10th Annual Conference of Knowledge Forum

Venue: National Institute of Advanced Studies (NIAS), Bangalore 27-28, November, 2015

Quantifying Sustainability to Assess Urban Transportation Policies and Projects - Case Studies from Bangalore

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Abstract: This work presents a new methodological framework for testing urban transportation policies and projects on the dimension of sustainability through development and use of sustainable transport model. This model is conceptualized to encompass economic, environmental and social indicators and is represented in terms of Composite Sustainability Index (CSI). The key effect of any transport policy measure, like parking charges, congestion charging, fare revisions, pedestrianization etc., is the change in travel behaviour, particularly the mode choice behaviour. To assess any such policy for sustainability, this change in choice behaviour is captured by a discrete mode choice model and the output of same is used to assess the change in CSI from base scenario to policy scenario. Case studies of congestion charging, Non-Motorized Transport (NMT) infrastructure in Bangalore are also presented. The next part of the research work focuses on developing methodology to test any transportation project against sustainability. To develop and demonstrate this, a bi-level optimization model is proposed for generating Feeder Bus Route Network and service frequencies for stations of Bangalore metro rail system. The proposed framework could be potentially useful in assessing various policies and projects on the key criteria of sustainability, and to also carry out scenario analysis.

Keywords: Sustainable transport; urban transport policy; urban transport projects, Feeder Bus, Bangalore, India..

1. Introduction

Urban form and transport system have an enormous impact on the way people travel. With rapid growing economies and population typically seen in developing countries, there is an increasing trend of expansion of urban sprawl and auto-based mobilization. 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, pedestrianization 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. The world is now facing the problem of depleting fossil fuel and increasing levels of green house gases resulting in excessive emissions which are responsible for global warming and climate change.

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Also the factors like safety, commuting time, accessibility to public transport system etc. need to be quantified in highly socio-economic disaggregated Indian cities.

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. More fundamentally, more emphasis should be on reducing the role of the private automobile as the prime mode of transportation and shifting travel toward other sustainable modes such as public transit, cycling and walking. Today, public transport systems are increasingly utilized by cities looking for cost effective and sustainable mobility solutions. However, even while planning their infrastructural and scheduling improvements to provide high level of service, they need to be assessed for sustainability over a certain period of time. Thus an easy, yet predictable model, is needed to test the same.

The notion of sustainability covers a wide range of issues from economical to societal. Sustainability of any service can be evaluated in terms of society, economy and environment represented in a 3D matrix as depicted in **Figure.1**. Each of these three pillars can be expressed in terms of various qualitative and quantitative indicators that help in measuring sustainability for a given state of transportation system. In this paper, the attempt is to choose quantitative indicators that are sensitive to change in traffic flows on the transport network, which enables measuring the impact of a proposed transport policy or project.

