SENSITIVITY ANALYSIS OF TRAFFIC CONGESTION COSTS IN A NETWORK UNDER A CHARGING POLICY

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ABSTRACT

The costs of congestion can be measured using three approaches: the total costs, the marginal costs and the 'excess burden'. Understanding variation in these measures with particular policies is important for planning and resource management. Assessing the cost distribution (e.g. according to priority routes or urban segments) is key to assessing the delivery of transport and wider social objectives. The aim of this research is to illustrate how the costs of congestion vary with policy-related demand changes around the city of Milan.

The case study used is the "Cerchia dei Bastioni" (called for administrative purposes Area C), an old urban area within the inner centre of City of Milan network, with a 'real life' charging policy applied to private vehicles. A large number of scenarios with differing demand levels and elasticity's by vehicle classes were explored and equilibrium assignment used to assign demand to the network. Alternative measures for congestion costs were calculated along with other link parameters. Further data collection included a parallel field survey of changes in PT speed was also undertaken.

The results indicate a high degree of correlation between changes in the different measures of congestion and changes in vehicle speed (at different levels of demand). Changes in the total cost of congestion are though more marked than changes in the Excess Burden of Congestion. Sub-optimal conditions appear to exist in certain parts of the network which it is conjectured arise as a consequence of the configuration of the network – in terms of one way streets and vehicle restrictions. Identifying a more optimal network is left for further research, as is identifying the precise conditions for which vehicle speeds can be used as a proxy for changes in congestion.

Keywords: Traffic congestion, Large urban network, Excess Burden of Congestion, Charging Policy, Public Transport

INTRODUCTION

Despite frequent use of the term, the concept of congestion is often understood but less frequently defined. Congestion can be present as a physically measureable phenomena but perceived congestion (by users of the road network, residents and others) may be as important as the more objective evidence in driving the need for policy measures. The definition given by the Highways Agency (1997) captures the wide understanding of congestion as: '*the situation when the hourly traffic demand exceeds the maximum sustainable hourly throughput of the link.*' Alternatively, Goodwin (2004) defines congestion as '*the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity*'. In addition, the evidence to date is that congestion, however defined, is closely linked to externalities that include environmental impacts (Barth and Boriboonsomsin, 2008) and safety (Brownfield et al, 2003). In the case of the first, the presence of congestion leads to a driving behaviour that includes frequent 'stop-start' and periods where the engine is near stationary with the engine idling, leading to increases in emissions of local pollutants. In the case of safety, congestion can lead driving behaviour whereby vehicles have reduced headways, drivers may lose attention to the driving task or due to frustration take risks in the task, increasing the accident rate. It is clear on an intuitive basis that congestion causes costs – to the driver, other traffic network users, residents and the environment. On a more rigorous basis, it is possible to not only define congestion but to calculate the costs of congestion and link these calculations to future policy priorities and instruments. One common policy approach associated with the costs of congestion is that of road charging schemes, where an understanding of the costs of congestion may create a more conducive public-acceptance of the scheme and also set an economic framework within which charges may be set.

This research is concerned with an investigation around the sensitivity of traffic congestion costs in a network within Milan and in particular how these costs vary with a charging policy specifically introduced to reduce congestion, but with a secondary goal to achieve environmental improvements. The starting point is to consider the definition of congestion and how the costs of congestion may be measured. Grant-Muller and Laird (2007) give an elaboration of two fundamental approaches to interpreting congestion: firstly a 'traffic engineering' perspective (which underlies many measures of congestion) and secondly an economic view (related to principles behind marginal costs of congestion). At the practical level of measuring congestion, approaches fall into four rough classes comprising travel time (or speed) based measures, volume based measures, area based measures and summary indices (or more complex model outputs). This opens also other questions about reliability and costs of traffic estimation (Waadt et al., 2009). More recent definitions have taken a three-dimensional concept of congestion, for example Marfia and Roccetti (2011) who define a road to be 'in a congested state (be it high or low) when the likelihood of finding it in the same congested state is high in the near future'. Moran and Koutspooulos (2010) frame a definition of congestion from the users perspective and as a stochastic process. In practice, the simpler measures are more commonly applied than relatively complex measures. Bilbao-Ubillos (2008) indentifies eight main costs, most of them financial and environmental, to measure the total cost of congestion compared to smooth traffic flows.

Regardless of the precise definition of congestion, it is seen as an issue in urban networks as well as inter-urban environments and as such it features heavily in national transport policies. It is invariably regarded negatively; and it is seen as a limiting factor on economic efficiency as well as a source of pollution. However, all networks, whether they are telecommunication networks, energy networks, transport, etc. are subject to congestion (Shy, 2001; Mayer and Sinai, 2003). Congestion arises in networks due to a mixture of network properties including sunk costs of construction, invariant capacity and the fact that networks invariably operate under conditions of economies of scale, scope or density. From a policy perspective it is therefore essential that any network, transport networks included, is managed properly. The size (scope and capacity) of the network needs to be sufficient for the needs of its users specifically and society in general. Typically there therefore exists a tension between the desires of the users of the network and the ability of the owners/managers to expand that network. The price to access and use the network needs to be efficiently managed so as to ensure excessive prices are not charged, and that operating, renewal/investment costs are recovered to an appropriate degree. In a transport context policy commentators often estimate the costs of congestion as part of this debate – particularly the aspect of the debate related to the provision of additional capacity. This has led to a wide range in the estimates. For the UK for example the range stems from £2 billion per year (Dodgson *et al.*, 2002) to the often quoted Confederation of British Industry (CBI) estimate of £20 billion per year (CBI, not dated cited in Grant-Muller and Laird, 2007). That is, there exists almost a factor of 10 between the estimates.

This large range stems from the fact that there are two principal definitions for the cost of congestion: the total cost of congestion (TTC) and the excess burden of congestion (EBC) (Grant-Muller and Laird, 2007). The *Total Cost of Congestion* effectively compares the current or predicted situation against a reference state of zero congestion. The concept is illustrated in Figure 1 where the Total Cost of Congestion is given by area A. In this figure V_0 trips experience a journey time cost of UC_0, whereas in the absence of congestion the cost experienced would be $UC_{no\ congestion}$. In contrast the Excess Burden of Congestion is deadweight loss that congestion imposes on society. This is illustrated in Figure 2 by Area B. The deadweight loss arises as users of transport networks invariably do not face the full marginal social costs (MSC) of travel. Marginal external costs of congestion (MECC)[1] () and therefore demand for travel exceeds optimum levels. Congestion levels also exceed optimum levels. This is illustrated in Figure 2, where the marginal private costs (MPC) are illustrated as well as the marginal social costs (MSC). The difference between the two is the marginal external cost of congestion (Walters, 1961, Glaister, 1981; Newbery, 1990; Button, 1993).

Total cost of congestion can only be reduced to zero if either demand is restricted to levels at which congestion does not occur, or a large capacity expansion occurs (or some combination of the two). In both of these situations the excess burden of congestion would be zero too. However, the excess burden of congestion can also be reduced to zero by introducing a congestion charge that leads to efficient prices being faced by users. In Figure 2 optimum demand levels occur at V_1 and a net user cost of $UC_{1+congestion\ charge}$.

