SUSTAINABILITY IMPACT ASSESEMENT OF TRANSPORTATION POLICIES – A CASE STUDY OF BANGALORE CITY

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1. ABSTRACT

The current study propose a model for assessing the impact of various transportation policies based on the variation in three pillars of sustainability- environmental, economic and social. The methodology consists of determination of the various indicators of sustainability pillars, before and after introduction of transportation policies like congestion pricing, parking policies etc. Various Indicators used comprise of air pollution, natural resource consumption, health, accessibility, mobility, commute and cost. These indicators representing a policy scenario are then summed to form a Composite Sustainability Index (CSI) after weighing them using an Analytical Hierarchy Process (AHP). The impact of policies and thus the various indicator values are found using a mode choice model incorporated with the policy variable.

The second part consists of a case study for the city of Bangalore where the sustainability impact due to introduction of congestion pricing in the CBD, during peak hour, was tested. A modal split model developed from Revealed Preference data (RP) was used in the study. Here only those indicators that are based on the total trip distance were estimated. The choice model estimated a reduction of 25.89% and 28.37% for car and bike trips to CBD during peak hour. Most of them shifted to bus (Public transit). There was a 23% increase in CSI, in other words sustainability, due to this shift.

Keywords: Sustainable transport, urban transport policy, congestion charging

2. INTRODUCTION

Urban form and transport system have an enormous impact on the way people travel. With the rapid growing economies and population typically seen in developing countries, there is an increasing trend of expansion of urban sprawl and auto-based mobilisation. This has a direct effect on the level and form of transport demand and pattern. In the absence of the implementation of proper policy measures like, parking charges, congestion charging, fare revisions, pedestrianisation etc, it also leads to an increased additional cost for transportation infrastructure and its operation, while at the same time, creating many environmental, economic and social problems. In India, the Ministry of Urban Development (2013) has released an advisory for the Urban Local Bodies of various Indian cities for the introduction of Congestion Charging in the central business districts of the cities. Congestion Charge is a measure to reduce congestion by charging a fee on motor vehicles (cars and two-wheelers) entering the congested areas (central business districts) of the cities. The aim of this charge is to ease out the heavy motor vehicle volume found in the central areas of the cities and at the same time generating funds for transportation infrastructure development.

Sustainable transport systems are those which aim to reduce emissions, fossil fuel consumption, and the consumption of natural land, while providing easy access to people. Here more emphasis is laid on reducing the role of the private automobiles as the prime mode of transportation and shifting travel towards other sustainable modes such as public transit, cycling and walking. Sustainability of any system can be evaluated in terms of society, economy and environment – the three pillars of sustainability. For comprehensive sustainable development it is essential to monitor these three pillars with potential indicators that are reflective of changes in the travel behaviour of commuters. In the present study, a model is developed to quantify sustainability in terms of a composite sustainability index (CSI) which capture the indicators of the three pillars of sustainability in a quick and comprehensible manner and that could used to assess various transport policies and projects. Later a case study is done using proposed methodology to test impact of congestion charging in Bangalore city. This is done so by using the proposed sustainability model to find the Composite Sustainability Index (CSI) pre and post the introduction of congestion charging. Bangalore is facing problems of inefficient mobility and decreased levels of performance in the urban transport sector with a peak hour speed of 13.2 kmph (CTTP, 2007).

3. LITERATURE REVIEW

There has been a growing body of literature advocating the development of sustainable indicators to support urban planning process (Litman, 2007: Joen 2005). Indicators in this context are standardized measures suitable for analyzing and evaluating the importance of targeted outcomes. For example, a measure such as vehicle kilometres travelled (VKT) per capita can be used as an indicator to evaluate the level of mobility in the part of city where the policy is to be brought in. Various methods have been proposed in the past to devise sustainable indicators that could be used to gauge progress towards sustainability. The general consensus is that urban sustainability can only be achieved by addressing various aspects that are related to the pillars of sustainability: (1) Environment, (2) Society, and (3) Economy. The existing body of literature suggests that the sustainability of alternative future policies can be evaluated by calculating several indicators (i.e quantifiable measures of particular outcomes) pertaining to a list of pre-defined themes that correspond to the three pillars of sustainability. The objective is then to combine those indicators to identify which of the alternative policies will result in minimizing negative environmental and social outcomes, while maximizing economic benefits.