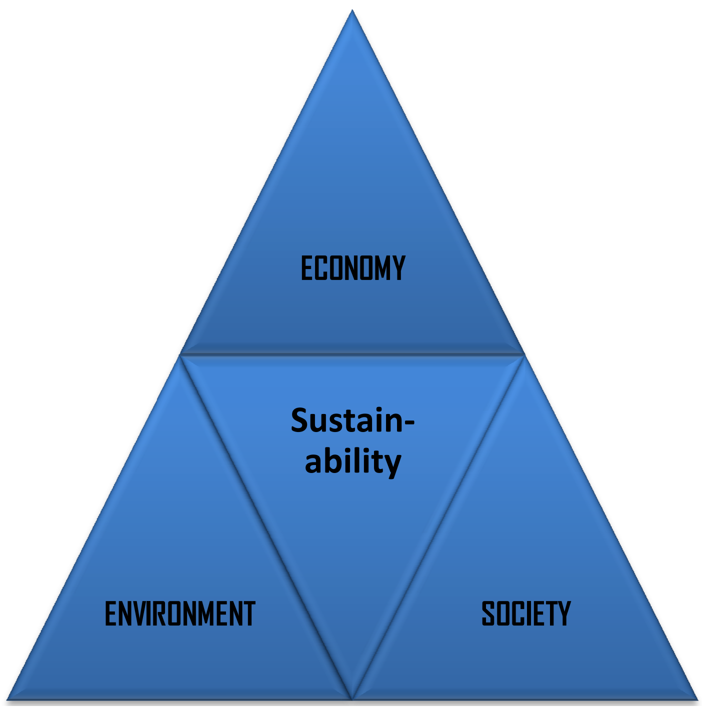

Figure.1: 3D Matrix of Sustainability

However the distribution of the three elements of the 3D matrix can vary from high-income to low-income economies. Essentially sustainability of urban transportation system can be judged on the basis of how well it serves and improves the quality of life of a system that refers to cities, regions and countries in this context of study. Approach to sustainable transport can be addressed through strong sustainability and weak sustainability. Strong sustainability refers to any kind of sustainable development without considering the cost involved in attaining the same. On the contrary weak sustainability refers to attainment of sustainability maintaining tradeoff between environmental, social issues and benefits involved in the process using Cost-Benefit-Analysis, which could be adhered to by developing countries, like India.

For comprehensive sustainable development it is essential to monitor the three pillars of sustainability with potential indicators that are reflective of changes in travel behavior of commuters. There are a number of practical ways of addressing social and economic concerns and simultaneously reducing environmental effects. For instance allowing mixed land use in urban areas moves residents closer to their places of business, reducing commute distance and footprint, providing incentives for public transport use, encouraging non-motorized transport through improved and effectively proven policy measures. **Table-1** summarizes the past studies done in related areas.

Table-1: Summary of Past Studies

Quantifying Sustainability	**Testing Policies**	**Testing Projects**
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)	Multi-objective Decision model with System Optimum conditions considering environmental parameters.(Teng & Tzeng, 1996)
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)	Multicriteria traffic-network model with emissions as objective function (Nagurney, 2000)
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)	Multiobjective network design for emission and travel time trade-off for sustainable urban transportation network (Sharma & Mathew, 2007)
Developing a Sustainability Assessment Model: The Sustainable Infrastructure, Land-Use, Environment and Transport Model (Yigitcanlar and Dur, 2010)		Environmental Impact Assessment for Transportation Projects: Case Study Using Remote-Sensing Technology Geographic Information Systems, and Spatial Modeling.(El-Gafy et.al., 2011)

Most of the studies in past have emphasized more on environmental parameters and social and economic factors have not been addressed well. While studies in past have devised various indicators, they have not attempted to build the sustainability model out of them and demonstrate its use to assess transport policies and projects. This study is an attempt to address this limitation of the past work.

2. Research Problem and Objective:

In Indian cities like Bangalore, there has been a steady increase in the public transport infrastructure including bus services, over the past few years. However use of private vehicles has not shown much decline owing to absence of proper complimentary transport policy measures that inhibits auto-mobilization and gauges for effective and sustainable public transport. The car, two-wheelers and auto-rickshaw are contributing most to the share of motorized modes of transport and the share of public transport is comparatively less. As a result, the cities are facing problems of inefficient mobility and decreased levels of performance in the urban transport sector. Thus it is necessary to put a model in place that captures the indicators of the three pillars of sustainability in a quick and comprehensible manner and that can be used to assess various transport policies and projects. Considering this aim, the following are the objectives of the study:-

- To define a sustainable transport model in terms of:
  - *Environmental Indicators*
  - *Economic Indicators and*
  - *Social Indicators that are relevant for Indian cities*
- To develop a model to test transportation policies against sustainability
- To develop a model to test transportation infrastructure projects against sustainability.

Based on above the work attempts to create a decision support framework, as shown in Figure-2.