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[1] The MECC refers specifically to the group of external costs imposed on other road users only. That is MECC refers to changes in delay, reliability and vehicle operating costs, but does not include changes in other external costs namely accidents and environmental costs, resulting from an additional vehicle-km. It does however appear that some authors use the term *marginal cost of congestion* and *Marginal External Cost of Congestion* inter-changeably (e.g. Dodgson *et al.*, 2002).

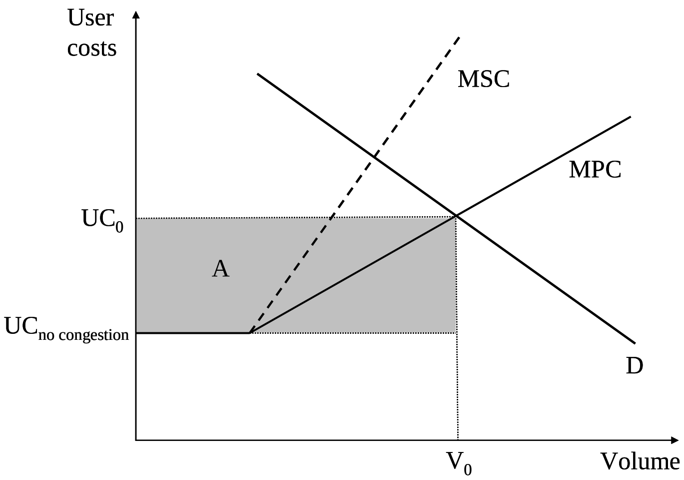


Figure 1: Total Cost of Congestion.

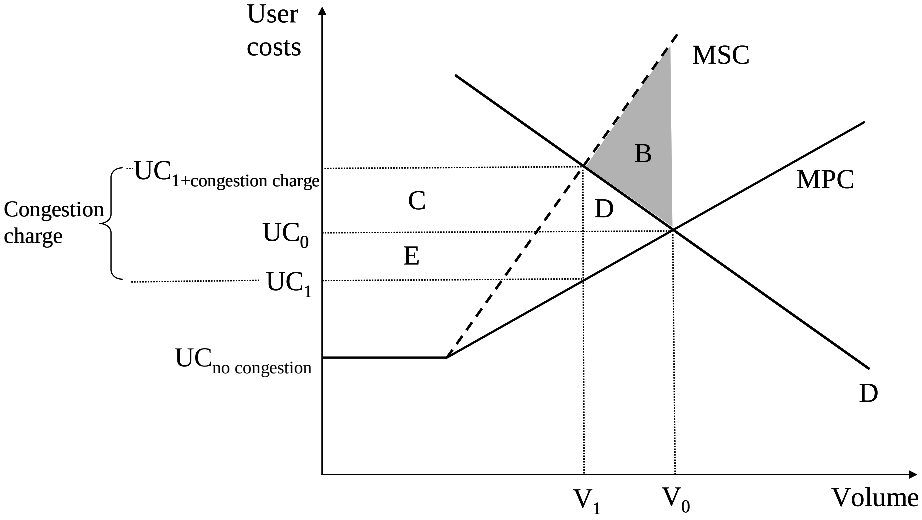


Figure 2: Excess Burden of Congestion.

The benefit of introducing the optimal congestion charge is equal to the size of the deadweight loss. This benefit is also equivalent to the congestion charge revenues (Area C+E) minus the loss of consumer surplus to road users (Area C+D) (Newbery, 1990).

An important difference between the Total Cost of Congestion and the Excess Burden of Congestion is that when the Total Cost of Congestion is zero no congestion exists on the network. When the Excess Burden of Congestion is zero however congestion can exist. This can be seen in Figure 2 as the Excess Burden of Congestion is zero when traffic volumes are at V_1, however, user costs at this level of demand, UC_1, exceed those when no congestion is present in the network.

Understanding variation in congestion costs with particular policies is important for planning and resource management. Assessing the cost distribution (e.g. according to priority routes or urban segments) is also key to assessing the delivery of transport and wider social objectives. However, there exists considerable variability in how the marginal external costs of congestion vary from one location to another (Lindberg, 2006). Some of this variation can be attributed to modelling methodology (link speed/flow, network assignment, etc.). However even when the same modelling methodology is applied the marginal external cost of congestion can differ dramatically between similar sized cities and between countries (see for example Milne, 2002; and the survey for the UK in Grant-Muller and Laird, 2007). This is due to the different levels of congestion in the cities, stemming from a mixture of topology, historical development of the network and economic development. These differences make it very difficult to transfer results from one city to another (e.g. Edinburgh to Glasgow, or Edinburgh to Bristol) or even to disaggregate results from a higher level down to a more disaggregate spatial level (e.g. from Great Britain to Scotland). It is therefore necessary to estimate congestion costs on a case by case basis to inform local, regional and/or national policy. Another feature of the literature is that typically most studies focus on one measure of congestion or the other and rarely are the two measures compared. This in most of the city wide studies reviewed by Lindberg (2006) the focus is on the marginal external cost of congestion and the excess burden of congestion.

The principal contribution of this paper therefore is to illustrate how the different costs of congestion vary with policy-related demand changes around the city of Milan. The findings have particular relevance and implications for city policy makers and the research community by illustrating the methodology to measure the different congestion costs. Given the complexities of measuring the costs of congestion, we also examine changes in vehicle speeds. These are of interest in terms of impacts of charging on particular modes, but also form the basis for further research into whether speeds are a reasonable proxy for changes in the costs of congestion. This will has immediate practical relevance to policymakers where congestion reduction targets have been set.

This paper has the following structure. Following this introductory section, the second Section sets out the methodology. The third Section introduces the City of Milan and the demand management schemes being analysed. Our results are presented and discussed in the fourth Section and our conclusions are set out in the final fifth Section.

METHODOLOGY

The approach used to assess the effect of the charging policy in the Area C in Milan is twofold concerning both the effects on road users in terms of the cost of congestion (that is the private component of demand) and on performance of public transport services in terms of travel times.

Cost of congestion analysis

For the road component, the aim is to investigate the relationship between changes in demand (due to charging policy), and costs or performance (due to changes in congestion). Costs and benefits and other performance can be calculated through an equilibrium assignment of different scenarios of private transport demand. Scenarios are built to simulate different levels of charging, assuming that a certain elasticity of demand with respect to price exists.

From a modelling perspective two assignments for each scenario are needed. The first assignment is a simple equilibrium assignment that uses as usual the marginal private cost (MPC) function of links (the basic cost function of links). With reference to Figure 2 this gives flow V_0 for every link. The second is a System Optimum (SO) assignment which allows the calculation of flows on links which minimize marginal social costs. This gives flow V_1 in Figure 2 for every link. SO assignment is simply worked out by an equilibrium assignment of the same network where the link cost functions are replaced by using the marginal social cost (MSC) function of links (e.g. in Sheffy, 1985; Van Vliet, 1982,). MSC functions are obtained by differentiating the link cost functions.

