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Impact of intercity tolls in Portugal – An environmental perspective

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Abstract

Alternative road pricing schemes are promising strategies to alleviate congestion and other environmental problems related to urban and regional road transportation. However, in practice, environmental issues are not often taken into account, especially at regional level. In 2010, due to the financial crisis in Portugal, several tolls were introduced in some motorways that were previously financed by the government. One of these cases was the A29 motorway, which connects the cities of Aveiro and Oporto. After the introduction of tolls about 50% of the Average Daily Traffic shifted to alternative routes or modes. This paper discusses the impact that tolls had on route choice, and evaluates the consequences in terms of emissions and energy use on the road network after tolls were implemented. Experimental tests were conducted during off-peak and peak periods before and after toll implementation. Vehicle dynamics were measured using a high-sensitivity GPS data logger. Using more than 10 000 km and 174 hours of data, a micro-scale methodology based on the Vehicle Specific Power (VSP) concept was used to extract second-by-second emissions in four alternative routes. The changes in traffic distribution caused by the introduction of tolls did not cause a significant impact in terms of emissions factors on the alternative routes. However, the findings indicate that the diversion of traffic from A29 to local roads implies an increase in CO_2 emissions and a reduction in local pollutants emissions such as CO and NO_x.

Keywords: Route Choice; Road Pricing Micro-scale emissions modelling; Tolls

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1. Introduction

Innovative road pricing strategies are increasingly being considered as an alternative to improve the efficiency on the transportation network. In a White Paper for Transportation, innovative road pricing

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schemes are suggested as a way to promote the use of public transport and the gradual introduction of alternative propulsion systems (European Commission, 2011). However, the introduction of extensive, national road pricing systems should involve careful impact analysis (Steininger et al., 2007). Regarding sustainability impact assessment, the European Union (EU) requests a detailed evaluation of the full effects of a policy proposal that should comprise the estimation of economic, environmental and social consequences (European Commission, 2001). In terms of environmental impacts, several studies have focused on the emissions impact assessment of cordon tolls introduction in urban areas (Bureau and Glachant, 2008; Meland et al., 2010; Mitchell et al., 2005; Rotaris et al., 2010). It has been demonstrated that road pricing shows potential as an air quality management tool. However, the authors did not find research focused on the impact of tolls introduction in intercity corridors. Therefore, the introduction of tolls on a motorway in Portugal was a valuable opportunity to study its consequences in different contexts. More specifically, this study aims to answer the following questions: 1) How can introduction of tolls change traffic distribution in a network? 2) How do speed profiles change on various routes? 3) What are the changes in CO_2, NO_X, CO and HC emissions and fuel consumption?

2. Methodology

2.1. Study area description

Due to financial constraints, a new electronic toll collecting system has been introduced on several motorways in Portugal (which was toll free before 15 October 2010). One of these cases is the A29 motorway, which connects the cities of Aveiro and Oporto. To connect these cities, there are four parallel alternatives roads (A1, A29, N1 and N109) that can be accessed via A25 (see Fig. 1a)). In addition, a rail system with 50 daily connections (CP, 2011) is available as an alternative. Table 1 provides key features of the alternative routes between Aveiro and Oporto. The national road N1 runs north through towns and industrial zones with a significant number of ramps and intersections. Nevertheless, there are some 3-lane segments bypassing intermediate towns which make this route faster than the national road N109. Although N109 is the shortest route, it is the slowest option since 90% of its distance is driven through urbanized areas. The alternative routes based on motorways have similar lengths.

The study area was divided into 6 sections (S0-S5), based on the latitude of the A1 interchanges and coinciding with the main east-west axes that cross the four main alternative routes (Fig. 1a)). Fig. 1b) shows the ADT on the motorways, before and after tolls introduction based on data for the last months before and after tolls introduction (Nov. – Dec. 2009/10 – Jan. – Mar. 2010/11). Until September 2010, A29 was the favourite option for the majority of drivers because unlike A1, this motorway had no tolls. (INIR, 2010). After the tolls were introduced on A29, about 50% decrease in the ADT was observed. Since A29 has a higher number of interchanges, the average traffic in each main section was estimated. As there was no detailed traffic volume data on the national roads, fig. 1 c) provides a rough estimation of ADT on these routes. The ADT values before the introduction of tools were based on traffic volume data available in noisy reports (APA, 2008) (S1-S4 for N109 and S4 for N1). For the remaining sections without the availability of data, the ADT ratio between A1 and N1 (ADTA1/ADTN1=2.15) in a traffic monitoring station located south of the study area was assumed (EP, 2011).