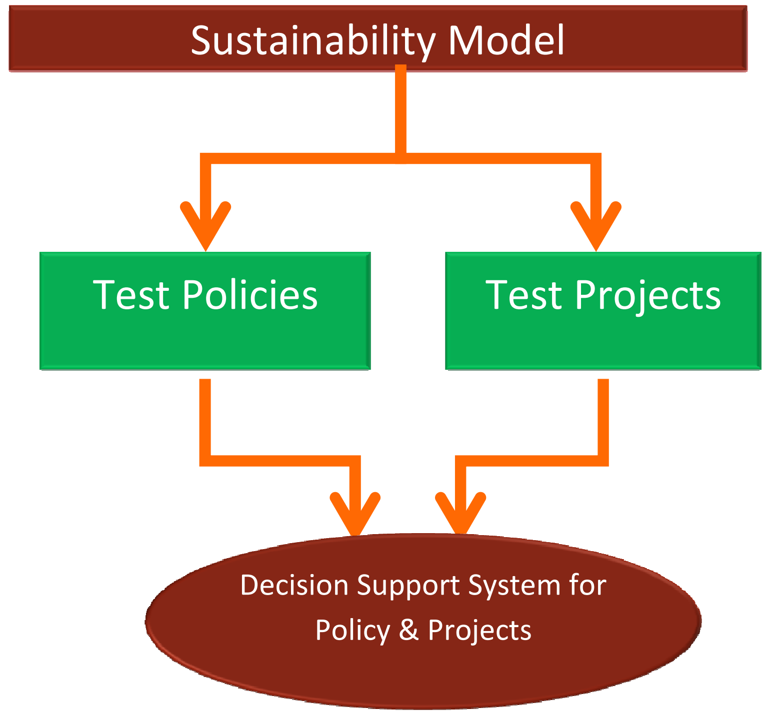

Figure-2: Decision Support Framework

The main contribution of this study is to develop a framework for incorporating sustainability considerations in transportation planning and decision making. Such decision support tools can be particularly versatile in capturing uncertainties commonly inherent in the decision making process by reflecting changing regional priorities and subjective preferences over time and space. Integrating sustainability considerations into the planning process will force decision makers to view different transportation plans in a much broader context, particularly with respect to evaluating the tradeoffs associated with implementing alternative transportation plans and possibly land use scenarios. It will also encourage decision makers to consider the idea of sustainable development priorities, recognizing that as transportation needs, land development patterns, and the quality of the environment and economy evolve, different sustainability dimensions may emerge as the transportation development priorities for a region. The subsequent sections describe the methodological framework in detail.

3. Development of Sustainable Transport Model

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 kilometers 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. Kelly (1998) identified several criteria for evaluating sustainability indicators in the study of an urban system. The study 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

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 Particulate Matter (PM) 2.5[gm]/km of vehicle type
		AP5	Fine particles<10 µm	Level of PM 10[gm]/km of 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 deaths per mode 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, based on ratio of actual to design speed or volume to capacity

				ratio.
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

The above table gives the raw value of each indicator for a certain flow scenario. These values are in different units and hence cannot be compared. Certain Indicators are obtained as absolute values while others may not be in standard form. 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:

$$\frac{\mathbf{100(}\boldsymbol{actual\ value - minimum\ value}\mathbf{)}}{\mathbf{(}\boldsymbol{maximum\ value - minimum\ value}\mathbf{)}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

Here, the actual, minimum and maximum value of indicator corresponds to the different flow conditions respectively.

- Actual value: Normal flow condition
- Minimum and Maximum value: Free flow and Congested 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.

$$SI_p = \sum_{i=1}^{n} \alpha_i . w_i . x_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

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, such that

$$\sum_{i=1}^{n} w_i = 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

The weight (w_i) for each indicator can be determined using Analytical Hierarchy Process (AHP).