Let *f(q)* be the basic link cost function

$$\mathrm{f}(\mathrm{q}) = \mathrm{T}0 * \left(1 - \mathrm{A} * \left(\frac{\mathrm{q}}{\mathrm{C}} \right)^{\mathrm{B}} \right) \qquad 1)$$

where *q* is the demand, in number of vehicles, *T0* is the time needed to travel the link without congestion, *C* is the capacity of the link, and *A* and *B* are coefficients to be calibrated. The MSC cost function is calculated using the definition of marginal social cost, *MSC=d(TC)/dq=d(q*MPC)/dq*, where *TC* represents the total costs and *MPC* the marginal private costs. Then the link cost function for MC assignment is

$$f_{MSC}(q) = T0 * \left(1 - A * (B+1) * \left(\frac{q}{C} \right)^{B} \right) \qquad 2)$$

Travel time analysis

For public transport, the effect of charging is assessed by comparing travel times before and after the application of charging policy.

Travel time data for transport modes are collected by ATM (the society managing the public transport in Milan) with a continuous survey (by GPS mounted on board and an AVM located in the control central station) on surface lines (both tramways and buses) along the entire day of service. In this analysis we focus only on the peak hours (8:00 and 9:00) since this interval is generally the most congested one based on historical information on travel times in the area. Four months of 2011 and 2012 (from January to April, discarding days when the Area C policy was not active) are considered. As an indication, the proportion of weekdays discarded when the policy was not active was about 7%.

For each line, and therefore per link, more samples per hour per day are available, giving a good statistical significance to the mean hourly value per day. Since the length of a link is fixed and known, average speed, v_{ave}, can be consequently calculated:

- for a line, as the ratio between the sum of the lengths, l_i, of the links, *i*, making up the line and the sum of average travel times, $t_{ave\,i}$, collected on those same links:

  $$v_{ave} = \frac{\sum_i l_i}{\sum_i t_{ave_i}} \qquad 3)$$

  Travel times are collected separately by transport mode, hence calculations are made for all modes and, separately, for tramway and bus.
- for a link, two different forms of calculation are possible: an average in time and in speed:
  - Average in time is the harmonic average of speed and it is calculated as the ratio between the length *L* of a link *i* and the average of *n* available travel times for the same link.

$$v_i = \frac{L_i}{\sum_n t_{i,n}} = \frac{L_i}{\sum_n \frac{1}{v_{i,n}}} \quad 3)$$

Generally, this average is the standard reference in transport literature (especially in uninterrupted flow) although its value is lower than the average in speed, depending on how much the distribution of t_i is scattered;

- Average in speed is the geometric average of speed and it is calculated as the average of speeds, calculated from the *n* available travel times for the same link:

$$v_i = \frac{1}{n}\sum_n v_{i,n} = \frac{L_i}{n}\sum_n \frac{1}{t_{i,n}} \quad 4)$$

THE APPLICATION SCENARIO OF MILAN: AREA C

The city of Milan and its surrounding constitutes a metropolitan area laid in the middle of Po valley, Northern Italy (Figure 3). Whilst forming an important destination in its own right, Milan also lies at a cross-road for the main routes towards the south of the country and for traffic with destinations to the North in Switzerland. This leads to a mixture of traffic including local commuting and destinations plus through traffic to other significant destinations. The network representing the whole of the Milan area has 49684 links, 23110 nodes and 829 centroids (Figure 4a). Exactly at the centre of the city of Milan there is the area of “Cerchia dei Bastioni” (Bastioni for brevity) (Figure 4b) that has 2732 links, 1814 nodes and 164 centroids (or zones) (Figure 5a); Area C is contained in the “Cerchia dei Bastioni” and is a slightly smaller since the ring roads surrounding the Area C are not included in (Figure 5a). An Origin-Destination (O/D) matrix for the “Cerchia dei Bastioni” was generated by AMAT (the Milan Agency for Mobility, Environment and Territory), extracting it from an O/D matrix calibrated for the whole city (AMAT, 2008).

The “Cerchia dei Bastioni” was the subject of a charging policy from 2nd January 2008 to 31st December 2011, called *“Ecopass*”. From 16 January 2012 the same area is the subject of a different policy called *“Area C”*. The differences between the two policies concern:

- the main purposes; the primary purpose of *Ecopass* was to reduce air pollution, while *Area C* aims to reduce congestion and then pollution;
- the amount of charging; 2 Euro vs 5 Euro, for *Ecopass* and *Area C* respectively;
- the vehicles allowed to travel; *Area C* is more restrictive with respect vehicle engines in order to limit pollution emissions;
- which vehicles must pay; in *Ecopass* only high-polluting engines were charged while in *Area C* all private vehicles must pay.

Area C has 43 access points each controlled by a video camera (Figure 6). Seven of them are dedicated exclusively to public transport. Video cameras detect the passage only of entering vehicles by reading license plates (since charging fare allows free circulation inside the area and multiple enters); then a central system recognizes vehicle type, owner and due charge and provides for fines or sanctions as needed.

Figure 3: The area in the Northern part of Italy where the city of Milan is placed.

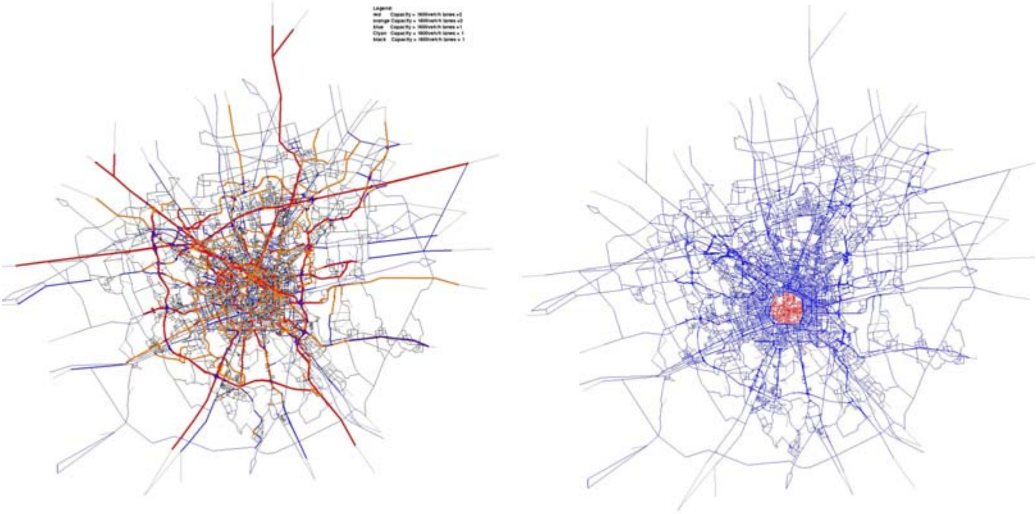

a) b)

Figure 4: The whole network of Milan with roads classified colours according to link capacity (4a) and with the “Cerchia dei Bastioni” area in red (4b).