Table 1. Characteristics of the main routes between Aveiro and Oporto (TL – traffic lights, R – roundabouts)

Route	Length (km)	Speed limits / (% of distance) (km/h)	Number of Lanes (% of distance)	Intersections			Ramps		Tolls
				Total	TL	R	On	Off	
A1	77.1	50 (2%), 90 (7%) 120 (91%)	2 (2%), 4 (82%), 6(7%), 8 (8%)	9	1	3	26	26	4.40
A29	77.0	50 (2%), 90 (7%), 100-120 (91%)	2 (2%), 4 (87%), 6 (11%)	9	1	2	35	33	4.25
N1	87.2	50 (2%), 50/70 (58%) 90 (7%), 120 (33%)	2 (48%), 3 (12%), 4 (33%), 6 (7%)	135	20	7	48	58	……
N109	75.7	50 (23%), 50/70, (68%), 90 (6%), 120 (3%)	2 (88%); 4 (2%), 6 (10%)	275	46	19	47	45	……

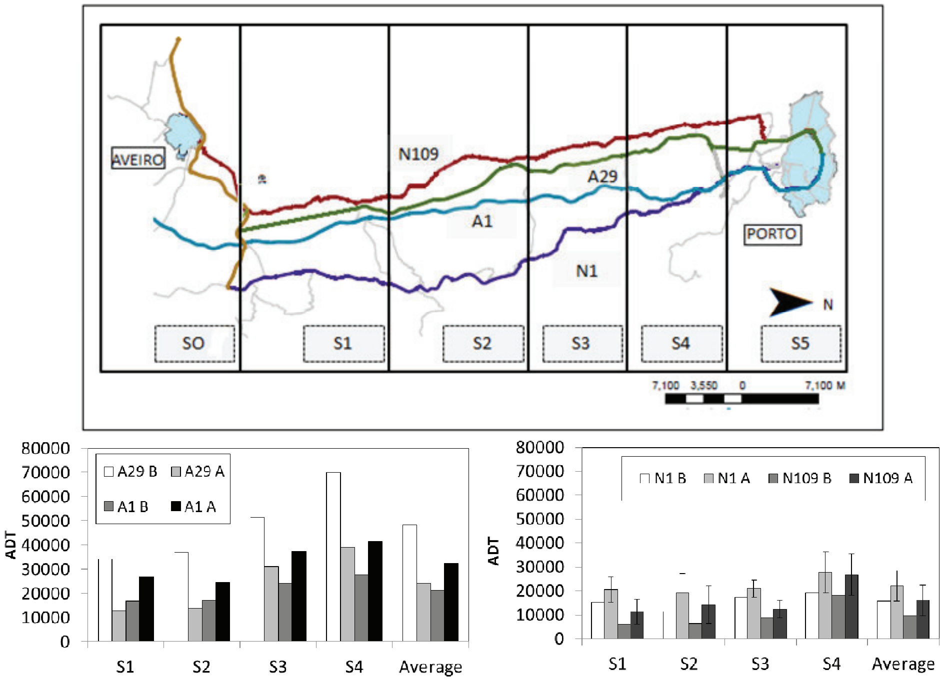
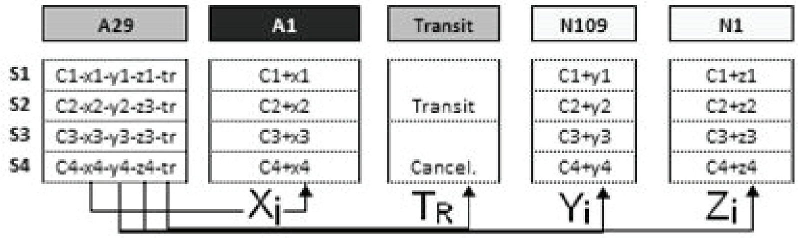