α is a binary variable with the following values

$$\alpha \begin{cases} = +1 \ \mathit{if\ indicator\ has\ positive\ effect\ on\ CSI} \\ - \ -1 \ \mathit{if\ indicator\ has\ negative\ effect\ on\ CSI} \end{cases}$$

Hence Composite Sustainability Index (CSI) over a single link is calculated as the sum of the weighted sustainability indices for each pillar P, as given below:

$CSI_{Link} = SI_{Environment} + SI_{Social} + SI_{Economic}$ …………………………..(4)

The Composite Sustainability Index (CSI) over the whole network can then be obtained as:
$CSI_{Network} = \sum CSI_{Link}$ ……………………………………(5)

As indicated earlier, higher value of CSI in equation (5) will imply better sustainability.

3.1 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. The aim here is to determine the mode shift under a policy scenario and then using the mode shift to determine the sustainability indicator under the new scenario. Discrete choice models are typically based on the theory of utility maximisation. Utility is an indicator of the value an individual gives a mode. The mode choice mode 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:

$\Pr(i) = \exp(V_i) / \sum_{j=1}^{J} \exp(V_j)$ …………………(6)

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 variables like travel time, travel cost, household income etc. The model is estimated using maximum likelihood method. 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. The model parameters in our study are estimated using Biogeme [3] [4].

3.2 Analytical Hierarchy Process

The AHP used for determining the weights of sustainability indicators is a tool for multi-criteria evaluation. According to the definition of World Bank (2014) Multi Criteria Analysis is a technique to assess alternative options according to a variety of criteria that have different units (e.g. dollars, tonnes, and kilometres). AHP was developed by Saaty (1980) and quite often is referred to, as the Saaty method. It allows for a pair-wise comparison between the different indicators for single respondent to obtain the relative priorities of that respondent. In our study these relative priorities are obtained from 7 expert respondents from the transportation field, which is then averaged to form the local weight of that indicator. It is these local weights which are used in the determination of sustainability pillars in section 4.1. So these weights determined for an indicator give an indication of the average priority in the mind of respondents attached with that specific indicator.

The essence of AHP lies in constructing a matrix expressing the relative values of a set of indicators. It is done by assigning these relative values a number on a scale. A basic, but very reasonable, assumption is that if indicator A is absolutely more important than indicator 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 adopted rating 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. The global indicator values were determined for indicators based on the responses from 7 experts in the field of transportation including academicians as well as experts from the industry. The highest weight among the environmental indicators was given to the greenhouse gas emissions (AP1), and the highest weight among the social and economic indicators was given respectively to the accessibility and transportation investments.

3.3 Framework for Assessing Urban Transportation Projects

Apart from policies it is also important to analyze infrastructure projects with respect to sustainability. Thus the second part of the work focuses on developing methodology to test any transportation project against sustainability, which may assist any transport planner/engineer to take decisions on implementing the project. To develop and demonstrate this, a case problem of feeder transit network design for a metro rail station is considered. Usually objective of any transit system network design is to optimize user and operator cost, however they are seldom tested on sustainability criteria (environmental, social, and economic). In this study a bi-level optimization model is proposed for Feeder Route Network Generation and Schedule Coordination of feeder buses with metro trains, where besides optimizing the user and operator cost at first level, the solution is also optimized for sustainability using CSI at the second level, and the best solution obtained from this model is recommended.

3.4 Proposed Model for Feeder Route Generation and Schedule Co-ordination

In this model the aim is to develop the feeder street transit route network for the Metro rail as well as schedule coordination of bus and train. Choosing suitable feeder street transit routes and their schedules is a critical process in the design of a good integrated transit route network. The problem to be addressed can be defined in the following general terms: given the transit demand matrix for feeder area and a description of the network specifying for each node its neighbouring nodes and the distance of all connecting links, the aim is to determine set of feeder routes and their schedule that correspond to a tradeoff between user and operator costs.

Considering the above aim, the proposed combined model for feeder route generation and schedule coordination is developed. In this model, the routes are generated in two levels, the first level generates the initial set of shortest paths based on the maximum and minimum route length criteria, and in the second level, search is made around these corridors by generating K shortest paths for each station-to-terminal node pair. Finally, using GA, one route combination out of all possible routing configurations is selected along with their corresponding optimal headway.

