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Estimating Congestion Cost In Delhi, India

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Abstract

The study uses relevance of three empirical elements vis-a-vis speed-flow relationship, generalised cost and demand curve in constructing cost curves to estimate congestion cost for inner ring road of Delhi for the year 2015. The study constructs two supply curves (i.e. individual cost curve and social cost curve) from existing engineering parameters and demand curve by sensitivity analysis by varying elasticity of demand with respect to time from −0.2 to −0.7. Twenty four regression analyses to find the best fit model between a dependent variable Space Mean Speed (SMS) and four independent variables (flow, density, average flow, peak hour flow) to construct twenty six cost curves have led to the estimation of congestion cost, marginal external congestion cost, congestion tax for considering ring road as homogenous section and six individual links of the study area in peak and off-peak periods. The study predicts road pricing in peak hours as a long-term measure in mitigating traffic congestion. The study also predicts elastic behaviour for all six links and "paradoxical behaviour" after demand elasticity attains a particular value, negative externality burden that motorist imposes on the society.

Keywords: Marginal external cost, Congestion cost, Cost curves, Social Cost, Individual cost, Marginal external congestion cost

1 Introduction

The spurt in mobility over the past decade has led serious concerns about the external costs such as congestion, noise, accident risks and air pollution. With the negative externalities arising from sprawling development, the shift from city to suburb to exurb to countryside continues to draw the attention of economists, scientists and policy makers. The theory of market failure helps them to throw light on urban sprawl. When a motorist enters the restricted road space in peak hours indirectly he pays a price in form of travel time, schedule delay, and other costs for using that facility. His availing the facility also marginally increases the travel cost for others commuters availing the facility simultaneously. This imposition of a cost, to be borne by others not by him is called a 'negative externality'. Traffic

Congestion is a classic case of negative externality. The reduction of speed reduces the level of service that road facility should provide is an external cost of travel time penalties that all other commuters should bear equally. External costs fall into two categories i.e. user-upon-non-user costs which the motorist imposes on non-travellers and user-upon-user costs which each individual motorist imposes on other motorists. Each motorist trip imposes both such externalities. Motorist tends to undervalue the social cost of his or her trip that impacts other travellers and non-travellers. Economists have rigorously shown in the market that the success lies in implementing the principle that goods should not be allocated beyond the equilibrium point where the marginal gain equals marginal cost to furnish that goods. The marginal costs should not be absorbed by suppliers of those goods but by consumers themselves.

The thesis is structured as follows: Section 1 gives overall view of congestion as an externality. Section 2 gives a brief survey of literature on estimation of congestion cost by engineering and economic approaches for the urban road of the city. In Section 3, we discuss methodology for constructing cost curves. In section 4, we show graphical representation of cost curves and thus congestion cost. Section 5 presents Results and Conclusions.

1.1 Congestion and Negative Externality

Congestion usually relates to an excess of vehicles on a portion of roadway at a particular time resulting in speeds that are much slower than normal or “free flow” speeds (Cambridge Systematic and TTI, 2005). The factor that complicates congestion assessment is the tendency of congestion to conserve equilibrium: it increases until delays constrain further peak-period vehicle trips, causing travellers to shift travel times, routes and mode, and reduce trips (Litman 2001, Cervero 2003). Studies have manifested that the increasing road capacity for solving congestion in the long run induces ever-increasing demand for travel (Braess's paradox) and is not viable solution to mitigate congestion (Sheffy, 1985). Road congestion can be understood by considering the road network as a common property resource which leads the market to be sub-optimal.

When road capacity is relatively fixed, the only economic efficacious solution seems to price or tax the use of roads differentially by setting congestion tolls, which makes the commuters to value their essential trips and discard non-important trips by 'internalising' the externality for the marginal social costs they impose on society. This shall force the users to take into account all social costs in making their decisions. Pigou (1920) proposed to internalize the external cost by charging it with a tax equal to optimal marginal external cost whosoever causes it. He argued that this taxation will adjust market to its optimal level. Singapore (1975) became the first major city to take the economist’s advice to prove that pricing to reduce congestion was both feasible and effective. London (2003) toed the line by adopting similar pricing scheme to reduce congestion. With rich experiences in view of Singapore and London, pricing to reduce traffic congestion is now recognized as an essential component for mitigating congestion in developed and developing countries. In developing countries like India inroads into implementation of congestion pricing is well in progress and needs to be studied extensively.

1.2 Global Vs Indian congestion cost values

Congestion costs as given in the Urban Mobility Report are based on delay estimates added with value of time (VOT) and fuel costs. India loses $10 billion/year due to congestion which include fuel wastage, slow speed of vehicles and waiting time at toll plazas and checking points, a study on operational efficiencies of freight transportation by roads has claimed (Times of India, 2012).The study further says each commuter in Delhi loses around 90 minutes every day & vehicles in all waste around 3 million litres of fuel each day.

1.3 Urban transport scenario in Delhi

In developing countries like India, urbanization and rapid high rate of growth is being witnessed in the country's metropolitan cities like Delhi. The city has total area of 1483 km^2 having urban area of about 500 km^2. The population of Delhi has grown from 13.85 million in 2001 to 16.75 million by 2011 (Census, 2011). The population has increased by 18 times during last six decades due to growth of opportunities in employment, industries and study hub.

2. A Survey of Literature on Estimating Congestion Cost

The literature takes into account either engineering approach or economic approach in explaining congestion cost.

2.1 Engineering approach

The engineering approach takes in account only speed and flow parameters in estimating the congestion cost. It completely neglects the "demand of road usage" that varies during peak and off peak hours. Traditionally, people contemplated cost of transportation in terms of "average costs" and, therefore, disregarded the negative externality each user imposes on others on a congested road. Since, externality is not taken into account; use of average cost tends to underestimate the true costs of congestion. More recently, a popular way to explain the costs of urban congestion in US has been estimated by cost of delays, i.e. the difference in travel time between actual speeds and free-flow speeds (Schrank and Lomax, 2005). While the costs of delay or free flow speed is an unacceptable benchmark as bringing all traffic to free-flow speeds would constitute an inefficient overprovision of road space because roads are never meant to be empty and therefore cannot serve as a meaningful policy goal. The marginal congestion cost of urban transport was estimated by many researchers (e.g., Mayeres et al., 1996; Bickel et al., 1997; O'Mahony and Kirwan, 2001). Mostly the following exponential congestion function has been used that expresses relationship between speed and flow to find congestion function relationship.

$$1/s = A_1 + A_2 \text{ x } (\exp. (A_3 \text{ x } q) \qquad (1)$$

Where s is average speed in kmph, q is million passenger car units (PSU) per hour and A_1, A_2, A_3 speed flow relationship parameters.

Mayeres et al. (1996) estimated exponential congestion function for Brussels as follows:

$$1/s=1.19928 + 0.005571 \text{ x } (\exp. (7.890545 \text{ x } q)) \qquad (2)$$

(minutes needed to drive 1 km in a certain period in a link as a function of the million PCU per hour).

The difference between Marginal Private Costs (MPC) & Marginal Social Costs (MSC) is the Marginal External Cost of Congestion (MECC) (Walters, 1961; Glaister, 1981; Newbery, 1990).The average time is the harmonic mean of speed and is calculated as the ratio between the length L of a link i to the average of n available travel times for the same link. The total costs spent in the network due to congestion is

$$[(MPC - T_0) \times Q] \qquad (3)$$

(MPC=Marginal Private Cost, T_0 is the time needed to travel the link without congestion, Q is traffic flow PCU/hr). Marginal external congestion costs (MECC) of an additional PCU km is given by

$\text{MECC}_{qi} = \sum \frac{\partial t_{i,j}}{\partial_{qi}} \times x_{i,j} \times VOT$; (Where $x_{i,j}$ is the number of passenger kilometer travelled in period i by mode j. VOT i,j is the value of time).

It is concluded that a part of the literature considers 'speed' as a proxy for estimating congestion cost for the purpose of monitoring but most of the literature presents only engineering parameters like speed and flow in estimating cost of congestion to society, while neglecting road demand during peak and non-peak hours. The literature seems silent on "Who shall be the last marginal driver and why should only he or she be penalized, when everyone should have equal rights of access for the public road space?" Most of the literature uses speed-flow relationship to find best fit line for estimating cost curves. India has heterogeneous type of traffic with poor lane discipline and as such parabolic speed-flow relationship is seldom applicable in such conditions.

