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Optimizing the modal split to reduce carbon dioxide emission for resource-constrained societies

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Abstract

With increasing demand for transportation and alarming levels of emissions witnessed today, the future of the transport sector is at a critical juncture. The challenge lies in satisfying the demand of increasing population and simultaneously reducing the emission level for the sustainable future development. This study deals with the problem of increasing demand and desired a reduction in emission level for the transport sector by finding an optimal modal split for passenger transportation, putting a constraint on emissions and minimizing the cost of investment. We applied the techniques of pinch analysis to derive the optimum mix. Various scenarios were developed having different emission level as constraint and results were compared based on the contribution of different modes of transport that might aid the policymakers to introduce policies to achieve emission reduction targets. It is evident from the estimated models that substantial reduction is possible with the introduction of newer technologies, adept transportation planning strategies.

Keywords: optimal energy mix; transport sector planning; emission constraint; cost optimization.

1. Introduction

With an ever-increasing demand for better and comfortable means of transport, the amount of energy needed by the transport sector is not only increasing in terms of absolute numbers but the share of energy need by transport sector is expected to go up to 20% by 2020 from the 10% in 2005 (Tiwari and Gulati 2013). Moreover, the transport sector has the largest share of petroleum consumption in India (Singh et al. 2008). With increasing population, urbanization and expansion of cities, the need for efficient transportation is undebatable. With the increasing affluence of the middle-income groups in developing nations, there is an increasing demand for comfortable and convenient modes of transportation. Consequently, the energy consumption in the transportation sector has been growing and currently comprises of 104 quadrillion Btu as of 2012 (International Energy Outlook 2016). The transport sector in future has to stand up to increasing level of demands as well as the expectations of decreasing emission level. Santos (2017) argued, "*Reducing emissions in transport is more costly than in other sectors, such as the electricity sector, and the reason for this is that transport still heavily relies on fossil fuels*". Thus, there is a two-way challenge posed to the

2352-1465

transport sector at this time: the challenge of catering to increasing demand levels and fulfill the need of decreasing emission level. One of the similar study conducted in developed nations by Walmsley et al. (2015) was on the optimization of future transport scenario of New Zealand. The study puts a cap on the emission level to 1992 emission level and satisfies the demand of 2050. Agenda 21 expressed environment as a major cause of concern especially for countries like India, which calls for reviews of policy and practices as well as developing alternative and sustainable modes of transport and upgrading vehicles for curbing emissions[*].

In this study, a methodology is applied to find the optimal model split for the transportation sector which might satisfy the increasing demand, taking into consideration the carbon emission and present a solution with the minimum amount of investment needed. The proposed methodology is demonstrated with the case study of Indian Transport Sector's 2032 scenario. Various scenarios are built with different emission constraint level to see how the mode share changes with different emissions target. Various factors like feasibility of the solution, convenience of the people and adaptability of the suggested reforms are also taken into consideration. The objective of this study is to determine an optimum mix of the various possible transportation modes satisfying the future transportation demand while keeping a check on the carbon emissions. The techniques of Pinch Analysis is adopted in this study and the methodology of limiting composite curve is applied for finding the optimal solution.

New technologies and modes of transport are incorporated in this study. Their contribution is taken into account depending on the potential availability and feasibility. Moreover, a savings of Indian Rupees (INR) 250,000 was reported for an assumed 1% shift of travelers to non-motorized mode in a single day in the city of Bangalore India; additionally, a savings of INR 1611.4 per day due to the reduction in air pollution and accident was also reported (Rahul and Verma 2013). In this context, it is prudent to mention that the present study would enable the policy makers to formulate strategies to incorporate new technologies and drive policy changes that would encourage a modal shift towards lesser carbon emission. Further, this study would mitigate two important gaps existing in the literature: (1) as majority of the research have shown the relevance of newer energy efficient technologies, alternate fuels (Anandarajah and Gambhir 2014) and shift to non-motorized transport (Jain and Tiwari 2016) to curb down the emission in India, this research focuses on the appropriate mix of modes that might aid to achieve such feat in India and (2) an appropriate optimization techniques that would enable the same.

The rest of the paper is organized as follows: the next section provides a review of the existing state of Indian transport sector, CO2 emission from different modes and methodology applied to optimize modal splits, followed by detailed description of the methodology used in the study, and the results. The final section discusses and highlights some of the major findings and future scope.

2. Literature review

India, the world's second most populous country with a population of 1.28 billion[†], has a huge transport sector. With an extensive network of railway lines reaching all corners of the country, it is the third largest railway network in the world. A land transport system with an extensive road network is the main source of transportation catering to 80% of the transportation needs (Ministry of Road Transport and Highways 2009). Total demand from the road transport system as of 2016 was 10 trillion passenger-km (National Transport Development Policy Committee 2014). The increase in population puts more pressure on the resources to satisfy the needs of the people. With a heavy load forecasted on the transport sector, high pollution levels are expected. Alarming level of pollution in the city of New Delhi has surpassed the permissible limits significantly (Kumar et al. 2015). If the same habits and trends continue, a similar case could be seen in other megacities of India (Gurjar et al. 2016).