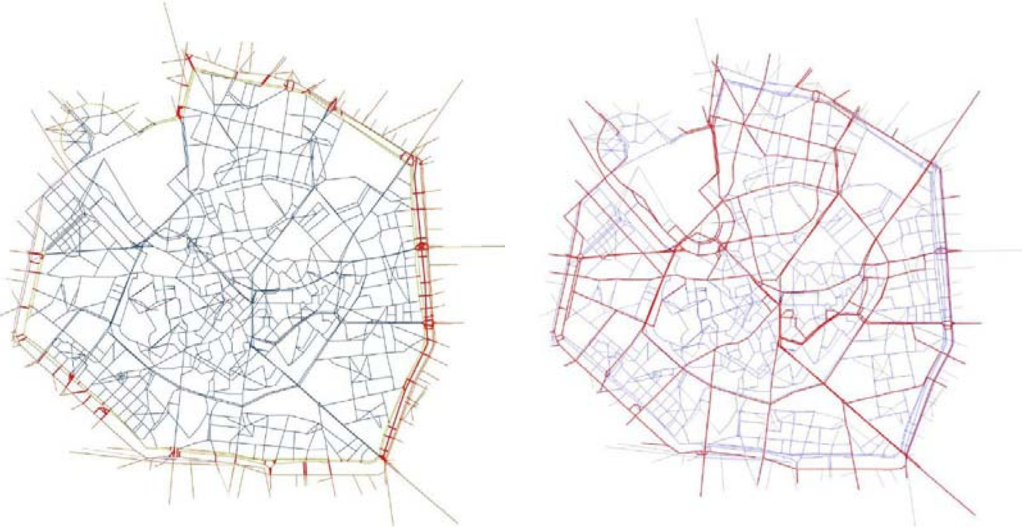

a) b)

Figure 5: The “Cerchia dei Bastioni” network with inside the Area C (dark links) (5a); the “Cerchia dei Bastioni” with roads used by Public Transport shared with private transport (red links) (5b).

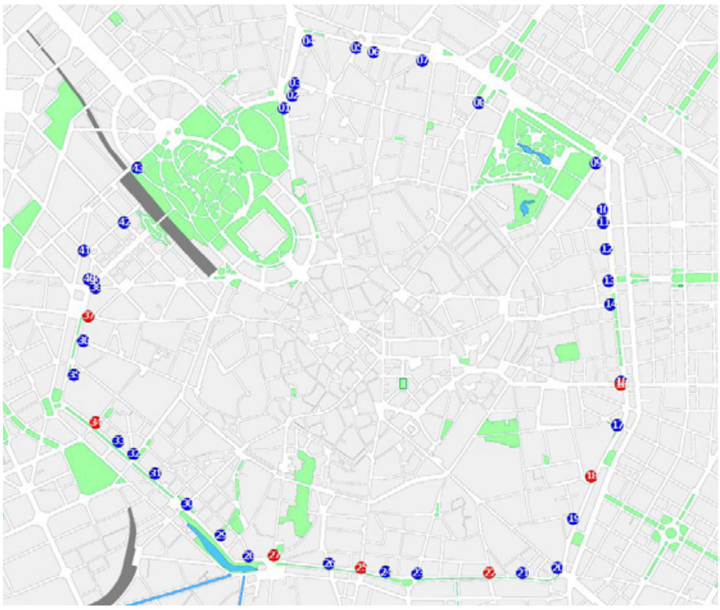


Figure 6: Locations of controlled points for accessing to Area C.

The information available concerns the current traffic demand and public transport performance. Demand is represented by the matrices O/D (Origin/destination) for the entire city and for the Bastioni, a smaller part within the inner centre of City of Milan network, where the charging is applied. These matrices are the result of a calibration work made by the agency AMAT since 2005 when a large survey on Milan and neighbouring municipalities was worked out. The number of centroids is 829 for the entire city network and 164 for the Bastioni network. Matrices are split into five classes: cars, motorcycles, light trucks, heavy trucks and taxes. It should be noted that heavy trucks are not allowed to enter in Area C. Therefore for the Bastioni network there are only four matrices based on the remaining modes. Assignment to the network was developed by Cube Voyager (used by AMAT) which performs a deterministic multiclass assignment to the network.

The current charging policy is represented in the base level of demand in the study, i.e. the reference scenario. In order to assess the effect of changes to the charging scheme that could be considered instead, demand is changed by firstly reducing demand in steps of magnitude, and secondly consideration of the possibility of an increase in demand. Scenarios were built for the Bastioni network with changing demand under two scenario types, representing firstly changes in the charging scheme for a subset of the traffic mix (the Main Scenarios) and secondly changes in charging for all vehicles (Secondary Scenarios):

- **Main Scenarios:** by changing the demand for cars and light trucks only, since motorcycles do not pay. Taxis pay a reduced charge, but this is included in their fare and paid by clients - a demand class generally less sensitive to price. Scenarios are obtained by reducing or increasing of the same percentage all O/D pairs; in particular, the percentages used were -10%, -40%, and -70% (coefficients 0.9, 0.6, and 0.3) to show an increasingly steep reduction in demand and a percentage of +10% (coefficient 1.1) to reflect an increase in demand and to study changes when congestion increases. These variations of cars and light trucks correspond to a changing of the whole demand of -2.3%, -8.9%,, -15.6% and +2.2% respectively. It is worth noting that when the current charging policy was introduced for Area C, the reduction of traffic entering into Area C in the first six months was around 34%. The exploration of variations in demand here include one change that would be of a similar size to this original impact (-40% demand), one which would represent a much higher additional charge and demand reduction (-70%) and two others that represent more marginal changes compared with the current scheme.

- **Secondary Scenarios:** by changing the entire demand (secondary scenarios), to see whether the different structure (different combinations of O/D couples) can change the results or not. Scenarios are obtained by changing demand by a percentage of -10%, -30%, and -50% (coefficients 0.9, 0.7, and 0.5).

RESULTS AND DISCUSSION

Cost of congestion modelling analysis

Tables from 1 to 4 report the results of assignment of demand scenarios described in the previous section. Table 1 and Table 2 refer to those scenarios where only cars and light trucks demand changes, and they are divided according to the type of assignments, MPC or MSC; Table 3 and Table 4 refer to those scenarios where the whole demand changes (so that every class demand changes with the same percentage).

The tables report results both for the entire area of Bastioni and only for Area C, both for all roads and only for roads with Public Transport. Variables are:

- the sum of Marginal Public Costs (MPC);
- the difference between MPC and T0, the free flow travel time (MPC-T0). This identifies the component of travel time due to congestion;
- the sum of calculated or assigned Marginal Social Costs (MSC);
- the total costs spent in the network due to congestion [(MPC-T0)*Q] where Q is the assigned link flow;
- the total costs of EBC;
- the ratio between total costs of EBC and the total cost of congestion;
- the sum of assigned link flows (Total flow);
- the average speed weighted on flow;
- the product between the number of vehicles and travelled kilometers (veh*km);
- the ratio Q/C where C is the link capacity; this value can be used to calculate the LOS of the network.