2.2 Economist approach of road congestion

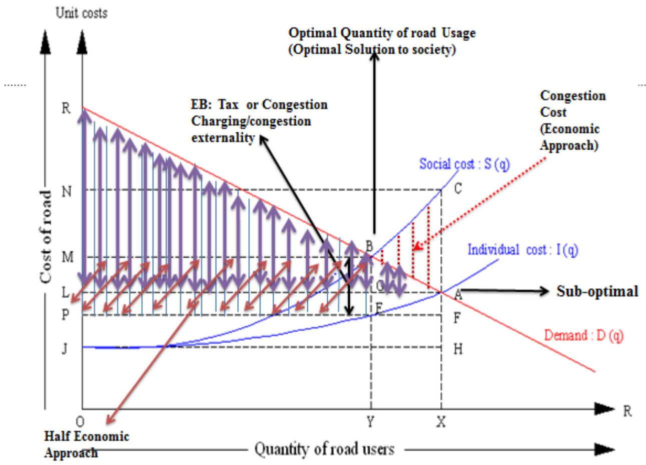


Fig. 1: Road congestion

From Section 2.1, we have seen traffic engineers have developed congestion cost from three fundamental traffic elements (speed, density and flow). Economists have built upon traffic engineers approach by bringing traffic demand into the analysis of congestion cost. Prud'homme and Bocarejo (2005) showed economic approach of congestion cost by graphical representation between quantity of road usage (veh-km/day) and the unit cost of road usage (Rs./veh-km). The same approach has been applied to the Inner Ring road of Delhi. Road usage D (q) is a demand curve representing the demand of using the road (monetary units per veh-km). I (q) is supply curve (unit cost per veh-km) designated by individual cost borne by a motorist while choosing the trip. Equilibrium will be reached at point A, where coordinates of I(q) and D(q) intersect. At point A, the motorist bears a cost equal to the benefit he derives from using the road is a "sub-optimal" condition. The social cost S(q) comprises of private cost faced by a motorist in already congested road space plus the increased cost imposed on all existing travellers as last motorist has reduced travel time of all other vehicles. The latter is external to the entry decision thus a congestion externality. So, at point B externality is added to individual cost is the optimal solution to the society. Beyond B, each additional vehicle creates a social cost greater than the social benefit it creates. This optimal situation can be reached by imposition of a "tax" equal to EB that will force travellers to move from point A to point B.

There are five different approaches to measure congestion cost as propounded by economists (Prud'homme, 1999). The arbitrary approach takes as reference situation a speed equal 50 kmph on a non-urban road and 20 kmph on an urban road. If the speed falls below this threshold, the road are said to be congested. This approach is also unacceptable and is doubly arbitrary as both acceptable speed and reference speed are both arbitrary. The engineering approach takes as reference situation as the speed at which maximal flow is witnessed. When actual speed falls below this speed, the road is said to be congested. Congestion costs are then defined as the difference between the time actually spent and the time taken at above mentioned speed. This approach ignores the demand for the road for peak hour and non-peak hours. The half economic approach takes as reference situation as optimal situation defined by point B (Fig. 1) that is reached by imposing tax equal to EB. The difference between the road usage (X) and the optimal level of road usage (Y) is taken as a measure of congestion. Congestion cost is denoted by PMBE in Fig. 1. Prud'homme (1999) argued that if tax is a measure of congestion cost it is to confuse the means (the internalizing tax) with the end (the elimination of the externality). The economic approach is the true approach to measure congestion cost. It takes as reference situation as optimal situation defined by point B that is reached by imposing tax equal to EB and produces the same indicator of congestion as the difference between X and Y. It describes congestion cost as the economic cost suffered by society when road usage is at X instead of Y. It can be defined as area of triangle 'BCA' or difference between the surplus associated with B and the surplus associated with A i.e. BCA = PRBE – LRA or BCA = PLGE – GBA.

Prud'homme has argued that roads are always less or more congested as natural equilibrium point 'A' is always greater than optimal point 'B'. This reflects that policy makers should not zero in on to eliminate congestion on roads, but should make the motorist to reach the optimal level of congestion i.e. point B. Prud'homme has further argued that reference situation cannot be considered an 'empty road' condition as roads are not built to remain empty. This unfolds the main difference between the engineer's approach and the economist's approach in defining traffic congestion as engineer defines optimal road usage and congestion only as a function of road characteristics (i.e. speed and flow/density); while an economist defines it as a function of both road characteristics and its demand. Optimal tax or charge is the congestion externality at the optimum not at the natural equilibrium and congestion charge is calculated from area of triangle 'BCA'. The excess burden of congestion is the deadweight loss arises when motorist does not bear the brunt of marginal social cost of travel. The benefit of introducing the congestion tax 'BCA' is equal to size of deadweight loss or loss in surplus.

3. Cost Curves for Inner Ring Road Considered As Homogenous Section

The Generalized cost has two parts: Individual cost and Social Cost.

3.1. Individual cost: I (q)

It can be interpreted as Marginal Private Cost (MPC) as it gives the cost faced by each motorist while choosing the trip. It is per km cost that includes fixed part and variable part. The fixed cost is money cost that is summation of direct cost, indirect cost, external cost for (fuel cost, amortization cost, maintenance cost etc). Variable part is equal to the Value of Time (VOT) multiplied by vehicular occupancy divided by average speed S(q). The average speed is a function of free flow speed (kmph) and flow (or density).

$$I(q) = \text{Fixed part} + [1/S(q)] \times VOT \quad (5)$$

VOT is the opportunity cost of travel. It the amount that a traveller would be willing to pay in order to save time or would accept as compensation for lost time. It varies considerably from working trips and non-working trips. In the present study, it is obtained from IRC SP-30 (Table 2).VOT observed in different modes from various studies is presented in the table 1 and table 2.

Table 1: Average Value of Time (VOT) for passenger transport (Rs./hour)

RITES (1998)		**Tota (1998)**		
Mode	Average VOT	Work Trip	Non work trip	Average VOT
Car	24.65	70	17.5	50.84
Bus	10.59	23.57	8.86	17.11
SC/MC	17.97	35.45	5.89	25.74

Source: RITES (1998) and Tota (1998) for TER

Table 2: Value of Time (VOT) and VOT plus Money cost passengers and Goods

S. No.	Nature of Journey by Passenger	VOT for Primary Route (Rs./hour)	Summation of VOT & Money cost for Primary Route (Rs./hour)
1	Cars	85.61	126.26
2	Two Wheelers	35.87	80.17
3	Bus Passenger	24.36	42.01
4	3 wheelers	-	60.3
Commodity Holding Cost (Rs. / Day)			
1	LCVs	3.8	71.29
2	HCVs	10.4	85.21
3	MAVs	23.3	77.39

(Source: IRC SP-30)

The value of time in present study has been calculated as weighted average for different modes of passenger trips. For the peak hours, working trips have been considered only; while for non-peak hour's average of work and non-work trips have been considered. The vehicle occupancy for buses is equal to 72, mini-buses equal to 27, car equal to 1.15, 3-wheeler, 2-wheelers equal to 1.

Six parameters are required to construct two cost curves and demand curve. Two basic parameters are required to construct the cost curves i.e. speed and flow (or density). The secondary parameters required are money cost of trip, VOT, free-flow speed, elasticity of demand with respect to time. The spot mean and flow data has been collected for six links of Inner ring road of Delhi for 12 hours by speed gun and videographic method. The space mean speed (SMS) is calculated from spot mean speed by following relationship:

$V_t = V_s + \frac{\sigma^2}{V_s}$ (where σ^2 is standard deviation of spot mean speed in kmph, V_s is spot mean speed in kmph). Density is obtained from space mean speed (SMS) and flow (PCU/hr).

3.2 The time-flow (or speed-flow) relationship and choice of functional form of congestion function

The three engineering parameters i.e. SMS, density and flow are tested by regression analysis for 256 data points to find a relationship between a dependent varaible and independent variables (i.e. between SMS Vs density, SMS Vs flow, peak hourly SMS Vs peak hour flow) to ascertain the best fit equation by Goodness of Fit (GOF) measure for linear, quadratic, cubic and exponential equations that satisfy the model and estimate the slope (ß) and constant (free flow speed) by using following relationship.

Avg. Speed (S) = Free Flow Speed (a) – ß ×density (k_1) (11)

GOF are checked in above cases for three measures of model i.e. R-squared, Significance values, and the generalized F test. R^2 come quite high equal to 0.68 in linear regression between SMS Vs density implying that Greenshield model suits the best for homogenous section.