Fig. 1. (a) Study routes map; (b) ADT traffic before (B) and after (A) tolls introduction on A29, A1, and (c) estimated ADT in N109, N1 sections (based on EP,2011 and noisy reports)

After the introduction of tolls, it is still unclear the number of drivers that have abandoned the motorways and selected other options including the traffic diversion to alternative free-toll roads, changes for other modes or destinations and cancelled trips. Thus, the error bars sets the possible maximum and minimum range values of the ADT after the introduction of tolls. It should be noted that the authors are conducting traffic counts in key points of N1 and N109 during the first semester of 2011 in order to provide more accurate estimates.

Fig. 2 provides a scheme of the traffic flows studied in this paper. This research focused specifically on the impacts caused by the traffic diversion from A29 to the alternative roads, i.e., on the comparison of emissions and fuel consumption of the traffic flows “x”, “y” and “z” before and after tolls introduction on A29. Since no reliable traffic data on the N109 and the N1 were available, different scenarios of traffic distribution among the national roads were performed. The number of drivers that changed to the A1 after tolls introduction on A29 was calculated based on the traffic increase observed on the A1. This assumption is strengthened by the fact that the ADT was relatively stable (before the introduction of tolls) and there were no significant changes in the transport network. During the last quarter of 2010, 4.5% increase in rail passengers was observed in rail system parallel to the previous free motorways. However, the effect of the recent rises in public transportation fees and the reduction in demand caused by roadway tolls and fuel costs increase are still unknown. The literature provides values of elasticity of traffic volumes to tolls that vary typically from 0.1 to 0.45, depending on conditions (Spears et al. 2010). However, considering the high degree of uncertainty, this study will also present different scenarios considering several levels of traffic reduction. It was assumed that traffic at peak hours is 13,5% of ADT (Costa and Macedo, 2008) and the traffic fleet composition remains identical after tolls introduction.



X_i *- ADT that used to travel on section s_i of A29 and changed to A1 , Y_i - ADT that used to travel on section s_i of A29 and changed to N109, Z_i - ADT that used to travel on section s_i of A29 and changed to N1, TR - ADT that used to travel on section s_i of A29 and changed to other modes/ cancelled the trip.*

Fig. 2. Scheme of the studied traffic flows

To characterize fleet composition (namely diesel and gasoline passenger vehicles proportion), statistical data of Portuguese Automotive Commercial Association (ACAP, 2011) were used. Thus, it was considered that light duty gasoline vehicles (LDGV) and light duty diesel vehicles (LDDV) represent 54,6% and 45,5% of the light duty fleet composition respectively. Since this research is focused on Light Duty Vehicles, heavy vehicles and motorcycles were not considered. According traffic data on a southern section of N1, LDV represent 80% of the fleet composition (EP, 2011).

2.2 Field data collection

During experimental tests, vehicles dynamics were gathered second-by-second, using GPS data-logger devices with a resolution of 5 Hz. Moreover, videotapes were performed in order to identify the critical zones and incidents that may affect emissions. Three distinct data sets were collected for all routes in both directions - NPH tests (**N**on **P**eak **H**our) - February, March, and April 2010, - PHB tests (**P**eak **H**our **B**efore tools introduction) - September, and October 2010, - PHA tests (**P**eak **H**our **A**fter tools introduction) - February, March, and April 2011. Based on hourly variation of traffic volume (INE, 2000) the peak period was considered to occur between 7:00-9:00 AM and 5:00-7:00 PM. So, all trips whose departure time was within this time interval were considered as peak hour test runs. The off-peak test runs were conducted between 10:00 AM-5:00 PM. Three different drivers were used and all of them tried to keep the average speed of the traffic flow and avoid strong accelerations. Even though driver's behaviours can originate some differences in emissions, the route selection is the main factor controlling emissions (Bandeira et al., 2011).