The following Table 1 summarizes the past studies done in related areas:

Table 1- Summary of past studies

Quantifying Sustainability	**Testing Policies**
Strategic Environmental assessment for sustainable urban development (Shepherd, and Ortolano, 1996)	Utilization of Sustainability Indicators and impact through policy learning in the Malaysian policy process (Hezri, 2004)
An Indicator based approach to measuring sustainable urban regeneration performance (Hemphill et. al., 2004)	Incorporating sustainability into transportation planning and decision making: Definitions, Performance Measures and Evaluation (Jeon & Amekudzi, 2005)
A tool for evaluating urban sustainability via integrated transportation and land use simulated models. (Maoh and Kanaroglou, 2009)	Impact of Modal Shift on Transport Ecological Footprint: A case study of proposed BRTS in Ahmadabad, India (Brajacharya, 2008)
Developing a Sustainability Assessment Model: The Sustainable Infrastructure, Land-Use, Environment and Transport Model (Yigitcanlar and Dur, 2010)	

Most of the studies in the past have emphasised more on environmental parameters and social and economic factors have not be addressed adequately. While studies in the past have devised various indicators, they have not attempted to build the sustainability model out of them and demonstrate their use to assess transport policies. This study is an endeavour to address this limitation of the previous research projects.

Manu studies in the past have also looked at the impact of congestion pricing on modal split. XU Wangtu et al(2008) in their study had established that congestion pricing influences the choice of mode and in turn the modal split. The study used the discrete choice model for modal split calculation by using SP survey data of Beijing city. Meng and Liu (2012) have proposed a combined modal split and traffic assignment problem assuming binary logit model for calculating modal split for a bimodal system. Using traffic data from downtown Singapore, they have concluded that cordon-based congestion pricing has significant influence on the mode-share of public transport system. Some of the studies also deal with the environmental and socio-economic impacts of congestion charging. Beevers and

Carslaw (2005) studied the impact on vehicular emissions for London and observed that the vehicle speeds increased significantly after congestion charging. They also found a 19.5% decrease in CO_2 emissions. There Rich and Nielsen (2007) compare various road pricing schemes for socio economic benefits in terms of the reduction in congestion time, car mileage, accidents, noise, maintenance cost etc. They established that the socio-economic surplus of the projects depends crucially on the congestion level.
However, these studies are limited to evaluating the impact of congestion charging on the modal split and evaluating the environmental, economic and social impact separately. The current study addresses this limitation by providing a composite measurement of sustainability impact of congestion pricing combining environmental, social and economic impact.

4. METHODOLOGY

4.1 Composite Sustainability Index Determination

Kelly (1998) identified several criteria for evaluating sustainability indicators in the study of an urban system. He notes that any devised indicator should be:

- Calculated by using already available or easily obtainable information
- Easily understandable without ambiguity and exceptional overlapping
- A measure of something important in its own right
- Comparable in terms of different geographical scales and the actors involved
- User driven
- Policy relevant
- Highly aggregated, i.e final indices should be few in number

Based on the study of past literature and the above criteria, a number of sustainable indicators are selected as shown in Table 2 to represent various aspects and domains of sustainability. The indicators are devised such that they are policy responsive.

Table 2 - Sustainable indicators for evaluation

Pillar	**Theme**	**Label**	**Indicator**	**Definition**
Environment	Air pollution	AP1	Greenhouse gases	Level of CO[gm]/km of vehicle type
		AP2	Acidifying gases	Level of NO_x[gm]/km of vehicle type
		AP3	Volatile organic compounds	Level of HC[gm]/km of vehicle type
		AP4	Fine particles< 2.5 μm	Level of PM 2.5[gm]/km of vehicle type
		AP5	Fine particles<10	Level of PM 10[gm]/km of

			μm	vehicle type
	Natural resources	NR1	Energy use from fossil fuel	Litres consumed per km
Society	Health	HL1	Exposure to NO_x from transport	Number of people exposed to harmful levels of NO_x
		HL2	Exposure to CO from transport	Number of people exposed to harmful levels of CO
		HL3	Traffic injuries and deaths	Number of traffic injuries and death per modal share over a year
	Accessibility	AM1	Accessibility to services	Average potential accessibility to services
	Commute	AM2	Vehicle kilometers travelled	Total VKT per mode
		AM3	Vehicle minutes travelled	Total VMT per mode
	Mobility	AM4	Congestion Index	Average level of congestion in the area under study
Economy	Cost(rupees)	EC1	Transport investment cost	Total rupees spent on upgrading and maintenance of road infrastructure
		EC2	Transport commuting cost	Overall cost of commuting
		EC3	Transport external cost	Total rupees due to externalities associated with health

In the present case study all the indicators are not used. Pragmatic methodologies to reach the indicator values are discussed in the results section. The task is then to use Principal Component Analysis (PCA) to arrive at final set of indicators that can be brought together to develop the Composite Sustainability Index (CSI). However, the above process gives the raw value of each indicator for a certain flow scenario. These values are in different units and hence cannot be compared. This prompts using normalization technique that can bring all indicators to same unit of comparison. For this, the method proposed is min-max method of normalization owing to its simplicity and easily obtainable values. Mathematically the normalized value is represented as:

$$\frac{100(actual\ value - minimum\ value)}{(maximum\ value - minimum\ value)}$$