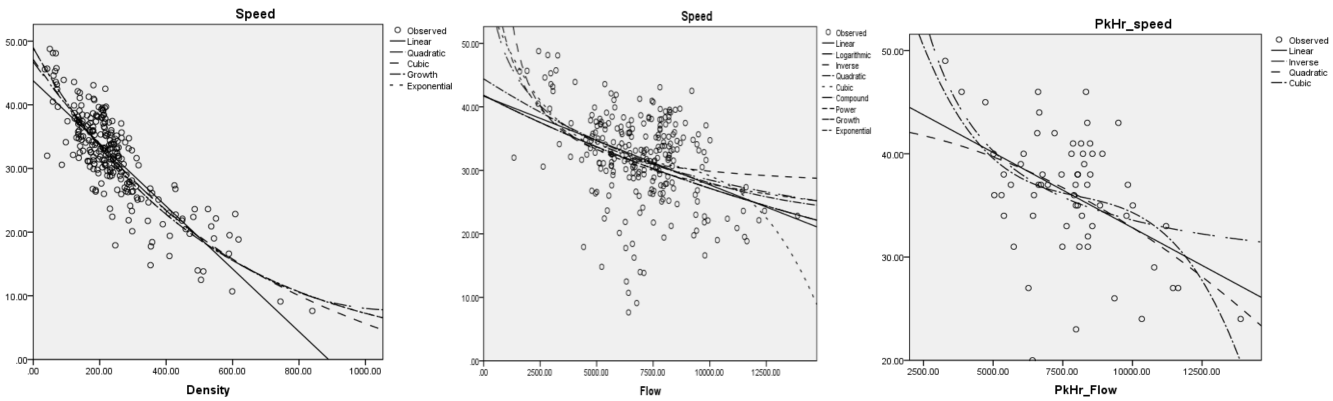


Fig 3: Shows Scatter plot between SMS Vs density, SMS Vs flow, peak hour SMS Vs peak hour flow for 256 data point for homogenous section of inner ring road of Delhi

The equation 12 obtained from regression analysis between SMS and density following Greenshield model with the best fit line.

$$V_{avg}=43.772 \text{ (in kmph)} - 0.049 \times \text{density} \quad (12)$$

Moreover, elasticity of demand (E) of -0.3 has been chosen for homogenous section as it gives the best results, while value of E above value -0.3 show erratic behavior in constructing demand and supply (cost) curves. For linear speed and density congestion function described by Greenshield model, the individual cost is given by the following equation:

$$\text{I(k)} = \frac{(\text{VOT} + \text{Money Cost}) \times \text{Vehicular Occupancy}}{(\text{a} - \text{ß x } \text{k}_1)} \quad (13)$$

3.3 Social cost

It can be interpreted as marginal social cost (per km cost borne by the driver) comprising the private cost faced by already congested road space travellers plus the increased cost imposed on all existing travellers. Numerically, it is equal to the individual cost curve I(k) plus the first derivative of individual cost multiplied by traffic density (or flow).

For linear speed and density congestion function described by Greenshield model, social cost is given by following equation:

$$\text{S}\,(\text{k}_1) = \frac{(\text{VOT} + \text{Money Cost}) \times (\text{Vehicular Occupancy}) \times \text{ß} \times \text{k}_1)}{(\text{a} - \text{ß x } \text{k}_1)^2} \quad (14)$$

3.4 Demand curve

Most of the literature suggests that elasticity of demand mostly varies from −0.3 to −0.7. Litman (2007) proposed demand elasticity of road usage ranging between −0.6 and −0.8 for London. Elasticity of demand adopted for London and Paris for congestion studies are −0.87 & −0.5 to −0.8 respectively. Matas and Raymond (2003) summarise that for Spain, short-term toll road price elasticities ranges from −0.21 to −0.83. Odeck and Brathan (2008) established that elasticities have an average value from −0.54 in the short run and −0.82 in the long run for 19 Norwegian toll roads. Luk (1999) estimates that Singapore toll elasticities are in the range of –0.19 to –0.58 with an average of −0.34. Since post charge condition is not known for Delhi, it is not possible to construct demand curve. We have calculated the traffic density in present (pre-charge) situation by estimating coordinates of individual cost curve. Using the most suitable value elasticity of demand ranging from −0.27 to −0.7 for the study area (Goodwin, 1996), we obtain the traffic density in post-charge situation (k_2) by equation 15.

$$E = \frac{(k_2 - k_1)/k_1}{(p_2 - p_1)/p_1} \quad (15)$$

(p_2–p_1) = Change in unit cost of travel.
(k_2–k_1) = Change in density with change in unit cost of road usage.
k_1 = Pre-charge traffic density.

After calculating k_2 corresponding to post charge situation at a particular demand elasticity (say -0.3), we get the coordinate of social cost curve by dropping a perpendicular from base of axis of traffic density at k_2 that intersects with coordinate of social cost curve at B (Fig 4), which is optimal solution to the society. The coordinate of I (k) corresponding to density k_1 and coordinate of S (k) corresponding to density k_2 at elasticity −0.3 are joined to get the inverse demand curve. The difference between coordinate of individual cost and social cost gives Marginal External Congestion Cost (MECC). The area of triangle 'BCA' (Fig 4) gives value of congestion cost which is calculated by multiplying one half of difference in hourly average peak hour densities in precharge and post charge situation and correspondent difference in average peak hour individual and social cost. The perpendicular dropped from base of density axis intersects the coordinate of individual cost curve at E and social cost curve at B, thus, measuring magnitude of congestion tax 'EB'. The congestion cost for peak hour for link 1 of homogenous section is calculated as given below:

$$= 0.5 \times \{S_{k\,(pk-hr)}) - I_{k\,(pk-hr)}) \times \{(k_{post-charge} - k_{pre-charge})\} \quad (16)$$
$$= 0.5 \times (29.62-12.55) \times (491-291)$$
$$= 1709 \text{ (Rs/veh.-km)}$$

It is ironic to note from equation 16 that the congestion cost of 1709 (Rs/veh-km) is only applicable for 200 number of vehicles per kilometer reduced on the road (i.e. by reducing density from 491 to 291) while increasing unit cost of road usage from 12.55 to 29.62 (Rs per veh-km).

Figures 4-9 show congestion cost curves between density (veh/km) versus unit cost of road usage (Rupees/veh-km) for 6 links of inner ring road of Delhi considering them all as a single unit. The following cost curves have been established at elasticity of demand (E) equal to -0.3 after obtained the best fit model in regression analyses between SMS and density.