For developing the combined model, the following inputs are required:-

Network: Details for all the links, including the link travel time, travel distance etc, within the feeder area and the initial set of shortest paths generated earlier.

Demand: OD matrix of station to every node and vice versa within the feeder area.

K-Shortest Paths: K-shortest paths for each station to terminal node pair of the initial set identified in previous level. The program requires as an input the matrix specifying the distance between each of the connected nodes in the network.

Route-Node Structure: For a given station, data structure is created to be read by the program. Data structure includes the nodes for different K-shortest paths for each terminal node.
Other data required includes number of passengers boarding and alighting at each stop (along the feeder routes) within a fixed period, number of passengers transferring from the rail transit station to a feeder route and vice versa within a fixed period, the ridership on each link of the feeder route, round trip time for each route, capacity value of different types of buses, value of travel time, waiting time, and transfer time cost of passengers and bus operating cost.

Decision Variables and Their Coding: In this problem, one feeder route (from K different routes for each station-terminal node pair) and the corresponding frequency of operation (out of a given range) have to be selected simultaneously so as to optimize the objective function. Therefore, decision variable will be the path number for each station to terminal node pair (route) and corresponding headway for each route.

Objective Function: With an attempt to overcome the drawbacks of the previous work [Verma and Dhingra (2005, 2006)], the present study carries out simultaneous optimization of feeder routes and co-ordinated schedules at upper level and assessing sustainability at lower level to get more effective results. The objective function of the upper level problem is defined to minimize the sum of operating cost of buses (operator cost), transfer time cost for passengers transferring from train to feeder buses, waiting time cost of passengers boarding along the feeder routes and in-vehicle time of the passengers travelling along the feeder routes (user costs) subject to load factor and transfer time constraint and the constraint for unsatisfied passenger demand. The lower level attempts to maximize CSI at each iteration for path configuration as obtained from upper level. The objective function can be mathematically represented as follows:

Upper level:-

Objective

Minimize:

$$\left[C_1 * t_{tt} * \sum_{j=1}^{n} d_{tt\,j}\right] + \left[C_2 * \sum_{i=1}^{(n+1)} \sum_{j=1}^{(n+1)} d_{ij}^{k_l} * t_{wt\,i}^{k_l h}\right] + \left[C_3 * f_{k_l}^{h} * T_{k_l}^{h} * 60\right] + \left[C_4 * \sum_{i=1}^{(n+1)} \sum_{j=1}^{(n+1)} d_{ij}^{k_l} * \left\{t_{avg\,ij}^{k_l} + \sum_{r\epsilon IS} t_{dw\,r}^{k_l h}\right\}\right] \quad \ldots(7)$$

Lower level:-

Maximise $CSI= (SI_{Environmental} + SI_{Economic} + SI_{Social})$ …….(8)

Where,

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

[p corresponding to environmental, economic and social indicator]

Subject to:

$$g_1 = \left[[q_{max}^{k}/CAP_b] \leq L_{max}\right]$$

$$g_2 = \left[[q_{min}^{k}/CAP_b] \geq L_{min}\right]$$

$$g_3 = \left[\left[t_{wt,ij}^{k} \leq t_{wt,max}\right]\right]$$

$$g_4 = \left[\left[t_{wt,ij}^{k} \geq t_{wt,min}\right]\right]$$

$$g_5 = Upd \leq x$$

Where,

l is terminal node varying from 1 to m; m is the total number of terminal nodes selected based on maximum/minimum route length criteria; k is the potential route from the set of K-shortest paths generated between station and the terminal node l; h is the headway on k^{th} potential route for the terminal node l; C_1 = Transfer time cost in Indian Rupees (Rs.)/min; C_2 = Waiting time cost in Rs./min; C_3 = Vehicle operating cost in Rs./min; C_4 = In-vehicle travel time cost in Rs/min; t_{tt} = transfer time from train to the bus stop; n = total number of nodes; $d_{tt\,j}$ = number of persons moving to node j along the potential feeder routes, from the rail station; $d_{ij}^{k_l}$ = number of persons moving along route k (for l^{th} terminal node) from node i to node j and is assigned based on proportionate frequency and travel time criteria (logit function) as given below