Table 2 indicates the number of tests as well travel times and average speed data according route and period. All field tests considered in the study were carried out during weekdays under dry weather conditions. Due to rainy weather, road works or road accidents the set of valid PHB tests on A1 and N1 was rather limited. It is possible to verify that the toll-free alternative roads N1 and N109 lead to a considerable increase in travel time. While the introduction of tolls has caused a reduction in travel times on A29, no significant changes were observed among the alternative routes. Although the data field collection took place between the Aveiro and Porto city centres, this paper will focus essentially on sections S1 to S4 that contain A29 sections with new electronic tolls.

Table 2. Number of test runs (n), speed and travel times during field data collection (m – mean; P95 - Percentile 95%)

Route	n			Travel time (min.)						Average Speed (km/h)					
	NPH	**PHB**	**PHA**	**NPH**		**PHB**		**PHA**		**NPH**		**PHB**		**PHA**	
				m	P95	m	P95	m	P95	m	P95	m	P95	m	P95
A1	12	2	16	48	52	49	51	51	57	96	103	95	100	91	96
A29	12	8	16	51	68	64	83	51	56	91	101	75	93	90	95
N1	12	3	16	80	90	97	103	94	108	65	71	54	57	56	62
N109	12	7	16	97	104	108	117	110	130	46	49	42	47	41	45

2.2. Emission estimation

Previous research has demonstrated that microscale emissions models are more responsive to variations in traffic dynamics and roadway congestion (Ahn and Rakha, 2008). In this study the Vehicle Specific Power (VSP) micro-scale approach was used. This methodology is based on the vehicle second-by-second speed, acceleration and slope and has proven to be very useful in estimating microscale emissions in gasoline vehicles (US Environmental Protection Agency - EPA, 2002), and diesel vehicles (Coelho et al., 2009). Moreover the VSP approach has proven to be useful to standardize the comparisons of emission rates for different vehicles and routes (Frey et al., 2008). The VSP values were categorized in 14 modes and an emission factor for each mode was used to estimate pollutants emissions (CO_2, CO, NO_X and HC) from Light Diesel Duty Vehicles (LDDV<1.8 L) and Light Gasoline Duty Vehicles (LDGV<3.5L). The calculation of the VSP variable follows the equation (1) however a comprehensive description and average emissions rates used in this research can be found elsewhere (Coelho et al., 2009; Palacios, 1999; US Environmental Protection Agency - EPA, 2002).

$$VSP=v[1.1a+9{,}81\sin(\arctan(grade))+0.132]+0.000302\times v^3 \tag{1}$$

where:

VSP = Vehicle Specific Power ($kW.ton^{-1}$); v = speed (m/s); a = acceleration (m/s^2); Grade= road grade

3. Results

3.1. Average speed and emissions per section

Figure 3 a) shows the average speed on two representative sections (S3 and S4), routes and time period in which the test run were carried out. Figure 3) b and c) shows the average total CO_2 and CO emissions produced for a generic LDGV. For both sections it is clear that the speed is mainly dependent on the route choice. However, a higher variability in section 4 was noticed due to higher congestion levels near Oporto suburbs. The average speed on A29 is higher after tolls introduction, due to the average 50% decrease in the traffic volume. During peak hour this difference is statistically significant (p=0,05) on section 4 of A29 where a higher reduction of traffic volume was detected. In fact, after the introduction of tolls, a free flow regime is observed on both motorways. On the other hand, a slight decrease in average speed (but not statistically significant) was observed on N109. It is clear that for all sections the motorway options (A1 and A29) lead to CO_2 savings when compared with the national roads (N1 and N109). However, regarding CO emissions an opposite trend is observed. Moreover, NO_X and HC emissions show a similar trend as CO. A comprehensive analysis of the time spent in each driving VSP mode showed that the higher frequency of high VSP modes on motorways leads to a significant increase in local pollutant emissions. On the other hand the higher travel time and a high occurrence of VSP mode 3 and 4 (caused by situations of idling and slow speeds) on national roads lead to an increase in fuel consumption and CO_2 emissions. Emissions factors per link are also primarily dependent on the route choice whereas the time period does not have a significant impact.