Generally, there is a linear relationship between variables a demand change for all scenarios for the entire area of Bastioni and Area C. Correlations between demand changes and average speed, EBC, Q/C ratio, and vehicle*km show a correlation indexes over 0.98, with a negative slope for average speed and a positive one for other variables. A relevant difference concerns their sensitivity to demand which is systematically higher inside Area C.

Negative values for EBC appear for Public Transport roads in Area C when demand is reduced about 40% for main scenarios (Table 2) and about 30% for secondary scenarios (Table 4). This is due to the particular structure of cost functions that when demand is low produces a quite different set of solutions between MPC and MSC assignments.

Table 1: Main Scenarios : Marginal Private Cost Assignments by changing vehicles and light trucks demand only.

MPC Assigments

		Demand changes only for Auto and Light Trucks classes (percentage of change for classes / on the total demand)									
		(-70% / -18.55%)		(-40% / -10.60%)		(-10% / -2.23%)		reference (0% / 0%)		(+10% / +2.23%)	
	(costs are in minutes)	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length
total network (BASTIONI Area)	MPC	691	3.09	714	3.20	746	3.36	756	3.40	767	3.46
	MPC-T0	84	0.40	107	0.51	139	0.66	149	0.71	160	0.76
	calculated MSC	985	4.47	1089	4.97	1234	5.66	1277	5.87	1328	6.12
	MECC (=MSC-MPC)	293	1.38	374	1.77	487	2.31	521	2.47	561	2.66
	TOTAL COST = (MPC-TO)*Q [TC]	91,102	410	116,967	530	154,509	704	165,853	756	179,039	817
	Total flow [veh]	1,091,396		1,183,166		1,284,234		1,310,148		1,338,794	
	Ave weighted Speed [km/h]	21.167		19.737		18.111		17.690		17.233	
	veh*km	95,553		103,435		112,084		114,365		116,815	
	Ave ratio Q/C	0.30		0.33		0.36		0.37		0.38	
	Total Cost on PT roads [TCPTR]	28,172	287.8	39,430	406.5	55,944	579.9	61,534	637.5	68,115	707.2
	PTR Ave weighted Speed [km/h]	22.199		20.686		18.966		18.472		17.934	
inside Area C	TOTAL COST =(MPC-TO)*Q [TC]	16055	134	25032	199	39123	301	44504	338	50770	382
	Ave weighted Speed [km/h]	18.41		17.39		16.13		15.71		15.27	
	veh*km	29,026		33,677		38,658		40,124		41,642	
	Ave ratio Q/C	0.19		0.22		0.25		0.26		0.27	
	Total Cost on PT roads [TCPTR]	7,407	116	12,833	198	21,354	326	24,611	374	28,359	431
	PTR Ave weighted Speed [km/h]	20.83		19.59		18.09		17.62		17.10	

Legend: MPC-Marginal Private Cost; MSC-Marginal Social Cost; T0=travel time at free flow; Q-assigned flow;C-link capacity; PT-Public transport

Table 2: Main Scenarios: Marginal Social Cost Assignments by changing vehicles and light trucks demand only.

MSC Assigments

		Demand changes only for Auto and Light Trucks classes (percentage of change for classes / on the total demand)									
		(-70% / -18.55%)		(-40% / -10.60%)		(-10% / -2.23%)		reference (0% / 0%)		(+10% / +2.23%)	
	(costs are in minutes)	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length	total	norm.ed by link length
total network (BASTIONI Area)	MPC (at assigned MSC)	679	3.03	702	3.14	732	3.28	743	3.33	754	3.39
	MPC-T0	72	0.33	95	0.44	125	0.59	136	0.64	147	0.69
	caluclated MSC	923	4.161	1022	4.63	1159	5.28	1204	5.50	1254	5.74
	MECC (=MSC-MPC)	244	1.13	320	1.50	426	2.00	461	2.16	500	2.35
	TOTAL COST MECC*Q'	60,438	22	81,836	30	113,342	41	124,017	45	136,155	50
	TOTAL COST of Excess Burden (TCEB)	16,883	77	19,499	90	22,891	106	23,353	108	23,957	111
	Ratio TCEB / TC	0.185		0.167		0.148		0.141		0.134	
	Total flow (at assigned MSC) [veh]	1,114,302		1,210,659		1,314,909		1,344,273		1,373,958	
	Ave weighted Speed [km/h]	14.32		12.57		10.77		10.29		9.80	
	veh*km	96,980		105,322		114,476		117,066		119,632	
	Ave ratio Q/C	0.32		0.35		0.38		0.39		0.40	
	Total Costs of Excess Burden on PT roads [TCEBPTR]	3,789	38	4,724	48	5,778	58	5,959	59	6,288	61
	Ratio TCEBPTR / TCPTR	0.135		0.120		0.103		0.097		0.092	
	PTR Ave weighted Speed [km/h]	15.475		13.449		11.371		10.783		10.199	
inside Area C	TOTAL COST of Excess Burden [TCEB]	1,499	19	1,986	23	2,829	32	2,969	33	3,238	35
	Ratio TCEB / TC	0.093		0.079		0.072		0.067		0.064	
	Ave weighted Speed [km/h]	14.438		12.731		11.000		10.446		9.907	
	veh*km	36,699		41,642		46,968		48,581		50,106	
	Ave ratio Q/C	0.23		0.27		0.30		0.31		0.32	
	Total Cost of Excess Burden on PT roads	-223	-3	-29	-1	406	4	489	5	683	8
	Ratio TCEBPTR / TCPTR	-0.030		-0.002		0.019		0.020		0.024	
	PTR Ave weighted Speed [km/h]	15.71		13.74		11.79		11.18		10.61	

Legend: MPC-Marginal Private Cost; MSC-Marginal Social Cost; T0=travel time at free flow; Q-assigned flow;C-link capacity; PT-Public transport

Table 3: Secondary scenarios: Marginal Private Cost Assignments by changing the total demand.

MPC Assigments

		Demand changes for all classes (percentage of change on the total demand)							
		(-50%)		**(-30%)**		**(-10%)**		**reference (0%)**	
	(costs are in minutes)	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**
total network (BASTIONI Area)	**MPC**	631	2.82	661	2.96	717	3.22	756	3.40
	MPC-T0	24	0.13	54	0.27	110	0.53	149	0.71
	calculated MSC	709	3.23	845	3.86	1097	5.04	1277	5.87
	MECC (=MSC-MPC)	78	0.41	184	0.90	381	1.82	521	2.47
	TOTAL COST = (MPC-TO)*Q [TC]	18,328	90	49,767	229	115,710	529	165,853	756
	Total flow [veh]	659,716		912,821		1,175,868		1,310,148	
	Ave weighted Speed [km/h]	28.129		24.154		19.730		17.690	
	veh*km	57,798		80,097		102,812		114,365	
	Ave ratio Q/C	0.17		0.25		0.33		0.37	
	Total Cost on PT roads [TCPTR]	3,475	35.7	14,092	143.7	40,321	417.0	61,534	637.5
	PTR Ave weighted Speed [km/h]	28.154		24.768		20.508		18.472	
inside Area C	**TOTAL COST =(MPC-TO)*Q [TC]**	4978	52	11380	102	28714	229	44504	338
	Ave weighted Speed [km/h]	19.53		18.74		16.87		15.71	
	veh*km	14,714		23,256		33,929		40,124	
	Ave ratio Q/C	0.10		0.15		0.22		0.26	
	Total Cost on PT roads [TCPTR]	647	11	3,808	60	14,445	221	24,611	374
	PTR Ave weighted Speed [km/h]	23.27		21.88		19.17		17.62	

Legend: MPC-Marginal Private Cost; MSC-Marginal Social Cost; T0=travel time at free flow; Q-assigned flow;C-link capacity; PT-Public transport

Table 4: Secondary scenarios: Marginal Social Cost Assignments by changing the total demand.