Here, the actual, minimum and maximum value of indicator corresponds to normal flow condition, free flow condition, and maximum flow condition

The CSI is conceived as a maximizing function i.e. higher the value of CSI better is the sustainability impact of any transportation policy or project that is being tested. In other words, in scenario analysis, the option with the highest CSI value will be best to adopt to achieve sustainability. To obtain CSI, firstly the sustainability indices are obtained for each of the three pillars of sustainability (SI_P), where P stands for social, environmental, and economic pillars.

$$SI_p = \sum_{i=1}^{n} \alpha_i w_i \,.\, x_i$$

Where,
x_i,… x_j are normalized variables
n is the no. of indicators influencing SI
w_i is the weight attached to x_i, determined using Analytical Hierarchy Process (AHP), such that $\sum_{i=1}^{n} w_i = 1$
α is a binary variable with a value of +1 if the indicator has positive effect on CSI and -1 if it has negative effect on CSI.

The Composite Sustainability Index (CSI) is calculated as the sum of the weighted sustainability indices for each pillar P, as given below:

$$\boldsymbol{CSI}_{Link} = \boldsymbol{SI}_{Environment} + \boldsymbol{SI}_{Social} + \boldsymbol{SI}_{Economic}$$

As indicated earlier, higher value of CSI will imply better sustainability.

4.2 Mode choice analysis

Discrete choice modelling based framework is used to capture the change in mode share and hence sustainability due to the introduction of a policy like congestion pricing. Discrete choice models are typically based on the theory of utility maximisation. Utility is an indicator of the value an individual gives a mode. This study uses the Multinomial Logit Model (MNL) which gives the choice probabilities of each alternative as a function of the systematic portion of the utility of all the alternatives. The general expression for the probability of choosing an alternative 'i' (i = 1, 2,..., J) from a set of J alternatives is:

$$\Pr(i) = \exp(V_{i)} / \sum_{j=1}^{J} \exp\,(V_j)$$

where
Pr(i) is the probability of the decision-maker choosing alternative i
V_j is the systematic component of the utility of alternative j

Utility is usually expressed as a linear function in parameters of variable like travel time, travel cost, house hold income etc. The model is estimated using maximum likelihood method i.e. maximise the likelihood that the sample is generated from the model with the selected parameter values. The values of the parameters which maximise the likelihood function are obtained by finding the first derivative of the likelihood function and equating it to zero.

4.3 Analytical Hierarchy Process (AHP)

AHP allows for a pair-wise comparison between the different indicators to obtain the relative priorities for them. Its essence lies in constructing a matrix expressing the relative values of a set of attributes. In AHP, each of these judgments' is assigned a number on a scale. One commonly used scale is given in Table 3.

Table 3 – Commonly used scale of comparison

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

A basic, but very reasonable, assumption is that if attribute A is absolutely more important than attribute B and is rated at 9, then B must be absolutely less important than A and is valued at 1/9. In the present methodology the above rating table is used to find out the local weight of indicators in each theme. This weight when multiplied with the weight of sustainability pillar, an assumed value of 0.33 for each, gave the global weight of each indicator. Table 4, 5 & 6 below give the global indicator value determined for indicators based on responses from 7 experts in the field of transportation including academicians as well as experts from the industry. Amongst the environmental indicators, high weightage is given to the greenhouse gas emissions (AP1) whereas accessibility and transportation investments are highly weighed social and economic indicators.

Table 4 - Global weight of environmental indicators

AP1	AP2	AP3	AP4	AP5	NR1
0.106	0.045	0.029	0.059	0.051	0.040

Table 5 - Global weight of social indicators

HL1	HL2	AM1	AM2	AM3	AM4
0.064	0.054	0.070	0.056	0.046	0.039

Table 6 - Global weight of economic indicators

EC1	EC2	EC3
0.143	0.130	0.057

5. CASE STUDY BANGALORE

A case study for the impact of congestion pricing in the CBD (Central Business District) was done for the city of Bangalore. The impact was determined as variation in sustainability index before and after the introduction of congestion pricing. For determining sustainability index, at first, the mode shift in the trips to CBD, from other zones, due to congestion pricing on private vehicles (car and bike) was determined. The model used to identify the impact of congestion pricing was a Multinomial Logit Model (MNL) developed for city of Bangalore by the authors. Table 7 shows the model developed.