$$d_{ij}^{k_l} = d_{ij} * \left[0.5 * \frac{f_{k_l}^{h}}{\sum_{r\epsilon OR} f_{r_l}^{h}} + 0.5 * \frac{\exp\,(t_{k_l}^{h})}{\sum_{r\epsilon OR} \exp\,(t_{r_l}^{h})}\right]$$

the above expression attempts to mimic the natural route choice behaviour where a person would attach equal importance to both frequency and travel time on alternate routes available between the same Origin-Destination (O-D) pair; OR = overlapping routes between nodes i and j; $f_{k_l}^{h}$ = frequency of feeder bus along the route k of l^{th} terminal node; d_{ij} = total demand from node i to node j; $t_{wt\,i}^{k_l h}$ = waiting time of passengers at node i waiting for the bus moving along the route k of l^{th} terminal node, for the headway value $h_{kl} = \alpha h_{kl}$; α is a calibration parameter that depends on the distributions of transit headway and passenger arrival; $T_{k_l}^{h}$ = round trip time that bus running

with headway 'h' takes on k^{th} route of the terminal node $l = T_{rtt}^{k_l} + T_{dwell}^{k_l h} + T_{layover}$; $T_{rtt}^{k_l}$ = running round trip time for any bus on the k^{th} route to the terminal node l; $T_{dwell}^{k_l h}$ = sum of dwell time of all the stops lying on k^{th} route to the terminal node $l = \sum_{(r \epsilon All\ Stops\ along\ route\ k)} (t_{dw\ r}^{k_l h})$; $t_{dw\ r}^{k_l h}$ = dwell time at intermediate station r along the route k of l^{th} terminal node = $\left[\frac{P_a t_a + P_b t_b}{n}\right]_r^{k_l h}$; P_a = number of persons alighting at the bus stops (depends on the headway of bus); P_b = number of persons boarding at the bus stops (depends on the headway of bus); t_a = time required to alight the bus; t_b = time required to board the bus; y = number of people who can board simultaneously in the bus; $T_{layover}$ = Layover time during one round trip; $t_{avg\ ij}^{k_l}$ = average travel time from node i to node j along the route k of l^{th} terminal node; $t_{wt.max}$ = maximum allowable waiting time; $t_{wt.min}$ = minimum allowable waiting time; UPD = unsatisfied passenger demand; x = Maximum allowable unsatisfied passenger demand in percent.
In the following the meaning of each constraint is briefly described:

- Constraint g_1 states that the load factor on any feeder route k should be less than the maximum allowable load factor L_{max} for that route.
- Constraint g_2 assures that the load factor on any feeder route k should be more than the minimum allowable load factor L_{min} for that route.
- Constraint g_3 states that the waiting time $t^k_{wt,ij}$ incurred while traveling between node pair i, j along the path k should be less than the maximum allowable waiting time $t_{wt,max}$ between the modes.
- Constraint g_4 assures that the transfer time $t^k_{wt,ij}$ incurred while transferring from one transit mode to other between a node pair i, j along the path k should be more than the minimum possible transfer time $t_{wt,min}$ between the modes.
- Constraint g_5 assures that the unsatisfied passenger demand is less than a maximum value x.

The output of this bi-level optimization would be a set of feeder bus routes and their corresponding frequencies that maximizes sustainability as defined by CSI, while also optimizing the user and operator cost involved. Thus, this case problem demonstrates the use of CSI in arriving at configuration/alignment of any transportation infrastructure project that scores high on sustainability. Similarly, CSI can be used for cases like, optimum alignment of road/rail corridors, road expansion, or a comparison between them to arrive at best solutions.

4. Case Studies

This section presents various case studies in brief with respect to transport policies (congestion charging, non-motorised transport (NMT) provisions) and projects (metro feeder route generation).

