management, economists widely regard congestion pricing as the most effective method due to the inclusion of the price mechanism, offering clarity, universality, and efficiency. The concept of congestion pricing dates back to the works of Pigou (1920) and Knight (1924), but was advanced by the theoretical and practical arguments from William Vickrey over approximately four decades. Vickrey (1963) recognized the potential impact of road pricing on influencing travelers’ choices of routes, modes of travel, and its implications for urban development. He also explored other methods for automated toll collection and proposed dynamic parking fees based on real-time occupancy rate (Lindsney and Verhoef, 2001).

There are different variations in implementing congestion pricing such as pricing a point on the road, for example, a bridge, tunnel, roadway, or an area where vehicles are charged upon entrance and exit, or traveling within the area (Sabounchi et al., 2014).

Singapore’s Electronic Road Pricing (ERP) system is one of the earliest congestion pricing schemes, which defined a restricted zone in the central business district. This system is flexible in terms of variable pricing based on time (off-peak and weekend schemes) and location, which encourages travelers to adjust their routes and travel times. ERP has effectively reduced traffic congestion and improved traffic flow in the city-state by 43%, and there was a significant shift from the restricted hours (7:30 - 9:30 am) to other hours for commute (Phang and Toh, 2004). The more recent developments in downtown congestion pricing implementations are studied by Lehe (2019), where cases of Singapore, London, Stockholm, Milan, and Gothenburg are compared, and briefly addressed in the following.

The London Congestion Charge, introduced in 2003, has played a crucial role in reducing traffic congestion in central London. It has led to a significant decrease in the number of vehicles entering the congestion charge zone and an increase in the use of public transportation and taxi services. The fee does not depend on time of the day...
or location (other than the congestion scheme area). Revenues from the scheme have been reinvested in improving London’s public transport infrastructure (Litman, 2005).

Milan’s AreaC congestion charging was started in 2012, and is based on the vehicle emission class, and user class. The charge has reduced traffic congestion of vehicles but not of motorcycles as they are exempt. The revenues are used to support public transportation (trams and buses) and bike shares (Lehe, 2019; Cornago et al., 2019).

Gothenburg introduced a time-varying cordon-based congestion tax in 2013. The scheme has reduced traffic reduction by 12% in the cordon during the charged hours. The revenues are close to Stockholm’s, despite having lower population (Börjesson and Kristoffersson, 2015).

The Oslo toll ring system started in 1990 to fund road improvements, allocates a significant portion (currently about 60%) of its toll revenue to public transport investments and maintenance. However, despite this investment in public transport, peak-hour congestion remains a major issue in the Oslo area, which results in increased pollution, longer travel times, and higher energy consumption. In a study by Aasness (2014), the conversion of the current flat-rate toll system to a congestion-based pricing scheme. Their findings indicate that changing the toll system to charge higher fees during peak hours has the potential to alleviate traffic congestion.

Other examples of area-based schemes are Valetta, Malta (Attard and Ison, 2010) and Durham, England (Santos and Fraser, 2006).

The debate surrounding congestion pricing often focuses on perceived inequities and its impact on different income groups. Equitable outcomes depend on factors such as travel patterns, system design, and revenue allocation (Eliasson, 2021). Congestion pricing’s equity profile is similar to consumption taxes; the wealthy, who drive more, pay more. However, variations within income groups cause inconsistencies. While charges seem income-proportional on average, lower-income individuals who drive more may be disproportionately affected within their group (Eliasson et al., 2018). If these charges aim for revenue, their distributional effects are relevant (Eliasson and Mattsson, 2006; Kristoffersson et al., 2017; Guo and Yang, 2010), but from a transport planning perspective, they correct prices for societal costs, reducing subsidies that primarily benefit the rich. Revenue use also affects equity, necessitating balanced pricing designs.

Aside from self-interest, there are multiple factors that impact the acceptability of congestion pricing, including environmental effects, trust in the government to design and manage the system and use revenues efficiently, viewing pricing as a fair allocation mechanism (Eliasson and Mattsson, 2006; Börjesson et al., 2016; Eliasson, 2014; Eliasson and Jonsson, 2011; Hamilton et al., 2014; Jaensirisak et al., 2003; Ma and He, 2020).