Table 7 - MNL model

Car = -0.0195 * Time of travel -0.00689 * Travel cost + 0
Public transit = -0.0195 * Time of travel + -0.00689 * Travel cost -16.8 * Access distance by walk - 0.0354 * Age + 16.3
Two wheeler = -0.0195 * Time of travel -0.00689 * Travel cost - 0.248
Auto rickshaw = -0.0195 * Time of travel -0.00689 * Travel cost + 0.208
Bicycle = -0.0195 * Time of travel -0.00689 * Travel cost - 0.363 * cycling distance - 0.0526 * Age - 1.29* sex - 0.522 * Education level -0.0533 * House hold income/1000 + 4.25
Walk = -0.0195 * Time of travel - 0.00689 * Travel cost -1.29 * sex - 0.522 * Education level - 0.374 * Walking distance - 0.0460 * Age - 0.00635 * House hold income/1000 + 4.74

The variation in congestion price was accommodated in the travel cost variable of the model. The simulation tool from Biogeme (Bierlaire, 2003; Bierlaire, 2008) was used to arrive at the aggregate probability after introduction of congestion pricing. It was assumed there will be no decrease in time variable for any mode. The study did not distinguish between workers and non-workers and assumed there was no shift in destinations. The value of congestion cost was found by dividing the total congestion cost for Bangalore by total motorized vehicle trips in Bangalore. The total congestion cost was estimated as 156 million Indian rupees (Rs), (Rahul and Verma, 2012). Table 8 shows the calculation of entire vehicle trips for Bangalore.

Table 8 - Vehicle trips in Bangalore

Vehicle type	**Number of passenger trips* (1)**	**Occupancy (2)**	**Number of vehicle trips (1)/(2)**
Bus	2634471	50	52690
Car	416304	2.59*	160736
2-Wheeler (bike)	1845476	1.53*	1206193
3 –wheeler (auto)	726425	2.49*	291737
		Total	1711356

*Source CTTP, 2007

The congestion cost imposed by each vehicle while making a trip came as 91 Rupees. So in the study we tried implementing a congestion cost of 90 Rupees for car and 2-wheeler.

5.1 Data source

House hold travel data for the city of Bangalore for the year 2009 obtained through secondary sources was used in the study. The CBD to the Bangalore city was determined along a radius of 2 Kilometer (Km) around the town hall. There were around 14 zones coming inside the radius. In order to study the impact of congestion pricing we used only trips having destination along these zones. Also the impact of congestion pricing was examined for trips during the peak hour. The sample had 485 trips made from 33 different zones to CBD. Out of the 483 trips, 386 were made in the morning and 99 in the evening. Out of the 386 trips in the morning, 342 were reaching their destination in CBD between 8 AM -11 AM indicating that 8 AM -11 AM were the peak hours. The maximum trips were reaching their destination in CBD between 9 AM -10 AM (180 trips). It was these trips which were used in the MNL model to determine the shift after introduction of congestion pricing. Table 9 presents some of the characteristics of trips coming to CBD.

Table 9 - Characteristics of trips to CBD

Characteristic		**Mean trip distance travelled (Km)**	**Percentage in total trips (%)**	**Sample size**
Age				
	<15	4.7	1.4%	7
	15-55	7.6	93.0%	449
	>55	6.8	5.6%	27
Purpose				
	Work	7.6	82.0%	396
	School	5.5	3.7%	18
	personal	11.5	2.3%	11
	Others	7.2	11.8%	57
Sex				
	Male	7.7	93.0%	449
	Female	5.5	7.0%	34
Occupation				
	Employed	7.6	92.8%	448
	Unemployed	7.9	4.6%	22
	Student	6.2	2.7%	13
Level of education				
	Illiterate	7.5	19.9%	96
	Educated	7.5	80.1%	387
House hold income (Rs.)				
	<5000	6.5	47.80%	231
	5000-15000	8.4	50.70%	245
	>15000	11.4	1.40%	7

5.2 Sustainability indicator determination

The sustainability indicators for evaluation were determined from the travel characteristics of the motorized modes. The indicators were determined for both scenarios, before and after introduction of congestion pricing, based on the on the total vehicle trips to CBD during peak hour and the distance travelled by them. The aim was to study effect of modal variation on the total vehicle trip distance and thus on the indicator variables. So only those sustainability indicators determined based on the trip distance of motorized vehicles were used in the study. These indicators included emission factors CO, NO_x and HC, fuel consumption for the natural resource used, Vehicle kilometers travelled and Vehicle minutes travelled for commute, and transport investment cost. In order to normalize the sustainability indicators the study required sustainability indicators value at maximum and minimum number of vehicle trips to the CBD, along with the sustainability indicators value before and after introduction of congestion pricing. The sustainability indicators value before introducing congestion pricing was determined using the personal trip distance data of the current trips to CBD during peak hour. The trip distance data for finding the sustainability indicators after introduction of congestion pricing was estimated by multiplying the variation of modal probabilities with vehicle trip distance data of earlier scenario. Here we assume that the entire trip distance to CBD will get shifted on congestion pricing. The sustainability indicator values at maximum number of vehicle trips to the CBD for both scenarios were determined using the vehicle trip distance for each scenario, and the ratio between the maximum traffic flow capacity across all links to CBD during peak hour and the actual flow across all links to CBD during peak hour (before and after introduction of congestion pricing).