MSC Assigments

		Demand changes for all classes (percentage of change on the total demand)							
		(-50%)		**(-30%)**		**(-10%)**		**reference (0%)**	
	(costs are in minutes)	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**	**total**	**norm.ed by link length**
total network (BASTIONI Area)	**MPC (at assigned MSC)**	624	2.78	651	2.90	702	3.14	743	3.33
	MPC-T0	17	0.09	44	0.21	95	0.45	136	0.64
	caluclated MSC	681	3.057	798	3.60	1024	4.66	1204	5.50
	MECC (=MSC-MPC)	57	0.28	147	0.70	322	1.51	461	2.16
	TOTAL COST MECC*Q'	10,815	4	32,636	12	81,229	30	124,017	45
	TOTAL COST of Excess Burden (TCEB)	3,972	21	8,972	43	18,988	89	23,353	108
	Ratio TCEB / TC	0.217		0.180		0.164		0.141	
	Total flow (at assigned MSC) [veh]	652,538		917,279		1,196,780		1,344,273	
	Ave weighted Speed [km/h]	23.91		17.82		12.55		10.29	
	veh*km	57,274		80,089		104,245		117,066	
	Ave ratio Q/C	0.18		0.26		0.34		0.39	
	Total Costs of Excess Burden on PT roads [TCEBPTR]	402	4	1,553	16	4,701	48	5,959	59
	Ratio TCEBPTR / TCPTR	0.116		0.110		0.117		0.097	
	PTR Ave weighted Speed [km/h]	24.580		18.637		13.181		10.783	
inside Area C	**TOTAL COST of Excess Burden [TCEB]**	1,272	15	1,501	18	2,621	30	2,969	33
	Ratio TCEB / TC	0.255		0.132		0.091		0.067	
	Ave weighted Speed [km/h]	18.665		15.766		12.240		10.446	
	veh*km	16,694		27,893		41,286		48,581	
	Ave ratio Q/C	0.11		0.18		0.26		0.31	
	Total Cost of Excess Burden on PT roads	-37	0	-181	-2	227	4	489	5
	Ratio TCEBPTR / TCPTR	-0.057		-0.048		0.016		0.020	
	PTR Ave weighted Speed [km/h]	21.77		17.73		13.30		11.18	

Legend: MPC-Marginal Private Cost; MSC-Marginal Social Cost; T0=travel time at free flow; Q-assigned flow;C-link capacity; PT-Public transport

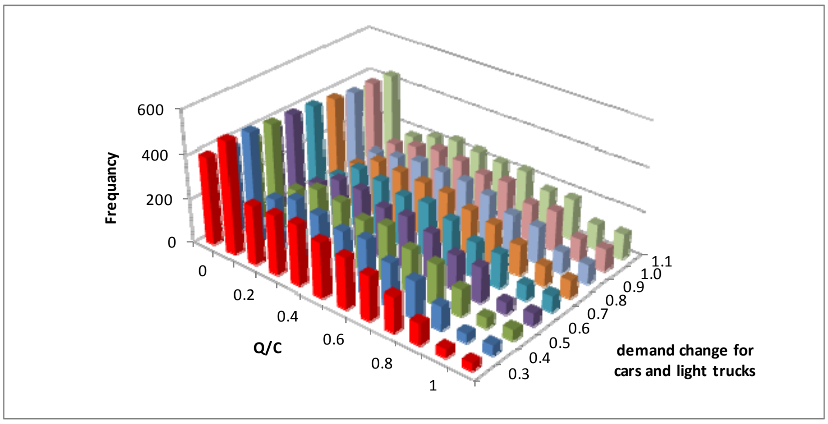


Figure 7: Q/C (flow/capacity) ratio distribution histogram (MPC assignment – demand changes only for cars and light trucks).

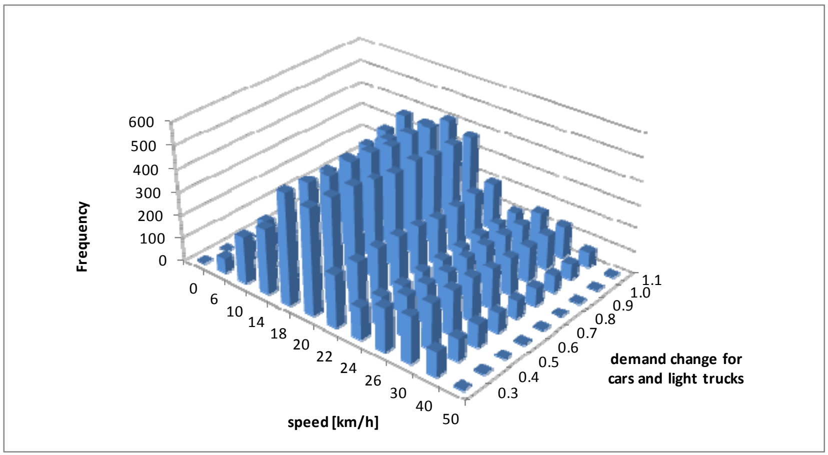
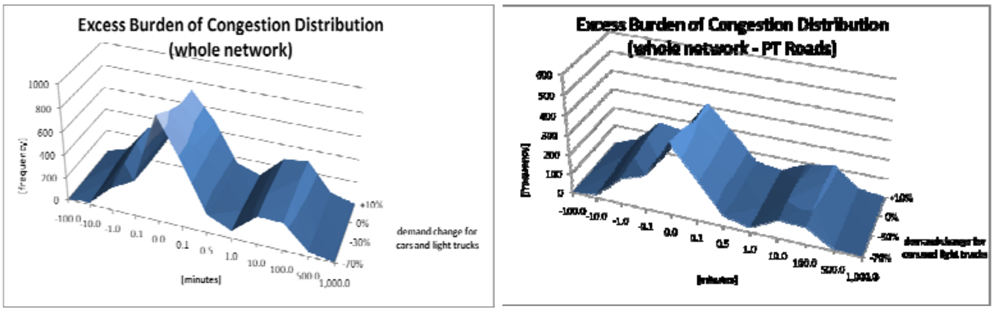


Figure 8 : Distribution of Average Link Speed (MPC assignment – demand changes only for cars and light trucks).