3.5 Cost curves for Inner Ring Road (homogenous section)for six different links at E=−0.3

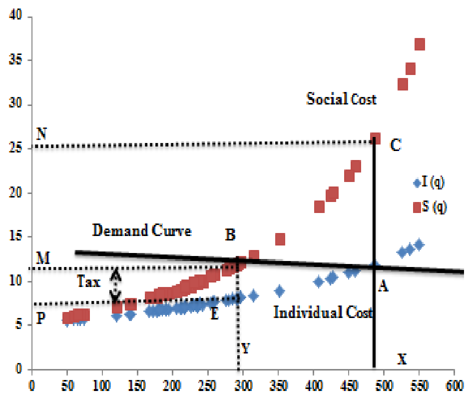


Fig. 4: Congestion Cost curve for **link1**

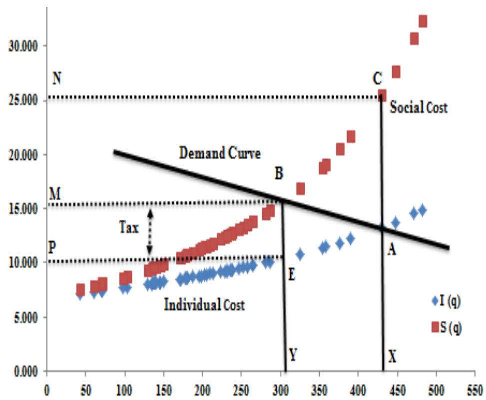


Fig. 5: Congestion Cost for **link 2**

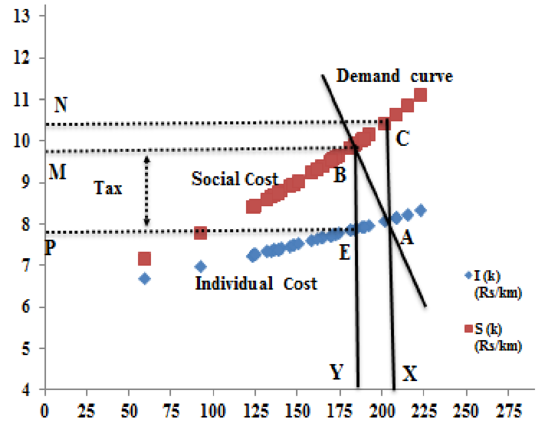


Fig. 6: Congestion cost curve for **link 3**

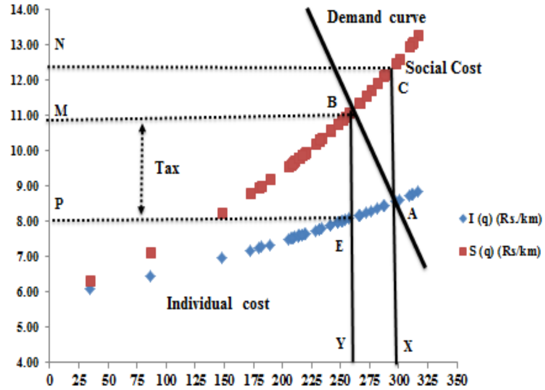


Fig. 7: Congestion Cost curve for **link 4**

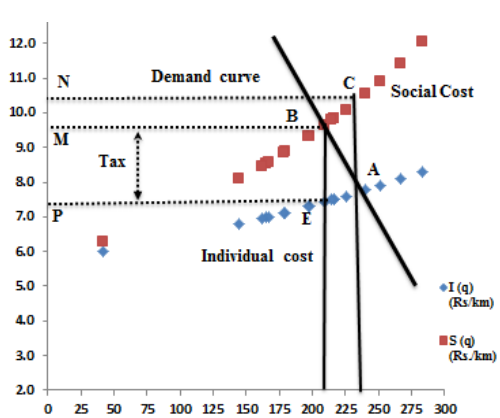


Fig. 8: Congestion Cost curve for **link 5**

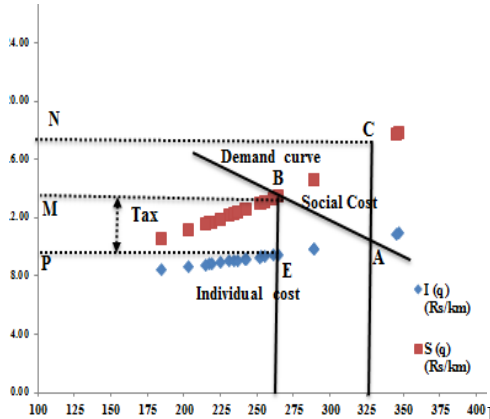


Fig. 9: Congestion cost curve for **link 6**

The homogenous section of inner ring road does not show any particular trend after changing elasticity of demand of an individual links. It was seen at elasticities greater than −0.3; the cost curves showed very 'erratic behavior'. Therefore, it isn't studied in details in the present study. We have focused on the behavior of individual links when considered them non-homogenous as they show a specific trend with change in E.

Table 3 : Shows cost curve values and peak and non peak hour congestion cost by economic & semi-economic approach at E =-0.3 **(Homogenous section)**

Link No.	Average Indiviudal Cost of link (Rs/veh-km)	Average Social Cost of link (Rs/veh-km)	Congestion Cost by economical approach (Peak Hour) (Rs/veh-km)	Congestion Cost by economical approach (Non-Peak Hour) (Rs/veh-km)	Congestion Cost (Semi economic Approach) (Rs/veh-km)	Marginal External Congestion Cost (avg. peak hour) (Rs/veh-km)	Tax (Rs/km)
1	7.882	12.13	1709	0.306	1180	17.06	4
2	9.30	13.02	793.4	0.378	1527	22.74	5
3	7.89	10.09	21.99	2.2	377	2.47	2
4	7.84	10.51	73.2	11.7	964	3.94	3.7
5	7.35	9.47	34	5	462	2.71	2.2
6	9.49	13.60	81.5	26.3	1190	6.46	4.5

4. Cost Curves for Individual Links (link 1 to link 6)

It is necessary to determine what type of functional form of the congestion function most suited the speed-flow (or density) relationship for individual links in Delhi. For this purpose, we tested 3 types of functional forms for regression analysis as given in Table 4 with the goodness-to-fit parameter, R^2 to choose the suitability of each function for all six links with a dependent variable and independent variables (SMS Vs flow, peak hourly SMS Vs density, SMS Vs Peak hour flow). It is evident from Table 4 that the linear function described by Greenshield model gives the best-fit line with R^2, coefficients ranging from 0.415 (lowest) to 0.824 (highest). On this basis, it is decided to use the linear form to describe the congestion function relationship for all the six individual links.

Table 4: Choice of functional form of congestion function for Ring Road of Delhi

Link No.	Equation	R^2 Value (SMS Vs Density)	R^2 Value (Peak hour SMS Vs Peak hour Flow)	R^2 Value (Avg. SMS Vs 15-minute flow)
1	Linear	0.764	0.595	0.565
2	Linear	0.677	0.527	0.702
3	Linear	0.824	0.392	0.472
4	Linear	0.415	0.107	0.129
5	Linear	0.759	0.48	0.45
6	Linear	0.801	0.034	0.132

Applying the same procedure in calculating cost curves as applied in Section 3 we thus obtain different cost curves while changing E from −0.27 to −0.7.

4.1 Link 1 (Ashram to Sarai Kale Khan; length 2.4 km)

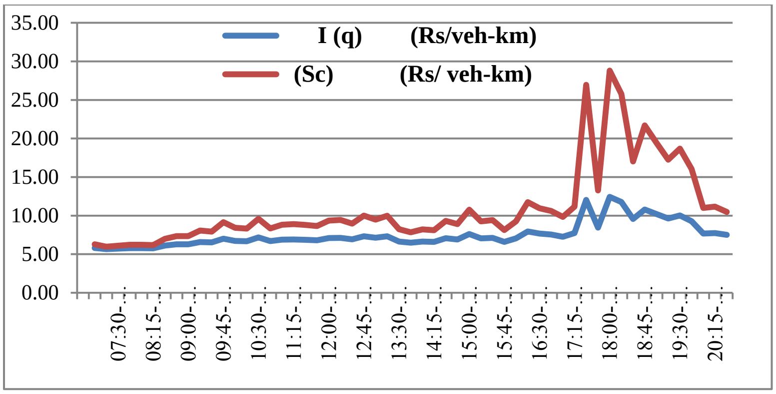


Fig 10: Shows variation in individual cost & social cost from 07:15 hours to 20:30 hours for link 1

It is evident from figure 10 that negative externality (difference in individual and social cost) is maximum during evening peak hours. The morning hours show low externality and is evenly distributed till 17:15 hours. This suggests that motorist impose externality burden maximum during the evening peak hours that can be mitigated by imposing congestion tax during the same period.

4.1.1 Congestion cost curves for link 1between unit cost of road usage (Rs/veh-km) Vs density(veh/km) by varying E from −0.27 to −0.7