The study considered the total link volume to CBD during the peak hour rather than an individual link volume. The maximum traffic flow capacity across all links leading to CBD was estimated from the link data. There were around 11 arterials (4 lane, 2-way) leading to CBD from other zones. The network capacity for each of this arterial was given as 4500 vehicles/hour in one direction in the network data without considering effect due to friction. The total possible maximum flow to CBD during peak hour thus came as 49500 vehicles per hour. The minimum possible vehicle trips to CBD were assumed as zero. The flow across all links to CBD during peak hour (before and after introduction of congestion pricing) was found from sample data using the trips which came to CBD during peak hour (9 AM – 10 AM). This was done after converting existing trips/hour to Vehicles/hour using occupancies, and the modal probabilities for two scenarios. All the above volumes and trip distance found were projected for a sample size (1.25 %), deleted incomplete data and for zones which were omitted. The 180 trips coming to CBD during peak hour became 90000 after projection.

5.3 Results and Discussion

5.3.1 Mode choice analysis

Table 10 shows the probabilities before and after introduction of congestion pricing for motorized modes along with the total distance travelled by each mode to CBD during peak hour.

Table 10 - Probabilities before and after introduction of congestion pricing

Mode	Probability before congestion pricing	Probability after congestion pricing	Percentage change (%)	Distance Travelled before congestion pricing (Km)*	Distance Travelled after congestion pricing (Km)**
Car	0.0224	0.0166	-25.89	21621.62	16023.78
Bus	0.497	0.576	+15.89	6755	7828.37
Bike	0.289	0.207	-28.37	542810.45	388815.1253
Auto	0.0373	0.0394	+5.63	7730.92	7975.22

*Determined form the distance travelled by each mode from sample

**Determined from the percentage change in Table 4

It can be seen from the table 10 that the probability of choosing car and bike to CBD reduces on introduction of congestion pricing. Percentage decrease of 25.89% and 28.37% occurs for car and bike respectively. Table 11 and 12 show the calculation of vehicle trips from the total 90,000 trips coming to CBD during peak hour, before and after introduction of congestion pricing.

Table 11 - Vehicle trips to CBD before introduction congestion pricing

Mode	Probability (1)	Occupancy	Trips to CBD (Person-Trips)(3) (1)*90,000	Trips to CBD (Vehicle -Trips)
Car	0.0224	2.59	2016	779
Bus	0.497	50	44730	895
Bike	0.289	1.53	26010	17000
Auto	0.0373	2.49	3357	1349
			Total	20023

Table 12 - Vehicle trips to CBD after introduction congestion pricing

Mode	Probability (1)	Occupancy	Trips to CBD (Person-Trips)(3) (1)*90,000	Trips to CBD (Vehicle -Trips)
Car	0.0166	2.59	1494	577
Bus	0.576	50	51840	1037
Bike	0.207	1.53	18630	12117
Auto	0.0394	2.49	3540	1424
			Total	15215

From table 11 and 12 one can observe that there is a reduction in number of vehicle trips to CBD after congestion pricing is charged. This is due to shift of people from car and bike to other modes, mainly public transit. From the total vehicle- trips in table 4 and 5 the ratio between maximum number of trips to CBD and actual number of trips to CBD before and after introduction can be calculated as 2.5 (49500/20023) and 3.25(49500/15215) respectively.

5.3.2 Sustainability Indicators

5.3.2.1 Value of indicators before introduction of congestion pricing

5.3.2.1.1 Environment module

Air pollution

The value of the air pollution indicators CO, NO_x and HC were found based on work of Sharma and Mathew (2007). They developed speed dependent emission functions for each type of vehicle. The form of the function used is a second-degree polynomial equation for various modes of transport to capture better emission measurements.

$$e_p^m(v_a) = C_1\, v_a^2 + C_2(v_a) + C_3$$

Here v_a represented speed of each mode in Kilometer/hour (Km/hr) and c_1, c_2, c_3 coefficients. e_p^m represent the emission factors for mode '*m*' and '*p*' pollutant in grams/kilometer (g/Km). Table 13 indicates the coefficient values for each emission factor for each mode along with their calculated emission. This is found both for actual flow and maximum flow across all links leading to CBD. An average speed of 15.3 km/hr for car, 13.38 Km/hr for public transit (bus), 10.14 Km/hr for auto-rickshaw (3-wheeler) and 14.34Km/hr for bike (motorized 2-wheeler) was estimated from the origin to destination travel time and travel distance. But this average speed considered the in between stop times also. In order to find the average running an equation linking actual speed, free flow speed and volume was used (CTTP, 2007).