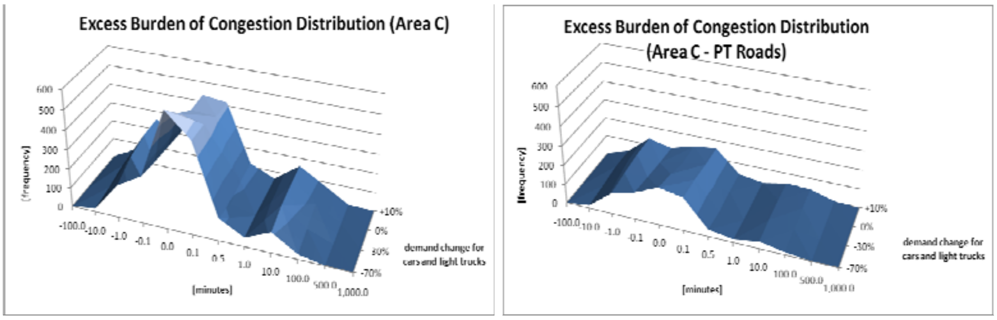
In figures from 7 to 12 some distributions of flow capacity ratio, link speed, and EBC are reported for the main scenarios. From Figure 7, it can be seen that as demand increases the flow/capacity ratio generally increases as might be expected. The largest changes are seen are seen with increases in demand at 0.6 or more, with noticeable changes in the number of links reaching saturation. A corresponding decrease in links with very low Q/C ratio is illustrated at the opposite end of the axis.

The distribution of average link speed under MPC assignment (Figure 8) shows that increasing demand is reflected in a decrease in average link speed. The change appears gradual and this may be attributed to the presence of speed limits suppressing speeds from the levels they may be otherwise. As a result the increase in demand at low levels may initially have little impact on those links with higher average speed and only result in noticeable changes as the links approach saturation. The greatest changes may be seen concerning the number of links with much lower speeds, i.e. less than around 14 km/hr where the increased demand is seen to increase quite sharply the number of links with these lower average speeds. These findings are very much aligned with the findings from Figure 7 and intuitive. However it is also apparent from Figure 8 that there is a noticeable separation in the speed distribution data at around 24 km/hr. This may indicate a distinction for example in terms of road type or with respect to differing conditions by time of day.



a) b)

Figure 9 : Distribution of Excess Burden of Congestion in Bastioni area (9a) and only for PT roads (9b) (demand changes only for cars and light trucks).



a) b)

Figure 10 : Distribution of Excess Burden of Congestion in Area C (10a) and only for PT roads (10b) (demand changes only for cars and light trucks).

A comparison between a) b) Figure 9 and a) b) Figure 10 highlights the difference between changes in EBC for Bastioni and Area C as demand increases. The EBC for Bastioni is seen to demonstrate a more gradual reduction, whilst increased demand has a noticeably greater impact on the values of EBC for Bastioni than for Area C. The main difference between the two sites in practice is that Area C excludes the ring roads that are included in the scope of the Bastioni region. There may be a number of factors that contribute to the distributions overall, but referring back to Figure 4, some high capacity parts of the network are not included in Area C which may offer greater flexibility and some additional capacity to absorb extra demand – at least for the moderate increases in demand. Standard deviation of EBC is lower inside Area C than in Bastioni, and for PT roads (in this case its value is about the half that for all roads).

Ex-post travel time analysis

The evaluation of the effect of the introduction of a charging scheme for Area C has also focussed on the analysis of speed of Public Transport means as described in previous section. Table 5 shows how the Public Transport average speed has changed in the Area C and the entire city for links and lines in the two peak hours, 8:00 and 9:00. Figure 11 and Figure 12 propose a comparison of the same results (before and after) in a graphical form. Based on data collected by the municipality the reduction of demand due to charging is about the 34%. It must be underlined that the averaged values of percentages are calculated on the row data (and not as the ratio of the final average values).

Table 5: Average speed [km/h] summary for Public Transport links and lines in Milan (Area C and the whole city)

Area_C	**ON LINKS**		number of links	time	8:00-09:59	8:00			9:00		
				year	2011-2012	2011 (A)	2012 (B)	%(B-A)/A	2011 (A')	2012 (B')	%(B'-A')/A'
		(on speed)	284	ave	**10.77**	**10.63**	**10.98**	***3.98***	**10.43**	**10.80**	***4.93***
				dev.std	3.45	3.48	3.56	*11.84*	3.53	3.51	*15.89*
		(on time)	284	ave	**10.04**	**10.09**	**10.49**	***4.63***	**9.57**	**10.20**	***9.07***
				dev.std	3.35	3.43	3.49	*13.09*	3.41	3.44	*23.33*
	ON LINES (on time)		number of lines	time	8:00-09:59	8:00			9:00		
				year	2011-2012	2011 (A)	2012 (B)	%(B-A)/A	2011 (A')	2012 (B')	%(B'-A')/A'
		All	29	ave	**9.40**	**9.25**	**9.51**	***1.53***	**8.76**	**9.27**	***6.15***
				dev.std	2.03	1.99	2.31	*8.68*	2.18	2.15	*11.95*
		Tramway	12	ave	**7.95**	**8.06**	**8.19**	***0.52***	**7.63**	**8.11**	***9.74***
				dev.std	1.79	1.30	1.74	*10.44*	2.01	1.82	*16.22*
		Bus	17	ave	**10.42**	**10.44**	**10.84**	***2.24***	**9.88**	**10.44**	***3.61***
				dev.std	1.52	1.87	2.07	*7.46*	1.78	1.84	*7.24*
City	**ON LINKS**		number of links	time	8:00-09:59	8:00			9:00		
				year	2011-2012	2011 (A)	2012 (B)	%(B-A)/A	2011 (A')	2012 (B')	%(B'-A')/A'
		(on speed)	5261	ave	**17.62**	**16.88**	**17.15**	***3.06***	**17.28**	**17.64**	***3.13***
				dev.std	7.33	7.03	7.16	*20.91*	7.23	7.83	*29.37*
		(on time)	5261	ave	**15.77**	**15.31**	**15.45**	***3.20***	**15.72**	**16.05**	***4.31***
				dev.std	6.62	6.60	6.44	*24.83*	6.77	6.88	*26.96*
	ON LINES (on time)		number of lines	time	8:00-09:59	8:00			9:00		
				year	2011-2012	2011 (A)	2012 (B)	%(B-A)/A	2011 (A')	2012 (B')	%(B'-A')/A'
		All	123	ave	**14.79**	**13.42**	**13.54**	***1.09***	**11.24**	**11.72**	***3.10***
				dev.std	4.11	3.65	3.62	*7.23*	4.86	4.80	*11.95*
		Tramway	17	ave	**10.41**	**10.53**	**10.76**	***1.94***	**10.15**	**10.54**	***5.04***
				dev.std	1.40	1.22	1.51	*5.52*	1.86	1.56	*9.79*
		Bus	106	ave	**15.49**	**14.72**	**14.78**	***0.71***	**15.52**	**15.72**	***2.13***
				dev.std	3.96	3.64	3.61	*7.94*	4.92	4.95	*12.96*