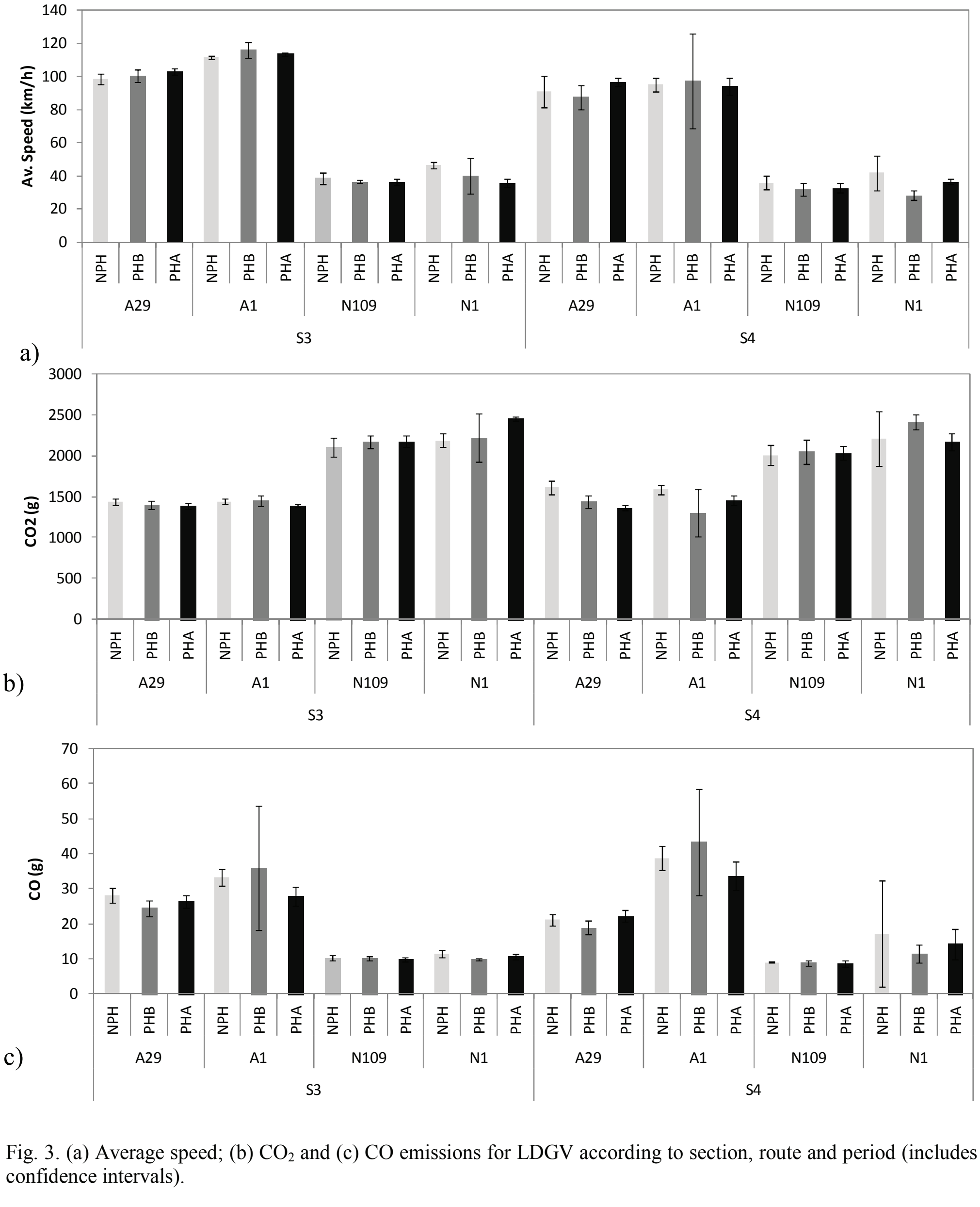


Fig. 3. (a) Average speed; (b) CO_2 and (c) CO emissions for LDGV according to section, route and period (includes T-student 95% confidence intervals).