There are several outcomes from the currently implemented congestion pricing scheme in Stockholm. The main outcome is less congestion, not only in the charged paths, but also in other paths connected to them due to the "network effect". Another
outcome is the high value of time savings restored due to less congestion which compensates for around 70% of the congestion toll revenues (Eliasson, 2008). There are also health and safety outcomes, among which are fewer reported cases of asthma for children (Simeonova et al., 2021). Singichetti et al. (2021) studied three cities of Stockholm, London, and Milan, and concluded that there are potential safety benefits in terms of accidents and injuries for road users following congestion pricing schemes implementations.

3 QUESTIONS

Stockholm’s congestion pricing scheme consisted of a time-varying cordon toll, with peaks in the morning (7:30-8:30 am) and in the afternoon (4:00-5:30 pm). While previous studies found that the charges were generally effective in reducing congestion in the city, it may be challenging to pinpoint the behavioral effects of the policy as compared to other general trends in society.

Seeing the temporary exemption for a subset of the GV fleet as a natural experiment, the objective of the current study is to investigate whether GVs changed their cordon crossing times towards periods with lower charges in 2013, after the termination of the exemption, as compared to 2012, when the exemption was still in effect.

Specifically, the research questions are:

- Was there a reduction in the number of cordon crossings (i.e. number of times that vehicles crossed toll stations)?

- Focusing on cars that traveled both years, was there a shift in cordon crossing times (i.e. time of the day that a vehicle crossed the toll station), in terms of mean and variance?

- Did the number of crossings in the peak toll period decrease?

4 METHODS

4.1 Data

The Swedish Transport Agency operates Sweden’s congestion pricing systems, billing vehicle owners through the use of automated number plate recognition. During tolling periods, such data are collected continuously, and then linked to vehicle registry data and archived for billing and reporting. For the current study, the agency provided a set of anonymized records for all detected GVs and a random sample of CVs. While the vehicle identification numbers were encrypted, a recycled encryption key allowed matching between similar 2-week periods in 2012 and 2013 records so that changes in crossing patterns for the same vehicle could be measured. Data were collected in 2012.
Table 1: Toll prices for the time of day

<table>
<thead>
<tr>
<th>Time</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:30-7:00</td>
<td>10</td>
</tr>
<tr>
<td>7:00-7:30</td>
<td>15</td>
</tr>
<tr>
<td>7:30-8:30</td>
<td>20</td>
</tr>
<tr>
<td>8:30-9:00</td>
<td>15</td>
</tr>
<tr>
<td>9:00-15:30</td>
<td>10</td>
</tr>
<tr>
<td>15:30-16:00</td>
<td>15</td>
</tr>
<tr>
<td>16:00-17:30</td>
<td>20</td>
</tr>
<tr>
<td>17:30-18:00</td>
<td>15</td>
</tr>
<tr>
<td>18:00-18:30</td>
<td>10</td>
</tr>
</tbody>
</table>

and 2013 on working days between May 23rd and June 4th from 6:30 am to 6:30 pm. To understand changes in travelers’ behaviour before and after the discontinuation of the toll exemption, the same groups of vehicles are selected in 2012 and 2013. The change in behaviour is analysed through changes in crossing times at the toll stations. The following subsections explain the study groups and the statistical tests implemented in the analysis to specifically address toll-exempted GVs.

4.2 Study samples

We select a sample of vehicles with relatively consistent behavior and define them as morning commuters, namely cars that crossed the toll cordon in 2012 and 2013 on at least three different days, before 12:00, in each year’s 2-week study period.