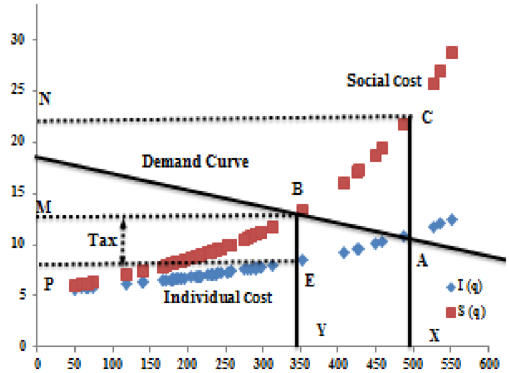


Fig 11: Congestion cost Curve between unit Cost Vs density; **E=0.27**

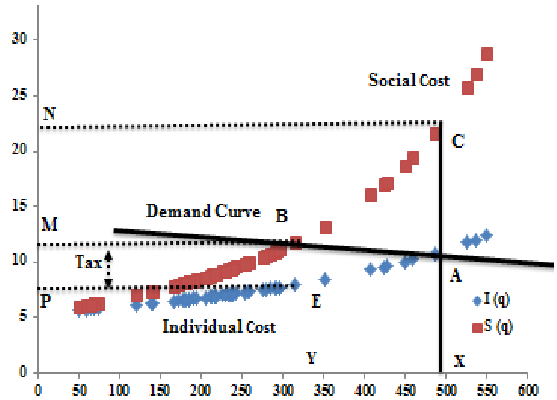


Fig 12: Congestion cost Curve between unit cost Vs density; **E=0.3**

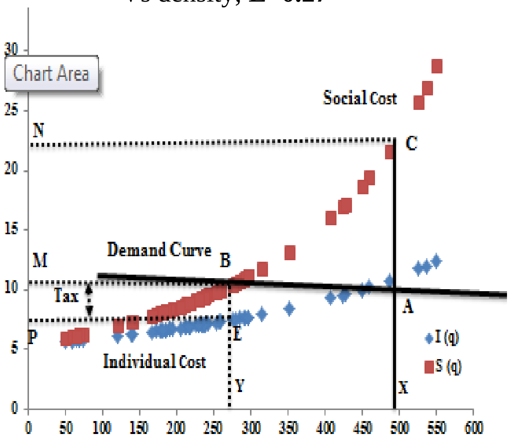


Fig 13: Congestion cost curve between unit cost Vs density; **E=0.4**

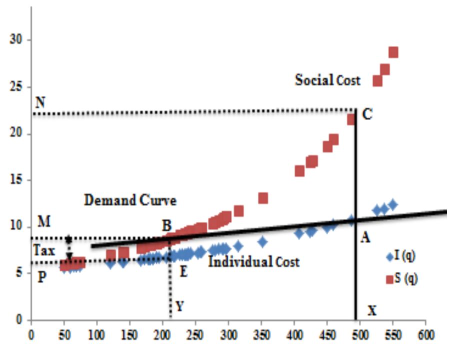


Fig 14: Congestion cost curve between unit cost Vs density; **E=0.5**

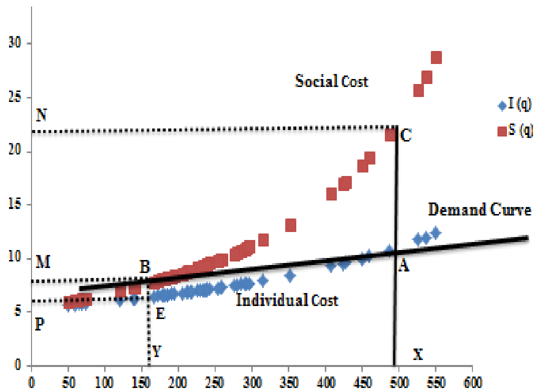


Fig 15: Congestion cost curve between unit cost Vs density; **E=0.6**

A high sensitivity (i.e. gradual curve from figure 10 to 14 above) indicates that relatively small change in unit cost of road usage causes relatively large changes in traffic density implying that density is more sensitive with change in unit cost of road usage. It can be inferred that motorist will find it very easy to pay toll for achieving better level of service. The link 1 thus shows highly ‘elastic behavior’. It is also evident that when E is changed from −0.4 to −0.5, the link shows ‘paradoxical behavior’ as inverse demand curve reverses its behavior underlying that maximum value of E can be freezed at value −0.4. The link shows very high value congestion cost for peak hours and very low congestion cost by non-peak hours.

4.2 Link 2 (Sarai Kale Khan to Ashram; 2.4 km length)

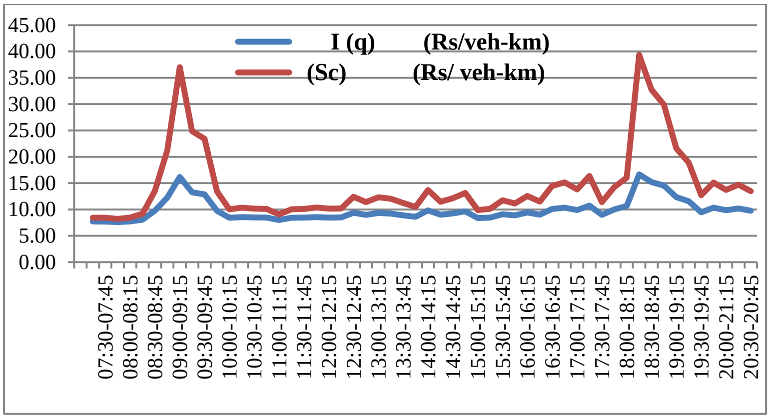


Fig 16: Shows variation of individual cost and social cost from morning to evening hours for link 2

Unlike link 1, link 2 has externality burden maximum during both morning and evening peak hours and is very less during rest of the day. The toll can be implemented during morning and the evening peak hours.

4.2.1 Congestion cost curves for link 2 between unit cost of road usage (Rs/veh-km) Vs density (veh/km) by E from −0.3 to −0.7

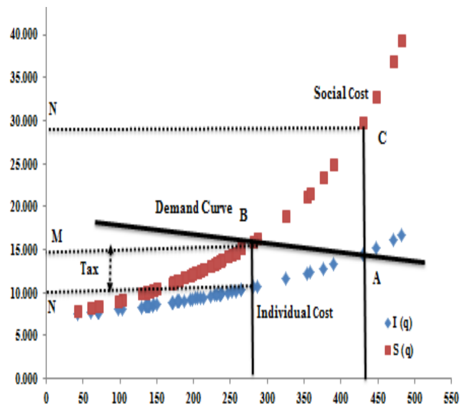


Fig 17: Congestion cost curve between unit cost Vs density at peak hour flow **E=−0.3**

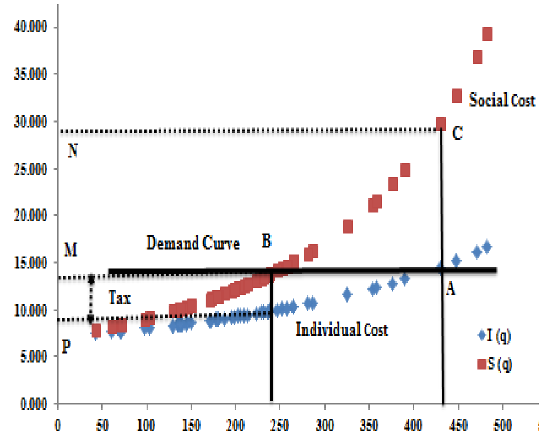


Fig 18: Congestion cost curve between unit cost Vs density at peak hour flow; **E=−0.4**

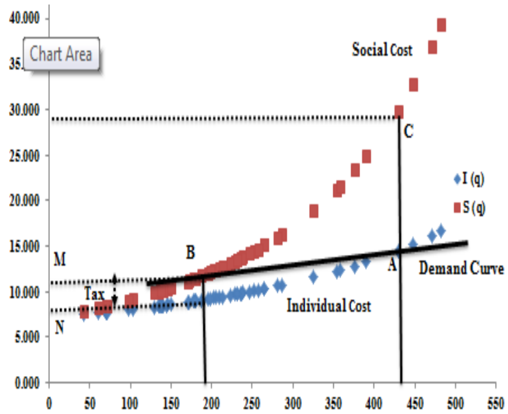


Fig 19: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.5**

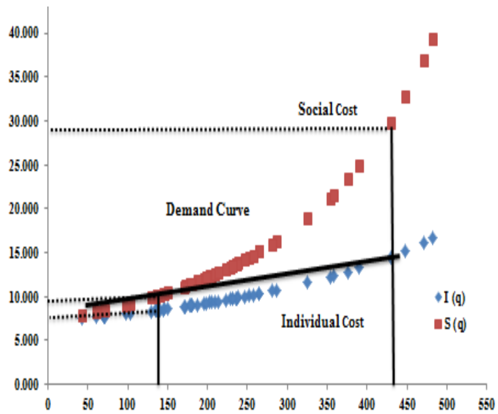


Fig 20: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.6**

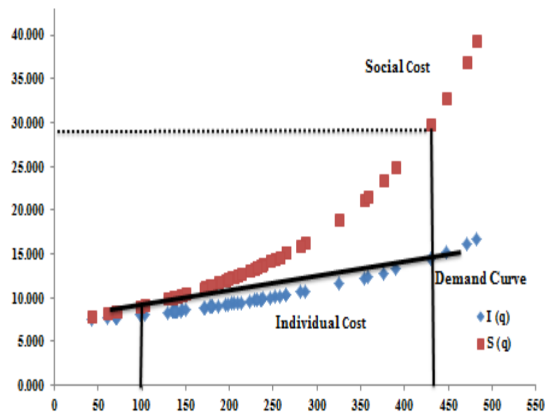


Fig 21: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.7**

Link 2 shows similar behavior as link 1 showing high sensitivity of demand curve from Fig. 17 to Fig 19. The link 2 also shows high elastic behavior. It is evident that when E is changed from −0.4 to −0.5, the link shows 'paradoxical behavior' as coordinates of inverse demand curve reverse in its behavior underlying that maximum value of E can be set at −0.4. The link has very high value congestion cost for peak hours and very low congestion cost by non-peak hours.