3.2. Emissions and fuel consumption impact of tolls introduction

The impact of tolls introduction in terms of emissions and fuel consumption was analyzed taking into account the traffic diversion from A29 to the alternative routes. It should be noted that on alternative routes, no statistically significant (5% level) differences in emissions factors were found regarding the introduction of tolls during peak hour periods. This can be explained because a) A1 motorway absorbed a substantial portion of the traffic and had enough capacity to accommodate the extra demand, b) the remaining traffic was distributed evenly on alternative roads without significantly increasing traffic flows. A rough estimation was carried out of the traffic volumes per hour the during peak period. It was found that after the introduction of tolls, the traffic volumes per hour/lane may not exceed 1100 vehicles over the sections 1-4 of N1 and N109. This fact suggests that the capacity of the infrastructures is not reached and consequently the speed and emission factors remain relatively stable.

Thus, it is reasonable to assume that, in terms of total emissions, the main impacts are related to the vehicles that previously used A29, but after the introduction of tolls may have moved to other routes with different emissions profiles. Table 3 shows the estimation of daily differences in total emissions after introduction of tolls, which is based on the equation 4 for all pollutants. Since it is unclear how many drivers have diverted to national roads, emissions changes were calculated according distinct traffic reduction levels. It was considered that the traffic volume diversion from A29 was equally distributed among N1 and N109.

$$EBi = (x_i+y_i+z_i).k.E_{iA29PHB}+(x_i+y_i+z_i).(1-k).E_{iA29NPH} \tag{2}$$

$$EAi=x_i.k.E_{i\,A1\,PHA} + x_i.(1-k).E_{i\,A1\,NPH}+ (1-tr).\ [y_i\,k.E_{i\,N109\,PHA)} +y_i.(1-k).E_{i\,N109\,NPH}) + (z_i\,k.E_{i\,N1\,PHA} + z_i.(k-1).E_{i\,N1\,NPH})] \tag{3}$$

$$EC_i = EB_i-EA_i \tag{4}$$

Where
i – Section i (S1 to S4)
EB_i - *Daily Emission before toll introduction on section i*
EA_i - *Daily Emissions after toll introduction on section i*
EC_i - *Daily Emission change on section i*
Ei- Average total emissions on section "i" on Route A29/A1/ N1/N109 during NPH/ PHB/ PHA
k – Traffic Volume Ratio at Peak hour = PH / ADT (0,135)
tr- Traffic reduction (transfers to public transport and cancelled trips)
x_i – *Estimated ADT that used to travel on section* s_i *of A29 and changed to A1*
y_i - *Estimated ADT volume that used to travel on section* s_i *of A29 and changed to N1*
z_i - *Estimated ADT volume that used to travel on section* s_i *of A29 and changed to N1*
Tr – Estimated ADT volume that used to travel on section s_i *of A29 and changed to other modes or have cancelled the trip.*

Table 3. Estimated net changes in daily emissions after the introduction of tolls by section according to different scenarios of traffic reduction

Traffic reduction	CO_2 (ton/day)				NOX (kg/day)				CO (kg/day)				HC (kg/day)				Fuel (106€/year)
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	Total
0%	**15,8**	**26,6**	**47,2**	**81,7**	-53,1	-8,5	-0,5	4,1	-346	-541	-1	81	-3,8	-5,7	0,6	1,0	3,72
5%	**3,1**	**3,8**	**40,3**	**65,8**	-56,0	-86,2	-1,8	0,8	-352	-555	-3	75	-4,0	-6,1	0,5	0,7	2,47
10%	-9,5	-1,9	**33,5**	**5,0**	-58,9	-92,0	-3,1	-2,4	-358	-569	-5	69	-4,3	-6,5	0,4	0,4	1,21
20%	-34,9	-64,7	**19,9**	**18,1**	-64,7	-13,5	-5,8	-9,0	-38	-596	-9	56	-4,7	-7,4	0,1	-0,2	-0,13

Traffic reduction scenarios: **O%** - All traffic that diverted from motorways, shifted to the N1 and N109. **5% 10% 20%** - Percentage of traffic that diverted from A29 (section i) but did not select N1 or N109 (choose other modes or cancelled the trip)