$Y = a – bx^n$

Where

Y = Speed

a = constant (speed at free flow) =40.72 Km/hr

b = Coefficient of x = 0.25

x = Flow in PCUs / hour / lane

n = Power of x = 0.52

The study determined a value of 779 cars, 895 buses, 17000 bikes and 1349 auto-rickshaw travelling to CBD during peak hour. Assuming equal distribution of vehicles across the 11 links leading to CBD a total PCU value of 606 PCU/hour/lane was found for each link. PCU value was assumed as 1 for car and auto, 0.5 for bike and 3 for bus. Putting the above flow in equation above a standard vehicle (car) speed of 33 Km/hr was found. Assuming same difference as that of average speeds a value of 31 km/hr, 28Km/hr, 32 Km/hr was obtained for bus, auto-rickshaw and bike. Speed at capacity condition for car was taken as 17 Km/hr (CTTP, 2007). Speeds of other modes at capacity condition were derived as 15 Km/hr (bus), 12 Km/hr (auto-rickshaw), and 16 Km/hr (bike).

Table 13 - Pollutant coefficient

Vehicle Type *	**Pollutant***	**C1***	**C2***	**C3***	**Actual trips**		**Maximum trips**	
					Speed (v_a) (Km/hr)	**e_p^m (g/Km)**	**Speed (Km/hr)**	**e_p^m (g/Km)**
Car	NO_x	0.0003232	-0.01358	0.1726	33	0.076425	17	0.035145
	CO	0.0020380	-0.22270	8.8100	33	3.680282	17	5.613082
	HC	0.0003123	-0.02808	0.7374	33	0.150855	17	0.350295
Bus	NO_x	0.0068150	-0.84510	27.550	31	7.901115	15	16.40688
	CO	0.0002483	-0.04090	1.698	31	0.668716	15	1.140368
	HC	0.0001958	-0.02934	1.139	31	0.417624	15	0.742955
Auto-rickshaw	NO_x	0.0003	-0.0210	0.4639	28	0.1111	12	0.2551
	CO	0.0061	-0.7781	27.4060	28	10.4016	12	18.9472
	HC	0.0198	-1.6526	36.8350	28	6.0854	12	19.855
Two-wheeler	NO_x	0.00002	-0.0038	-0.1815	32	-0.28262	16	-0.23718
	CO	0.00430	-0.4952	18.1330	32	6.6898	16	11.3106
	HC	0.00080	-0.0991	3.4116	32	1.0596	16	2.0308

Source: (Sharma and Mathew, 2007)

The indicators value when maximum number of vehicle trips came to CBD was determine using ratio of current number of trips during peak hour (peak hour volume) to CBD to maximum number of trips possible to CBD if all the networks were running according to capacity=49500/20023= 2.5. It was assumed that the total vehicle distance for each mode will also increase by the same ratio in all networks leading to CBD if they run full. Table 14 gives the total value of each emission factor across the entire modes for actual number of trips to CBD. Table 15 gives the total value of each emission factor across the entire modes for maximum number of trips to CBD. In table 14 and 15, e_{NOx} ,e_{co} e_{HC} were obtained from table 13.

Table 14 - Emission factors across entire modes for actual number of trips

Vehicle type	e_{NOx} (g/Km) (1)	e_{co} (g/Km) (2)	e_{HC} (g/Km) (3)	Vehicle distance (Km) (4)	Emission (g)		
					e_{NOx} (1)*(4)	e_{co} (2)*(4)	e_{HC} (3)*(4)
Car	0.0764248	3.680282	0.150855	21621	1652.381	79571.38	3261.629
Bus	7.901115	0.668716	0.417624	6755	53372.03	4517.179	2821.049
Auto-rickshaw	0.1111	10.4016	6.0854	542810.5	60306.24	5646097	3303219
Bike	-0.28262	6.6898	1.0596	7730.92	-2184.91	51718.31	8191.683
				Total	113145.7	5781904	3317493

Table 15 - Emission factors across entire modes for maximum trips

Vehicle type	e_{NOx} (g/Km) (1)	e_{co} (g/Km) (2)	e_{HC} (g/Km) (3)	Vehicle distance (Km) (4)	Emission (g)		
					e_{NOx} (1)*(4)	e_{co} (2)*(4)	e_{HC} (3)*(4)
Car	0.035145	5.613082	0.350295	54052.5	1899.664	303401.1	18934.3
Bus	16.40688	1.140368	0.742955	16887.5	277071.1	19257.96	12546.65
Auto-rickshaw	0.2551	18.9472	19.855	1357026	346177.4	25711845	26943754
Bike	-0.23718	11.3106	2.0308	19327.3	-4584.05	218603.4	39249.88
				Total	620564.1	26253108	27014485