4.3 Link 3 (AIIMS to Moolchand ;distance 3.8 km)

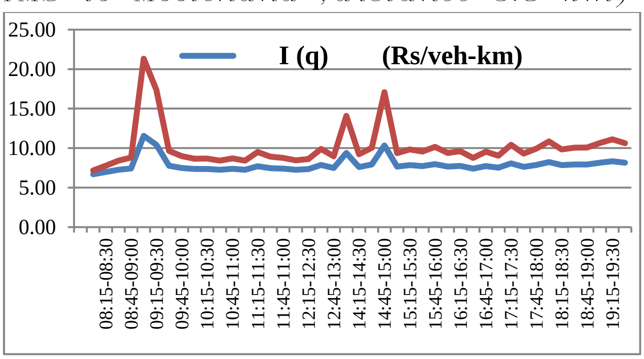


Fig. 22: Shows variation in individual cost & social cost from morning to evening hours in link 3

It is evident from Fig. 22 that externality is maximum during morning hours (8:30-9:50 hours) followed by peaks in mid-noon (14:45-15:30 hours). The toll can be implemented in the morning peak hours.

4.3.1 Congestion cost curves for link 3 between unit cost of road usage(Rs/veh-km) Vs density(veh/km) by varying E from -0.3 to -0.7

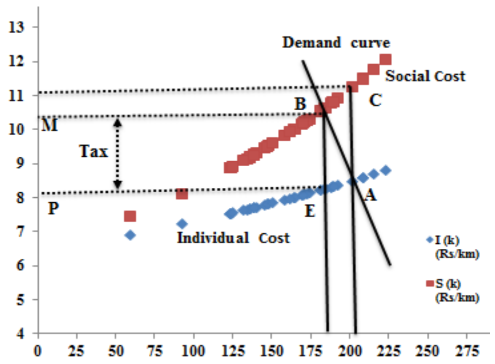


Fig 23: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.3**

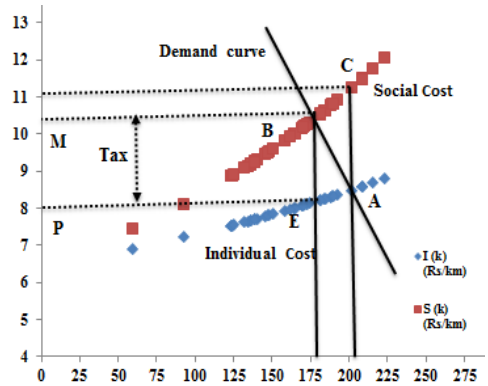


Fig 24: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.4**

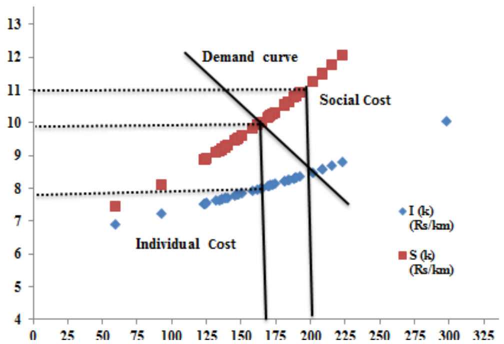


Fig 25: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.5**

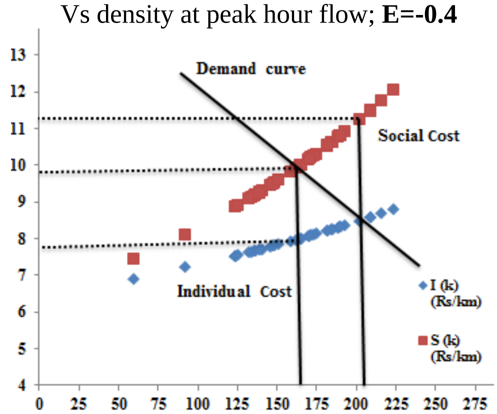


Fig 26: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.6**

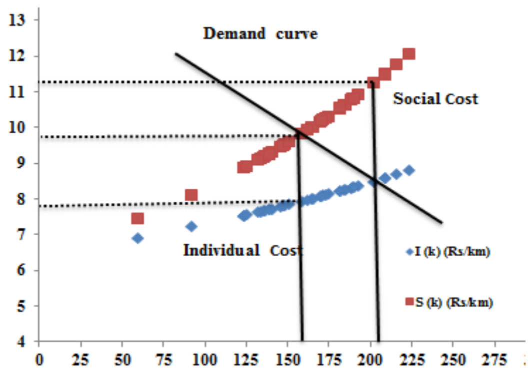


Fig 27: Congestion cost curve between Unit Cost Vs density at peak hour flow; **E=-0.7**

Less gradual demand curve from figure 23-27 indicates that density is less sensitive with change in unit cost of road usage, underlying that motorist has no alternative but to use the road. It also shows inelastic behavior of the link 3. Congestion tax is not recommended for link 3 as the link shows inelastic behavior leaving people with no other alternative to switch routes during peak hours. The link shows very low congestion cost that also suggests that imposition of tax is not a feasible option.

4.4 Link 4 (Mool Chand to AIIMS, 3.8 km)

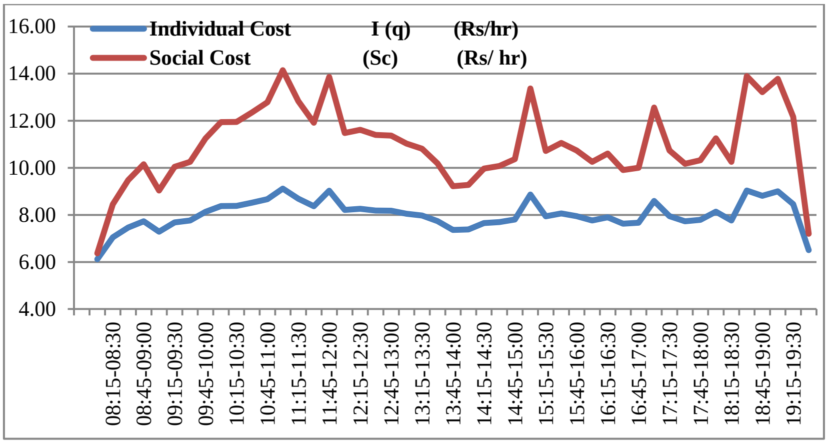
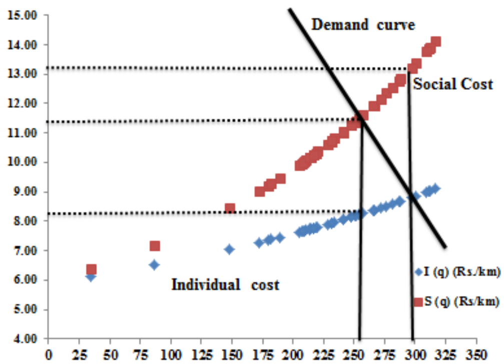


Fig 28: Shows variation in individual cost & social cost from morning to evening hours in **link 4**

The figure 28 shows that negative externality is unevenly distributed with several peaks ranging from morning to evening hours. The congestion cost is less for peak hours but more for non-peak hours.