4.3 Statistical analyses

This is an empirical study grounded in various statistical tests, as listed in Table 2. Essentially, we compare cordon crossing events in 2012 and 2013 for both GVs and CVs (control), focusing on morning trips (6:30 am – 12:00 am). As the data was not normal, all tests are non-parametric. Primarily, we examine whether there was a change in the number of trips after the introduction of the toll. Here, we account for cars present in the data set in either year. Then, we investigate the characteristics of the behavioral change, focusing on vehicles in the data set that travel both years. Since the number of observations for each vehicle was not always the same in both years, the data was not completely paired. Therefore, we consider the combination of all crossing times to generate pairs; for instance, if a vehicle has three observations in 2012 and two in 2013, we account for six pairs. Lastly, we study peak-toll behavior by comparing the number of crossings in the peak toll interval for GVs and CVs both years, as well as the share of peak-toll crossings to other crossings.
Table 2: The statistical tests implemented.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description and motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normality</td>
<td>We use the Kolmogorov-Smirnov (KS) test [Massey Jr, 1951], with a 0.05 significance level to test the normality of the samples.</td>
</tr>
<tr>
<td>Comparing medians</td>
<td>We apply the Wilcoxon signed-rank test for dependent (paired) data, with the null hypothesis is that there is no significant difference between the medians of the paired samples.</td>
</tr>
<tr>
<td>Comparing variances</td>
<td>For paired data, we use the Fligner-Killeen test, as proposed by [Michael and Edwardes, 2001] for data with many ties. The null hypothesis is that the variances of the two distributions are equal. For the whole distributions, we use Levene’s test for equality of variances.</td>
</tr>
<tr>
<td>Distribution shape</td>
<td>We conduct KS-tests [Massey Jr, 1951] with regard to the number of times each vehicle crossed the cordon during peak hours, and the ratio of this and number of crossing events.</td>
</tr>
</tbody>
</table>

5 FINDINGS

The analysis point at three key findings:

- For GVs, but not for CVs, the number cordon crossings decreased substantially between 2012 and 2013, as illustrated in Figure 1 from 69,563 to 46,764 (32.8%) (Table 3). A whole-sample comparison of the distributions of the number of crossings per car each year confirmed that there was a significant difference for GVs, with \( p = 1.7E-11 \) in a two-sided Wilcoxon test, but not for CVs (\( p = 0.08 \)). A one-sided Wilcoxon test confirmed that the number of trips for GVs was reduced in 2013 (\( p = 8.6E-12 \)).

- The ending of the toll exemption seems to have resulted in a slight shift towards later travel times for GVs. In a comparison of the average crossing time per vehicle in 2012 vs. 2013 (two-sided Wilcoxon tests), we found significant shifts for GVs (\( p = 4.3E-6 \)), but not for CVs. One-sided tests revealed that this shift was towards later times for GVs (\( p = 2.2E-6 \)). However, analyses per car showed that the tendency to shift crossing time between 2012 and 2013 was similar for GVs and CVs (Table 4). The shares of significant tests for CVs and GVs were 21% and 20%, respectively, in two-sided Wilcoxon tests that compared the median crossing time for each individual vehicle across the two years. One-sided tests suggested that the median crossing time for GVs shifted to later times in 2013 for 11% of the vehicles and to earlier times for 10% of them. Moreover, an assessment of the crossing time variance did not result in a difference across the two groups, with 15% and 13% significant tests for CVs and GVs, respectively.

- The omission of the toll exemption seems to have reduced traffic in the peak-toll period (7:30-8:30 am). Statistical tests comparing cordon crossings in this interval found a significant difference between 2012 and 2013 for GVs (\( p = 3.5E-4 \)), but not for CVs (Table 5). A one-sided test confirmed that there was a
significant decrease in the number of peak crossings \((p = 1.7\text{E}-4)\). Consistently, the ratio of peak-toll crossings to other crossings was different for GVs, but not CVs. Further, the variance was different in 2013 vs. 2012 for GVs (Levene test of variance \(p = 7.2\text{E}-3\)), but not for CVs.

In conclusion, the termination of the toll exemption had a considerable effect on the number of crossings, in particular on the number of crossings in the peak-toll period. There is some, albeit limited, evidence that this shift is towards later times for GVs.