Natural resource consumption

This indicator expressing the natural resource consumption is the gasoline and diesel consumption by each mode. It can be determined by dividing the total vehicle distance travelled using a mode by its mileage. Table 16 shows the mileage for each mode. For our study, we assumed a mileage of 46.1Kilometer/Liter (Km/L) for 2-wheeler ((38.4+53.3)/2), 16.8 Km/L ((13.6+20)/2) for car, 24.9 Km/L for auto and 3.27 Km/L for bus.

The total vehicle miles determined for each mode were 21621.62 Km, 6755 Km, 542810.45 Km, and 7730.92 Km for car, bus, bike and auto respectively. On dividing it with their respective mileage we got an indicator value of 1287 L, 2065 L, 11774.6, 310. 48 for car, bus, bike and auto respectively. The total fuel consumption summed to 15437.08L. When the total vehicle distance for each mode increase by 2.5 for maximum vehicle trips; fuel consumption of 3217.2L, 5162.5L, 29436.5L, and 776.2L were obtained for car, bus, bike and auto respectively.

Table 16 - Mileage of various modes

Vehicle Type	**Fuel (Km/liter)**
Gasoline Motor Scooter (2-stroke)	38.4
Gasoline Motor Scooter (4-stroke)	53.8
Electric Motor Scooter	N/A
Gasoline Minicar	24.9
Gasoline Car	13.6
Diesel Car	20.0
CNG Car	N/A
Electric Car	N/A
Diesel Bus	3.27
CNG Bus	N/A
Fuel Cell Bus (methanol)	N/A

Source: Bose and Nesamani (2000)

5.3.2.1.2 Social module

Commute

Indicators pertaining to the level of commuting included total vehicles kilometer travelled (VKT) and total vehicles minutes travelled (VMT). The general idea here is that higher values of VKT and VMT will be associated with higher levels of commuting distance and time. For current trips the total VKT came as 578917.37 (21621.62 + 6755 + 542810.45 + 7730.92). Dividing the VKT of each mode with their average speed VMT of each mode was estimated. Using an average speed of 33 km/hr for car, 31 Km/hr for public transit (bus), 28 Km/hr for auto (3-wheeler) and 32 Km/hr for bike the total VMT was estimated 1.07 $*10^6$ minutes (18112 hours). For maximum number of vehicle trips to CBD VKT and VMT was estimated 1447293.425 Km and $5.443*10^6$ minutes respectively.

5.3.2.1.3 Economic module

Cost

The indicator elicited in the study pertaining to cost was transport investment cost. It was determined by multiplying an assumed transport investment cost of 200 Indian Rupees (INR) /Kilometer with total VKT. It was obtained as 115.8 $*10^6$ Rupees and 289.5 $* 10^6$ Rupees for current and maximum trips. Table 17 shows the indicators with their actual, maximum, minimum and normalized value determined earlier in table format.

Table 17 - Values of indicators before introduction of congestion pricing

Pillar of Sustainability	Indicator	Indicator value for actual number of vehicle trips	Indicator value for minimum vehicle trips	Indicator value for maximum vehicle trips	Normalized Value
ENVIRONMENT					
Air pollution	Level of CO[gm]/km of vehicle type	5781904 g		26253108 g	22.0237
	Level of NO_x[gm]/km of vehicle type	113145.7 g	0	620564.1g	18.2327
	Level of HC [gm]/km of vehicle type	3317493 g	0	27014485g	12.2804
Natural Resources	Energy consumption l/km.	15437.08L L	0	38591.9L	40
SOCIAL					
Commuting	Vehicle Km Travelled(VKT)	578917.37 Km	0	1447293.425 km	40
	Vehicle Minutes Travelled(VMT)	$1.07 *10^6$ min	0	$5.443*10^6$ min	19.7
ECONOMIC					
Transport Investment	Transport Investment Cost	$115.7 *10^6$ Rs	0	$289.5*10^6$	40

5.3.2.2 Value of indicators after introduction of congestion pricing

After introduction of congestion pricing the VKT became 16024Km, 7828Km, 388815Km, and 7975Km (table 4) respectively for car, bus, bike, and auto. Due to change in vehicle proportion the ratio of current number of trips during peak hour (peak hour volume) to CBD to maximum number of trips possible to CBD if all the networks were running according to capacity came as 3.25 (49500/15215). The speed of modes when actual number and maximum number of vehicles came to CBD was assumed same as earlier (before congestion). The values calculated for indicators for the above mentioned vehicle distance and ratio, using similar procedure as above is given in the table 18 below.