4.4.1 Congestion cost curves for link 4 between unit cost of road usage (Rs/veh-km)Vs density (veh/km) by varying elasticity of demand (E) from -0.3 to -0.7



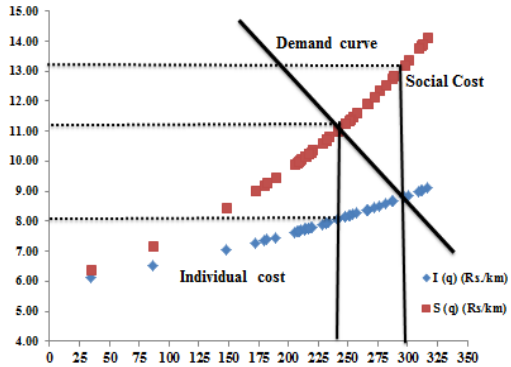


Fig 29: Congestion cost curve between unit density at peak hour flow; **E=-0.3**

Fig 30: Congestion cost curve between unit cost Vs cost Vs density at peak hour flow; **E=-0.4**

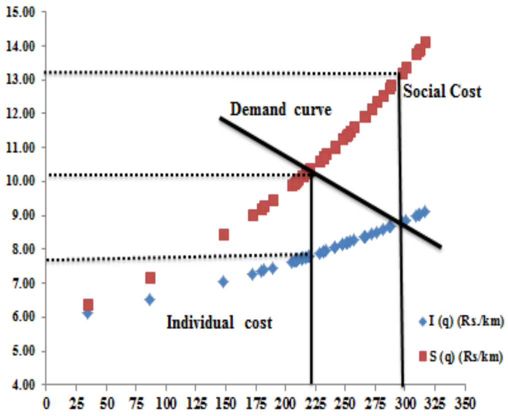


Fig 31: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.5**

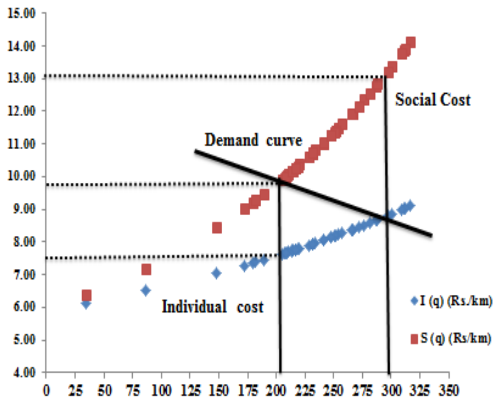


Fig 32: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.6**

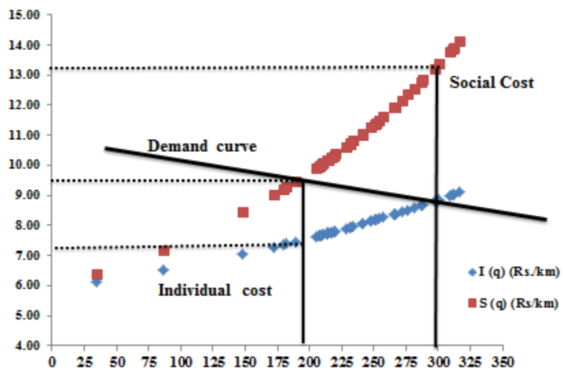


Fig 33: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.7**

Link 4 shows similar inelastic behavior as link 3.So, congestion charge or Tax is not recommended for link 4. The link shows very low congestion cost which also suggests that imposition of tax is not a feasible option.

4.5 Link 5 (Daula Kaun to AIIMS; 4.9 km)

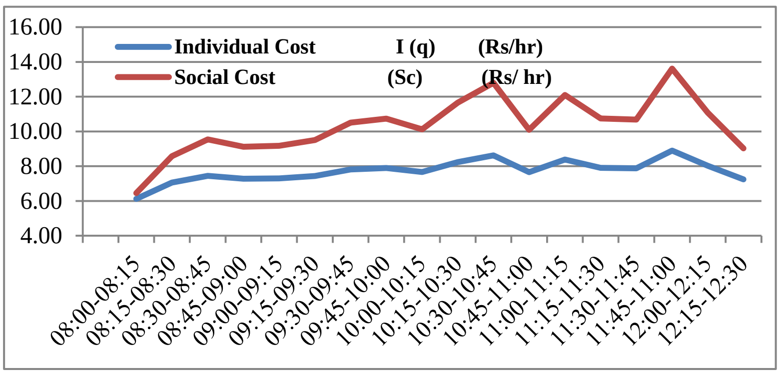


Fig 34: Shows variation in individual cost & social cost from 8:00 am to 12:30 pm in link 5

The above figure shows that negative externality is evenly distributed from morning to evening hours and the magnitude of social cost is less than link 1 and 2 but more than link 3. It reflects the marginal social cost burden in link 5 on motorist is throughout the day. Even though congestion cost is less than link1, 2 and 3 for peak hours but for non-peak hours it is uniformly distributed.

4.5.1 Congestion cost curves for link 5 between unit cost of road usage (Rs/veh-km) Vs density(veh/km) by varying E from -0.27 to -0.7

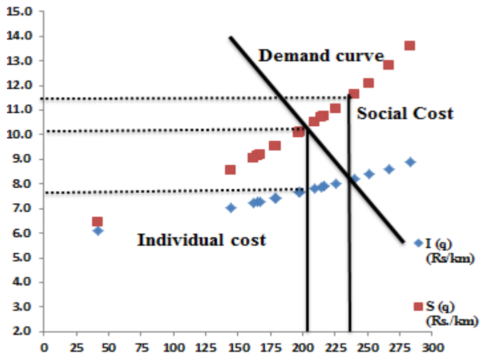


Fig 35: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.27**

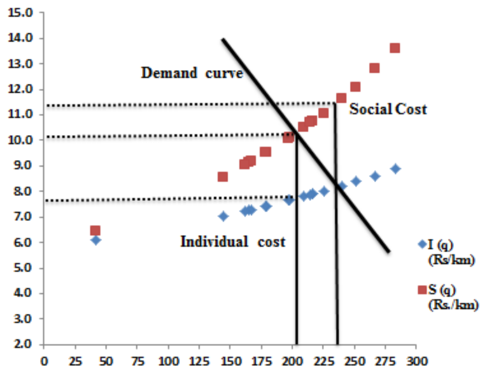


Fig 36: Congestion cost curve between unit cost density at peak hour flow; **E=-0.3**

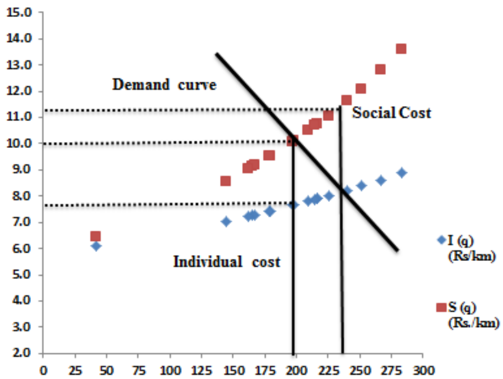


Fig 37: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.4**

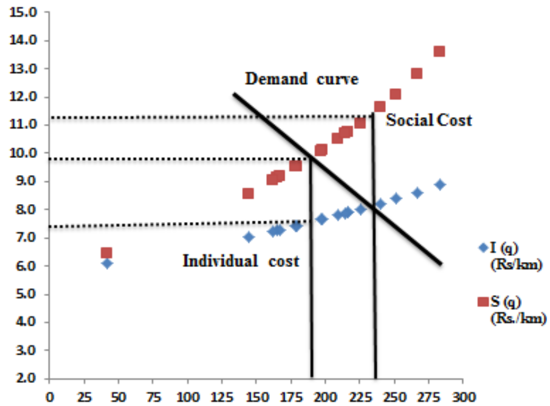


Fig 38: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.5**

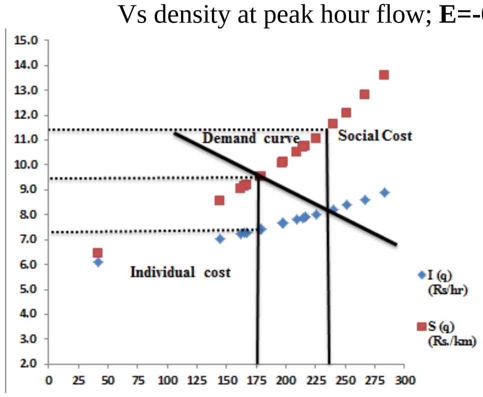


Fig 39: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.6**

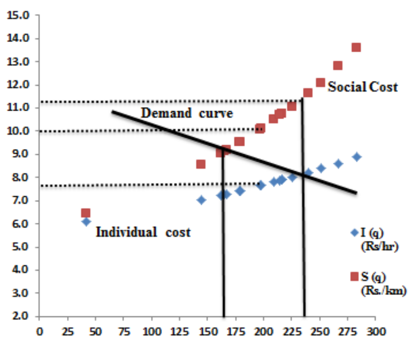


Fig 40: Congestion cost curve between unit cost Vs density at peak hour flow; **E=-0.7**

Link 5 shows inelastic behavior. So, congestion charge is not recommended for link 5. The link also shows low congestion cost as compared to link 1 and link 2.