4.1 Congestion Charging in Bangalore

A case study for the impact of congestion pricing in CBD (Central Business District) was done for the city of Bangalore. The impact was determined as the variation in the composite sustainability index before and after the introduction of congestion pricing. The value of congestion charge was found by dividing the total congestion cost imposed by each vehicle type in Bangalore by the total vehicle trips by that vehicle type. Accordingly, a value of 40 Rupees for car and 20 Rupees for two-wheeler is used. The CBD was determined along a radius of 2 Kilometer (Km) around the town hall. It included some of the highly congested areas in the city including Shantinagar, Cubbon Park, and Chickpete. The sustainability indicators and the composite sustainability index before introduction of congestion charging are obtained as follows.

$\mathbf{SI}_{\text{Environmentall}}$= (-)2.86
$\mathbf{SI}_{\text{Social}}$ = (-)1.43
$\mathbf{SI}_{\text{Economic}}$= (-)2.22

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

Hence, $\text{CSI}_{\text{before}}$ = (-)6.51

Following the same procedure sustainability corresponding to the changed modal share after introduction of congestion pricing is determined as below.

$\mathbf{SI}_{\text{Environmentall}}$ = (-)2.81
$\mathbf{SI}_{\text{Social}}$ = (-)1.40
$\mathbf{SI}_{\text{Economic}}$= (-)2.19
$\mathbf{CSI}_{\text{after}}$ = (-)6.40

The CSI after the introduction of congestion charging is increased by 1.7%. It indicates an improvement in sustainability on introduction of congestion charging (Verma 2015).

4.2 NMT Provisions in Bangalore

In the present section, the methodological framework developed in the previous sections is used to evaluate the sustainability impacts on providing NMT infrastructures, for the year 2021, in the Central Business District (CBD) of the Bangalore city, as well as around the bus stops carrying trips to this CBD. The year 2021 is selected because of the availability of population and employment growth factors for that year. The CBD is determined at a radius of 2 kilometer around the Town hall in Bangalore.

In order to understand the sustainability impact of providing NMT infrastructures on NMT as a main mode as well as on NMT as an access mode to public transit, three separate case studies were done as given below.

1. In case study 1, only intra zonal trips inside the CBD were used in evaluating the sustainability impact. Because the two kilometer radius of the CBD was well within the limit of an acceptable trip distance of 2.1 kilometer (Rahul and Verma, 2014), found for cycling in the city of Bangalore, most of the trips inside the CBD were expected to have trip distances conducive to promote NMT as the main mode, and this later was proved right on analyzing the trip data of CBD. Further, considering only intra-zonal trips confined the origins and destinations of the trips within the CBD, and this confinement ensured that these trips would have the benefits of NMT facilities for their entire trip length. So, this case study analyzed the impact of providing NMT infrastructures, along an acceptable distance found out when NMT is used as the main mode. Acceptable distance gave the maximum distance after which a person using NMT will shift to a faster mode of travel (Rahul and Verma, 2014). The difference in CSI between the scenarios before and after introduction of NMT facilities is as shown below.
   $\text{CSI}_{\text{difference}}$ = -6.557 – (-6.555) = -0.002

2. In case study 2, only inter-zonal trips with their destination as the CBD were considered. Because these inter zonal trips can be expected to have trip distances conducive for promoting public transits as main modes, this case study was expected to give the impact of providing NMT infrastructures, along an acceptable distance found out when NMT is used as the access mode, around bus stops as proposed in Rahul and Verma (2014). These trips utilized NMT infrastructures inside the CBD as well as around the bus stops carrying public transit trips to the CBD. For this case study, NMT facilities were assumed to be provided along a distance of 750 meter around bus stops (Rahul and Verma, 2014). The difference in CSI between the scenarios before and after introduction of NMT facilities, for case study 2, is as shown below.
   $CSI_{difference} = -20.560 – (-20.484) = -0.076$
3. In case study 3, both the intra zonal trips inside CBD and the inter-zonal trips to the CBD were considered. The difference in CSI is calculated as given below.
   $CSI_{difference} = -18.531 - (-18.431) = - 0.100$