Table 18 - Values of indicators after introduction of congestion pricing

Pillar of Sustainability	Indicator	Indicator value for actual number of vehicle trips	Indicator value for minimum vehicle trips (V_x^{min})	Indicator value for maximum vehicle trips (V_x^{max})	Normalized Value(V_x^*)
ENVIRONMENT					
Air pollution	Level of CO[gm]/km of vehicle type	4161857 g		24557092 g	16.9477
	Level of NO_x[gm]/km of vehicle type	104018 g	0	735447 g	14.1435
	Level of HC [gm]/km of vehicle type	2380232 g	0	25179526 g	9.453
Natural Resources	Energy consumption l/km.	273.41 * 106L	0	39172.6292L	30.8
SOCIAL					
Commuting	Vehicle Km Travelled(VKT)	420642 Km	0	1367086.5 km	30.8
	Vehicle Minutes Travelled(VMT)	$7.9*10^5$ min	0	$5.1*10^6$ min	15.5
ECONOMIC					
Transport Investment	Transport Investment Cost	$84.12*10^6$ Rs		$273.41*10^6$	30.8

5.3.3 The Composite Sustainability Index (CSI)

The sustainability indices before introduction of congestion charging are obtained as follows

$\mathbf{SI}_{\text{Environmentall}}=$

$$\alpha_{AP1} * w_{AP1} * v_{AP1}^* + \alpha_{AP2} * w_{AP2} * v_{AP2}^* + \alpha_{AP3} * w_{AP3} * v_{AP3}^* + \alpha_{NR1} * w_{NR1} * v_{NR1}^*$$

= (-1)*0.106*22.037 + (-1)*0.045*18.23272 + (-1)*0.029*12.2804 +(-1)* 0.040*40

= (-)5.113

$\mathbf{SI}_{\text{Social}} = \alpha_{AM2} * w_{AM2} * v_{AM2}^* + \alpha_{AM3} * w_{AM3} * v_{AM3}^*$

= (-1)*0.056*40 + (-1)*0.046*19.7

= (-)3.146

$\mathbf{SI}_{\text{Economic}}= \alpha_{EC1} * w_{EC1} * v_{EC1}^*$

= (-1)*0.143*40

= (-)5.72

$$CSI_{before} = SI_{Environmental} + SI_{Social} + SI_{Economic}$$

Hence, CSI_{before} = (-)13.979

Following the same procedure sustainability corresponding to changed modal share after introduction of congestion pricing is assessed for post policy scenario.

SI$_{Environmentall}$ = (-1)*0.106*16.9477 + (-1)*0.045*14.1435+ (-1)*0.029*9.453 +(-1)* 0.040*30.8
= (-)3.954
SI$_{Social}$ = (-1)*0.056*30.8 + (-1)*0.046*15.5
= (-)2.443
SI$_{Economic}$= (-1)*0.143*30.8
= (-)4.392
CSI$_{after}$ = (-)3.954 + (-)2.443 + (-)4.392
CSI$_{after}$ = (-)10.789

The CSI (in other words, sustainability) after the introduction of congestion charging is increased by 23%. It indicates an improvement in sustainability on introduction of congestion charging.

6. CONCLUSION

The aim of the study was to propose a model for testing transportation policies and projects against sustainability. This was done by developing a Composite Sustainability Index (CSI) which encompasses the three pillars of sustainability – environmental, social and economic. The three pillars were expressed in terms of various indicators like air pollution, natural resource consumption, health, accessibility, mobility, commute and cost. Based on the rankings given by a group of transportation experts, AHP technique was used to obtain the weights given to these sustainability indicators for the calculation of CSI. The indicators with higher weightage included greenhouse gas emissions for environment, accessibility for society and transport investment cost for economy.

In the second part, as a case study, the sustainability impact of introducing congestion charging during peak hour in CBD of Bangalore city was quantified using CSI. This was done with the help of a mode choice model. It was developed using Revealed Preference (RP) survey data. The modal split before and after the introduction of congestion charging was obtained adjusting the travel cost variable in the utility function of private vehicles. The results showed a decrease of 25.89% and 28.37% for car and bike trips to CBD during peak hour with majority of this shift shifting to public transport. A good quality public transport system is required to accommodate this shift.

The modal split thus obtained was then used to calculate CSI. The results revealed a 23% increase in CSI after the introduction of congestion. The increased CSI indicates decreased pollution, natural resource depletion, congestion and also the transport investment.

7. ACKNOWLEDGEMENT

Authors would like to thank UMTC (Urban Mass Transit Company) for sharing the relevant data of Bangalore. The support of officials from BMRDA and KUIDFC are highly appreciated.

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