4.6 Link 6 (AIIMS to Daula Kaun; 4.9 km)

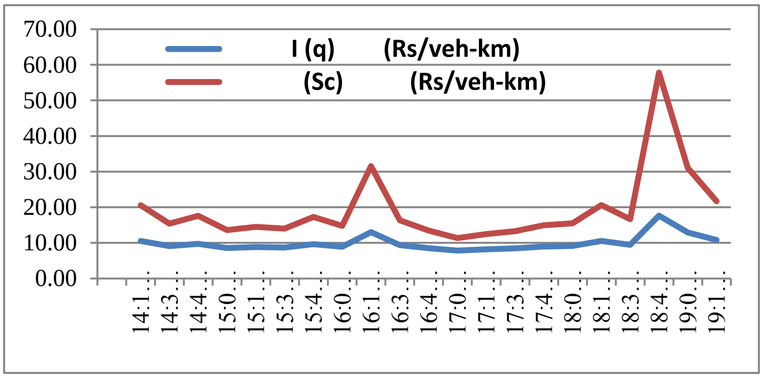


Fig 41: Shows variation in individual cost & social cost from 14:15 hours to 19:30 hours for link 6

It is evident from Fig. 41 that externality is maximum among all the six links during the evening peak hours (18:30-19:15 hours). So, the burden on society is maximum during the evening peak hours. Toll can be implemented during the evening hours.

4.6.1 Cost Curves for Link 6 between unit cost of road usage (Rs/veh-km) Vs density(veh/km) at E=-0.3

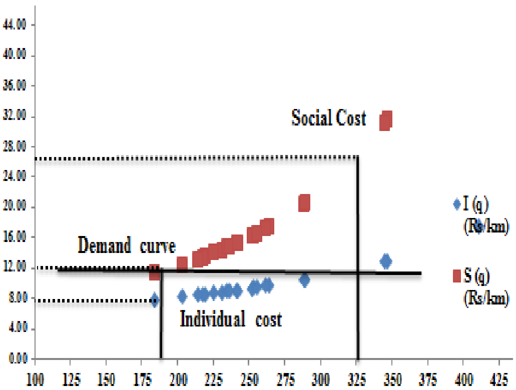


Fig 42: Congestion cost curve between Unit Cost Vs density **at E=-0.3**

The link 6 shows highest elastic behavior among all 6 individual links as shown in Fig 42. It can be observed that a very high elastic behavior is reflected at a low value of E at -0.3. The coordinates of inverse demand curve reverses its behavior at same low value of E, while changing density from 325 to 183 (veh/km). Congestion cost is very lower than link 1 & 2; but higher than link 3 and link 5.

4.7 Results of Cost curves for 6 links

Table 3: Summary of values of cost curves during peak and non-peak hours and congestion cost by economical &semi-economical approach for E ranging from -0.27 to -0.7 for link 1 to link 6

Link No. & Name	Elasticity of Demand	Average Individual Cost of link (Rs/veh.-km)	Average Social Cost of link (Rs/veh.-km)	Congestion Cost (Peak Hour) (Rs/veh.-km)	Congestion Cost (Non-peak Hour) (Rs/veh-hr.)	Congestion Cost (Semi economic Approach) (Rs/veh.-km)	Marginal External Congestion Cost (Rs/veh.-km)	Tax (Rs./km)
Link 1: Ashram to Sarai Kale Khan	0.27	7.49	10.91	937	0.24	1708	12.53	5
	0.3			1041	0.266	1300		4
	0.4			1388	0.355	1124		4
	0.5			1735	0.444	1107		5
	0.6			2081	0.532	238		0
Link 2: Sarai Kale Khan to Ashram	0.3	9.82	14.28	1151	0.451	1436	16.2	5
	0.4			1535	0.602	1199		5
	0.5			1919	0.752	770		4
	0.6			2303	0.903	218		1.5
	0.7			2687	1.053	0		0
Link 3: AIIMS to Moolchand	0.3	8.29	10.92	28.89	2.7	372	2.82	2
	0.4			38.53	3.7	412		2.3
	0.5			48.16	4.6	344		2
	0.6			57.79	5.5	330		2
	0.7			67.42	6.4	237		1.5
Link 4: Moolchand to AIIMS	0.3	8.01	10.98	99.8	15.4	758	2.97	3
	0.4			133.1	20.6	713		3
	0.5			166.3	25.7	556		2.5
	0.6			200	30.8	477		2.3
	0.7			233	36	462		2.4
Link 5: Daula Kaun to AIIMS	0.3	7.71	10.31	49.1	6.8	761	2.6	3.7
	0.4			65.5	9.1	431		2.2
	0.5			81.9	11.3	428		2.3
	0.6			98.3	13.6	338		2.2
	0.7			114.6	15.9	367		2.2
Link 6: AIIMS Daula Kaun	0.3	9.92	19.12	329.6	81.8	696	9.2	3.8

It is evident from Table3 that with increase in E from −0.3 to −0.7, peak hour congestion cost by economical approach increases while by semi-economical approach decreases for each individual links. The congestion cost for links 1, 2, and 6 is high for peak hours and very low for non-peak hours. The congestion cost for links 3, 4, and 5 are low for peak hours and not so high for non-peak hours. The value of tax shows an increase in value from 1.5 to 5 (Rs/km). The average individual cost and social cost vary from 7.5 to 9.12 (Rs/veh-km) and 10.31 to 19.12 (Rs/km) respectively.

5 Results And Policy Implications

In this paper, we have developed the methodology for estimating the congestion cost by economic approach by considering the demand of road users. We have applied this methodology to the inner ring road of Delhi to calculate the individual cost, social cost, congestion cost. Our results suggest that motor vehicles impose large externality that most of the users do not shoulder (links 1, 2 and 6).

There is a growing realization of Ministry of Urban Development and policy makers in India that the congestion mitigation steps in urban transport need to be addressed on a priority basis. Towards relieving congestion, umpteen measures that are taken included widening of roads, construction of flyovers and bridges did not relieve traffic congestion instead it increased more latent demand for road usage in Delhi. Bus Rapid Transit system (BRT) was kick started in 2008 to mitigate congestion but was scrapped in 2015 in Delhi. Delhi metro was introduced in 2010 with the aim to shift private vehicle users towards it. Even though metro caters average of whopping 25 lakh daily ridership (2018) spread over a network of 288 km, yet it failed to reduce externalities in the capital. With few feeder buses available and cheap, faster, interstate connectivity of metro network has attracted more people from other states to the capital. In 2015, odd-even scheme was experimented in two phases for 15 days in the capital to reduce traffic congestion and pollution that hogged international headlines. The study at IIT Delhi (2015) estimated the maximum impact on pollution by odd-even scheme was only 3%; while IIT Kanpur study concluded that the impact on pollution was just 1%.

It has become the need of the hour, given India is hugely investing in transport sector (about 2% of GDP) without achieving the desired results. An efficient transport system would go a long way in reducing externalities like: traffic congestion, air pollution (due to vehicular emission), traffic crashes, and energy crises. The transport sector is also a leading contributor to carbon emissions and particulate matter in India. From the safety point of view, road traffic injury is the eighth leading cause of death globally. The transport sector utilizes more than half of the India’s petroleum products. Since India has scarcity of its own crude oil resources, so the wastage of fuel due to traffic congestion will have serious implications for our energy security in a next decade. In spite of failure to relieve congestion by adopting various above engineering techniques, there is very little progress in implementing economical approach like road pricing which has a rich success story in other parts of state and that optimal road pricing based on Marginal Social Cost principles is the good way to go ahead. There is urgent also need to implement tougher car ownership policies to cap more than one car ownership per family based on quota system known as certificate of entitlement that ensures first bid for the certificate before purchasing a new car. Bank loans favouring easy car purchases should be stopped. The city authorities must consider adoption of measures that favor modal shift towards public transport that caters must of the modal split. Moreover, zoning and land-use reforms to mitigate congestion and planning an appropriate institutional framework are some of the policy options that can be initiated to mitigate the negative externalities of urban transport in Delhi.

In the present study, link wise congestion pricing is not a viable option, so long term solution seems in implementing congestion pricing, at Entry i.e. at link 1 and exit i.e. at link 6 for relieving congestion in inner ring road of Delhi. More studies like the present one with extensive data on whole of ring road would surely go a long way ahead towards the aim of implementation of optimal road pricing in Delhi.

Acknowledgement

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