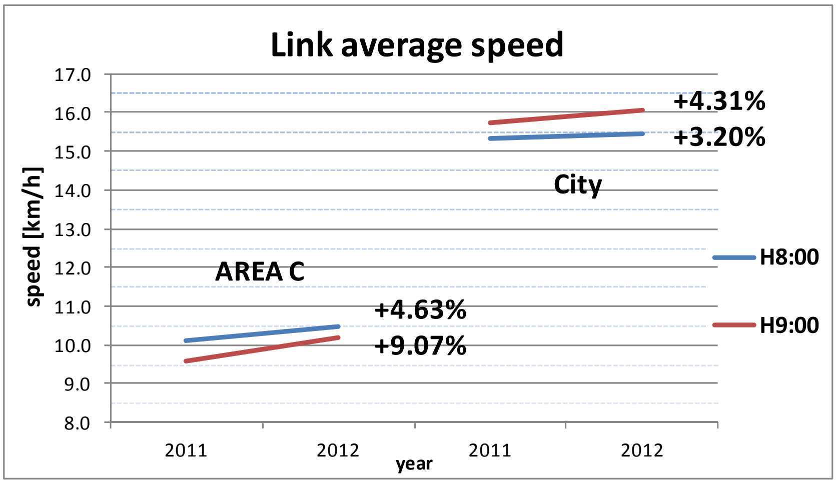


Figure 11 :Comparisons of average (time) speed on links before (2011) and after (2012) the introduction of charging both for Area C and the entire City.

Results show that in all cases there was an increase of speed during Area C charging with respect the same period of the previous year. By considering the whole city like a reference case (or like a comparison group, although the reduction of demand in Area C can have produced a reduction of the demand also in the whole city), we see that also in the whole city in that period there was an increase of speed. The increase has generally lower values and therefore we can assess a specific effect of charging. The effect is more evident for the 9:00 than 8:00, and for links than for lines. Bus mode seems to achieve higher benefits from charging than tram mode.

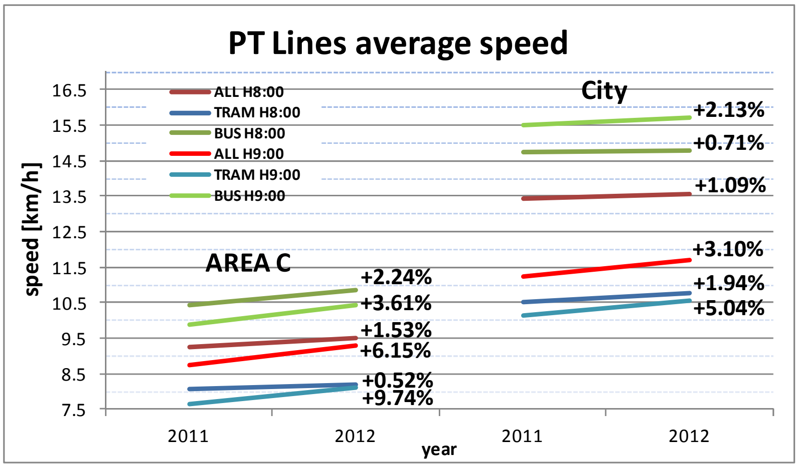


Figure 12: Comparisons of average speed on Public Transport lines before (2011) and after (2012) introduction of charging both for Area C and the entire City.

CONCLUSIONS

The objectives of the study were to consider how the costs of congestion may vary with policy-related demand changes around the city of Milan. The scenarios of demand change effectively represent hypothetical variations in the charge within the so-called Area C scheme – a subarea at the heart of the Bastioni sector (which is itself a part of the wider Milan city). The demand variations were introduced within two main scenarios, representing charging variations for a subset of vehicles and for the whole traffic respectively. The levels of demand change were set with consideration for the size of demand change observed when the Area C scheme was first introduced. In summary these were marginal further demand change (+ or – further 10%), a further equivalent decrease in demand (-40%, roughly comparable with the -34% observed) and finally a significant demand reduction (-70%). Two measures for the costs of congestion were calculated – one being an estimate of the total cost of congestion (TCC) and the second being the excess burden of congestion (EBC). These were calculated for both the immediate Area C region and the wider Bastioni sector in order to explore possible shifts in costs. Other traffic related measures relating to speeds were also calculated. The study has generated some interesting insights as well as producing a series of questions for further study, with the main findings as follows:

- A strong correlation is seen between the cost of congestion measures and also vehicle speeds (r = 0.98). This leads to the conjecture that speeds may be used as a proxy for the costs of congestion, a phenomena that is worth further future study.
- From the two measures for the costs of congestion, it can be seen that the Total cost of congestion is much larger than EBC (EBC is between 13% and 18% of TCC for main scenarios). However Total cost falls more quickly than EBC as cordon charges increase (demand reduces) – this at low demand levels EBC is almost one fifth of TCC whilst at higher demand levels it is closer to a tenth. This raises the possibility of value in further research into the non-linear relationship between the two measures and the need for careful policy interpretation of each of the two measures in practice.
- Sub-optimal conditions can occur on certain parts of the network even though the network is moving towards a more optimal position (from a congestion perspective). This is evidenced by the fact that for some links EBC can be negative. It is attributed to particular characteristics of cordon charges, one way systems and PT only links. It is

worth noting that what may be viewed as sub-optimal conditions in terms of congestion and system efficiency may be perceived as very acceptable and even positive conditions from the perspective of some stakeholder groups (for example residents or regular commuters with ‘rat-running’ behaviours)

- Finally, a travel time (speed) analysis was carried out by way of ex-post analysis of the impact of introducing the Area C scheme (representing the change in demand of -34% compared with the previous charging scheme, Ecopass). The changes in demand in Area C are clearly not entirely independent of the whole city, although the conditions at the whole city level could be considered as an approximate comparison group. For the whole city, an increase in traffic speeds is seen for both links and lines (PT). However, the increase in speed is more marked for Area C than for the whole city, reflecting the immediacy of the impacts around the direct locality of the charging policy. The effect is more evident at 9:00 than 8:00, and for links than for lines.

A number of topics for further research have arisen alongside the main research findings:

- A more elaborate set of scenarios could (in principle) be explored to look at the impact of re-investing congestion charges back into the transport network (through improved PT or better circumferential road routes around cordon , or a form of active traffic management using ‘intelligent transport’ schemes;
- Further analyses that separate the data in city segments or main route roads vs the rest would be interesting to calculate some simple measures around equity in terms of distribution of impacts;
- A more in-depth study should consider the network design issue – this relates to the presence of one way streets, regulatory restrictions on traffic in particular areas and possibly planning/engineering issues around road width or quality that impact on route choices and traffic flow. It is conjectured that these types of factors may be underlying the presence of some negative EBCs in the cost calculation. A set of wider considerations may be included in such a study such as the impacts on particular sub-groups or sub-areas of the study region, who may perceive particular positive advantages from the current network design;
- As mentioned above, further research is needed to better define the relationship between changes in vehicle speed and EBC/TTC.

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