Regarding CO_2 emissions and fuel consumption, the introduction of tolls has caused a negative impact on these parameters. In sections 3 and 4 even with a hypothetical 20% decrease in traffic volume, the emissions would increase. These sections are particularly sensitive because there is an higher density of intersections and traffic lights leading to the increase of the fuel consumption and CO_2 emissions. The last column of table 2 shows the estimation of annual costs related to the change in the traffic distribution. This estimation was based on the average gasoline and diesel prices in Portugal, on the 1st of September 2011. It is clear that the introduction of tolls leads to the decrease of local pollutants emissions, namely NO_X and CO which is consequence of less traffic circulating on motorways. It should be noted that the differences in section 3 and 4 were minimized because a significant volume of traffic has changed to A1 where speed limit is higher than A29 (120km/h - A1; 100 km/h - A29) leading to an increase in local pollutants emissions. Figure 4 shows the relative impact of tolls introduction and different levels of traffic reductions (considering all sections).

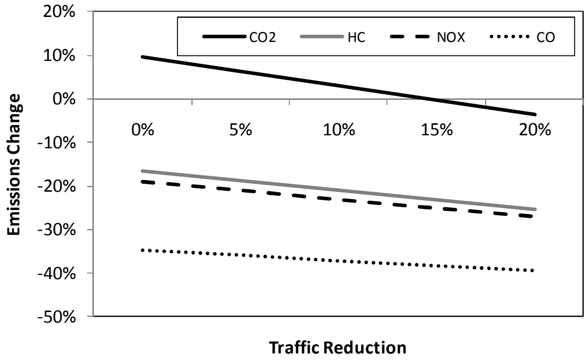


Fig. 4. Relative changes in emissions (due to tolls) on all routes for different levels of traffic reduction.

Since it was demonstrated that at different periods (with different traffic volumes) emissions did not vary substantially, it was assumed that in the sections analyzed, the emissions vary linearly with traffic volume. Regarding CO_2 emissions, only for traffic reduction values higher than 17%, it is possible to offset the emissions increase related to the traffic diversion from the A29 to the national roads. Concerning local pollutants, considerable reductions are achieved for all scenarios. A what if-analysis of different and extreme scenarios of traffic distribution among the national roads N1 ad N109 was performed. However, given that the emissions factors in N109 and N1 are relatively similar, a little impact on total emissions between the extreme cases (100% of traffic shifting to N109 and 0% for N1 and vice-versa) was observed (up to 3% for CO_2 and 5% for local pollutants).

4. Conclusions

This paper provides an empirical assessment of the impact of tolls introduction on an intercity corridor. Based on second-by-second vehicle dynamics data collected immediately before and after tolls introduction, emissions and fuel consumption for a generic light passenger vehicle were estimated. Then, taking into account the ADT data from motorways, an extrapolation of total emissions change was done.

More than the period of the day (peak and non-peak) and the presence or absence of tolls, the selection of a specific route has shown to be the most important factor regarding the emissions factors on the analysed sections. Seemingly, although 25000 vehicles per day have shifted from A29 to alternative routes and modes, the new traffic distribution after the introduction of tolls had no significant impact on the performance of network in terms of speeds, travel times, and emissions factors. Thus in terms of total emissions the main changes are the result of the traffic deviation from A29 to the alternative routes. Since it is unclear the volume of traffic reduction caused by the introduction of tolls, different scenarios of traffic reduction were performed. It was found that unless there was a significant decrease in traffic volume (higher than 17%), CO_2 emissions and energy consumption may increase up to 10%. For local pollutants, a significant decrease (between 15% and 40%) is expected considering only the traffic volume that left the A29.

As future work, the impact on air quality, namely the pollutants concentration at critical locations (most densely populated areas) will be assessed. It should be noted that although the total emissions of local pollutants are lower due to tolls introduction, the new places where they are produced would be an important factor to evaluate using air quality dispersion models. Further research should be conducted in order to increase the detail in vehicles categories (engine size, and technology) and to assess the emissions impact of other vehicles categories. A traffic monitoring campaign on national roads will be conducted to increase the accuracy of the estimation. It would be also interesting to assess potential economic impacts related with fuel imports, higher travel times and other externalities affecting the economic growth.

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