These results should be considered with some limitations in mind. One regards the fact that some GVs were not exempt from tolls. We lacked information regarding which vehicles were registered before this date. This data shortcoming suggests that the shift in behavior during the peak toll period was an underestimate of the true behavioral impact of the toll. Additionally, we encountered a lack of complete CV data, with relatively few records as compared to GVs, which further restricted our results. Our results should be considered with these limitations in mind.

Table 3: Descriptive statistics for commuters’ toll cordon crossing events that we analyzed (6:30-12:00 am).

<table>
<thead>
<tr>
<th></th>
<th>CVs</th>
<th></th>
<th>GVs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of all observations</td>
<td>13,051</td>
<td>13,868</td>
<td>69,563</td>
<td>46,764</td>
</tr>
<tr>
<td>Number of all unique cars</td>
<td>4628</td>
<td></td>
<td>17,059</td>
<td></td>
</tr>
<tr>
<td>Number of unique commuters</td>
<td>359</td>
<td></td>
<td>2076</td>
<td></td>
</tr>
<tr>
<td>Median crossing time</td>
<td>8.46(b)</td>
<td>8.48</td>
<td>8.48</td>
<td>8.57</td>
</tr>
<tr>
<td>Mean crossing time</td>
<td>8.59</td>
<td>8.62</td>
<td>8.57</td>
<td>8.66</td>
</tr>
<tr>
<td>Std crossing time</td>
<td>0.81</td>
<td>0.82</td>
<td>0.68</td>
<td>0.72</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.39</td>
<td>0.32</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Average number of trips per car</td>
<td>5.79</td>
<td>5.55</td>
<td>6.23</td>
<td>5.90</td>
</tr>
<tr>
<td>(p)-value of KS-normal(a)</td>
<td>3.5E-11</td>
<td>9.2E-11</td>
<td>2.4E-52</td>
<td>6.3E-49</td>
</tr>
</tbody>
</table>

\(a\) A Kolmogorov–Smirnov normality test with a \(p\)-value < 0.05 indicates that the distribution is significantly different from the normal distribution.

\(b\) To facilitate computation we express time in terms of hours and decimal-hours, rather than hours: minutes, e.g., 8.46 would reflect the time 8:28.

Table 4: The percentage of cars with significant crossing time shifts between 2012 and 2013.

<table>
<thead>
<tr>
<th>Individual-car analyses: share of significant tests [%]</th>
<th>CVs</th>
<th>GVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilcoxon, two-sided (median)</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Wilcoxon, one-sided: later in 2013 (median)</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Wilcoxon, one-sided: earlier in 2013 (median)</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Fligner-Killeen (variance)</td>
<td>15</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 5: Results of non-parametric statistical tests that compared cordon crossing events in the peak morning toll interval (7:30-8:30 am) in 2012 and 2013.

<table>
<thead>
<tr>
<th>Peak toll interval crossing time shift</th>
<th>CVs Statistic</th>
<th>p-val</th>
<th>GVs Statistic</th>
<th>p-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of peak crossings (Wilcoxon two-sided)</td>
<td>7,835</td>
<td>0.65</td>
<td>255,529</td>
<td>3.5E-4</td>
</tr>
<tr>
<td>Number of peak crossings (Wilcoxon one-sided: higher in 2013)</td>
<td>8,456</td>
<td>0.68</td>
<td>327,132</td>
<td>1</td>
</tr>
<tr>
<td>Number of peak crossings (Wilcoxon one-sided: lower in 2013)</td>
<td>8,456</td>
<td>0.32</td>
<td>327,132</td>
<td>1.7E-4</td>
</tr>
<tr>
<td>Ratio of peak interval and other crossings (KS\textsuperscript{a})</td>
<td>0.11</td>
<td>0.16</td>
<td>0.10</td>
<td>2.0E-5</td>
</tr>
<tr>
<td>Variance test (L\textsuperscript{a})</td>
<td>0.10</td>
<td>0.75</td>
<td>7.2</td>
<td>7.1E-3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Abbreviations: KS: Kolmogorov-Smirnov test; L: Levene test.

Figure 1: Density plots of time of the day crossings based on different fuel categories. The width of each plot reflects the number of vehicles observed at the toll stations at any given time.
References