In all the three cases, the CSI after the construction of NMT facilities decreased on a negative scale, and this decrease in the negative scale revealed an improvement in the sustainability inside the CBD. All these case studies were done at a strategic level (Saelensminde, 2004), and this meant that the studies did not consider any specific sections of the network along which NMT facilities are built. By NMT facilities, the authors intended continuous, un-encroached, well-maintained, and separate footpaths and cycle ways; proper crossing facilities for NMT; and parking facilities for cycles at public transit stops (Wardman et al., 2007; Rietveld, 2000; Ortuzar et al., 2000).

4.3 Bangalore Metro Feeder Route Generation

Namma Metro, also known as Bangalore Metro, is a metro rail system in the city of Bangalore, Karnataka, India. The agency responsible for its implementation and operation is the Bangalore Metro Rail Corporation Ltd (BMRCL), which is a joint venture of the Government of India and the Government of Karnataka. The existing operational purple line of Bangalore metro rail has six stations in Reach-1 from Byappanahalli to MG Road, out of which Indiranagar metro station is selected as the study area because of its land use pattern and better trip generation compared to other stations. Metro feeder routes were developed using the proposed methodology for this station. To analyze the sensitivity of results due to introduction of CSI, the feeder routes were developed for three different cases given below.

Case 1 - Optimal total cost and corresponding CSI value: In this case upper level objective function is optimized and corresponding solution CSI value is calculated.

Case 2 - Optimal CSI value and corresponding total cost: In this case lower level objective function is optimized and corresponding solution total cost is calculated.

Case 3 - Optimal total cost and CSI value: In this case total cost is optimized and corresponding solution CSI value is calculated. Then a check is carried out for both total cost and CSI values. If both the solutions are improved in the current generation compare to previous generation, then those solutions are stored. Thus the best solution so far is obtained at the end.

The comparison of total cost and CSI values obtained for Case1, Case2, is presented in **Table.3.** The result shows that the first case gives the best values of total cost and the number of buses required, but lower value of CSI. When only CSI value is considered second case gives the best result, but very high values for the total cost and the number of buses required. The results with Case3 which give a number of solutions to decision makers providing a balance between CSI and total cost are presently being generated.

Table 3: Comparison of Case1 and Case2 for feeder route generation

	Total cost	**Solution CSI**	**Fleet Size**
Case1	4761	-0.51	80
Case2	25219	-0.46	251

5. Summary & Conclusions

This work presents a new methodological framework for testing urban transportation policies and projects on the dimension of sustainability through development and use of sustainable transport model. This model is conceptualized to encompass economic, environmental and social indicators and is represented in terms of Composite Sustainability Index (CSI). A discrete choice modelling based framework is presented to assess various urban transportation policies against sustainability such as, parking charges, congestion charging, fare revisions, pedestrianization etc.. To assess any such policy for sustainability, this change in choice behaviour is captured by a discrete mode choice model and the output of same is used to assess the change in CSI from base scenario to policy scenario. Similarly, a methodological framework is presented to demonstrate the use of CSI in testing urban transport projects and a case problem of Feeder Route Network Generation and Schedule Coordination of feeder buses with metro rail is taken for this purpose. The framework is presented as a bi-level optimization model. The proposed framework could be potentially useful in assessing various urban transportation policies and projects on the key criteria of sustainability, and to also carry out scenario analysis. The following are the main conclusions from this work:-

- An increase of 1.7% in CSI after the introduction of congestion charging indicating an increased sustainability after the introduction of congestion charging. The increased sustainability was the result of a decreased pollution, natural resource depletion, congestion, and transport investment.
- There is an increase in the values of CSI for all the three case studies after the construction of NMT facilities. This increase in the CSI indicates an improvement in the sustainability.
- The case study on metro feeder route generation demonstrates the difference in result between using objective of total cost as compared to community objective (CSI).

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