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[*] Retrieved on 13/07/2018 from the report "Agenda 21 - An Assessment" available at http://www.envfor.nic.in/divisions/ic/wssd/doc2/main.html

[†] http://censusindia.gov.in

2.1. A review of the Indian transport sector

The demand is expected to grow at about 15 percent per annum to reach 168875 billion passenger kilometer (bpkm) in 2031-32 from 10375 bpkm in 2011-12 (National Transport Development Policy Committee 2014). The use of existing modes of transportation might not be continued because neither it would lead to a sustainable environment nor is the existing infrastructure equipped to handle it. This demand has traditionally been fulfilled by railways, private cars, buses, two wheelers, three wheelers, bicycles, and walking. The major fuels on which vehicles on roads run currently in India are petrol and diesel. There is a small share of CNG vehicles coming up but petrol and diesel remain predominant. A major portion of railways in India are electrified and is moving towards the complete electrification.

From the date in Table 1, it is evident that a major share of public transport is catered by buses. In recent times, many Tier II cities in India like Bhopal, Ahmedabad, and Indore have facilitated BRTS to make public transport more accessible and convenient.

Table 1: Modal split for different modes of transportation in 2011-12

Modes	Demand (in bpkm)
Railways	1588
Car (Petrol/Diesel/CNG)	680
Bus	5157
2 Wheelers	1002
3 Wheelers	271
Walking	773
Cycling	904
Total	10375

Source: Data compiled from Schipper et al. (2009)

2.2. Emission from major modes plying on roads

Pollution emitted by a particular mode of transport can be estimated from the running emissions as well as the life-cycle emissions. In this study, for the modes which are currently existing, running emissions are taken and for the vehicles which are to be added to satisfy the increasing demand, life-cycle emissions are considered. Table 2 illustrates the emissions in grams of CO_2 per km caused by these modes.

Table 2: Emissions from existing modes of transportation

Modes	Emission of CO_2 (g per km)
Car (Petrol/Diesel/CNG)	238
Bus	960
2 Wheelers	55
3 Wheelers	110
Walking	0
Cycling	0

Source: Data has been compiled from Jaiprakash and Habib (2018)

2.3. A review of the optimization techniques

A study by Walmsley et al. (2015) discussed the reduction in carbon emission released by transport sector for the case of New Zealand using the technique of pinch analysis with the emissions for 2050 New Zealand's transportation demand being set at the 1990 level. The solution included suggestions like complete electrification of railways and use of biofuels for running cars. Demand was forecasted from current population growth trend. Various technologies like pure electric vehicles and hybrid electric vehicles were considered in the study. However, the feasibility of the solution is not taken into account. For example, the usage of biofuels was proposed in the final solution but no comment on the availability of such high amount of bio-fuels was considered. Similarly, the affordability of people for electric car and hybrid electric cars was also not taken into account. The paper fails to look at the economic aspect of the system and only counts on the emission reduction.

There are different technologies which have been studied to reduce the emissions from the transport sector. One such solution was discussed by Tan et al. (2004). Coconut biodiesel can tackle the problem of depleting oil reserves and increasing pollution level. It may be blended with the conventional fuel and can be used with some engine modification. Although biodiesel's use on a large scale has not been tested yet, some case studies indicate that it is a promising solution. Usage of biodiesel also ensures a better energy security as it reduces the dependence on the imported fossil fuels. Another promising replacement of fossil fuels in vehicles is hydrogen, produced from renewable resources. Agnolucci (2007) discussed the hurdles for acceptance of hydrogen in vehicles. The lack of available infrastructure in terms of refueling tank in various parts of the country is one of the major bottlenecks. The decisive role of government policies has also been discussed in this paper. A major shortcoming of all these studies is that the impact and feasibility of one technology is studied in isolation from others. For example, Tan et al. (2004) studied economics, technology, and potential of coconut biodiesel in isolation from other promising technologies like hydrogen and electric vehicles.

Various studies done for the emissions in the transportation sector lack a general perspective of the overall system. There are many studies which discuss economics and the possibility of various fuels and technology in detail but most of them fail to comment on how the overall system would react once that technology is introduced. Some studies do not comment on the overall economics of the system. This is a system level optimization problem which also takes into account the economics of the passenger transport sector. The present study discusses the effect of newly introduced technologies on the overall system. The demand split between existing technologies and the newly introduced technologies are studied together.

To tackle the problem of increasing demand and pollution level, this study develops the scenarios for future India so that the demand can be fulfilled by keeping a check on the emissions. Different scenarios are developed to cater to high demand levels and follow a pollution constraint for the sustainable future.

3. Future Technologies

There are various promising technologies which would be prevalent by 2032 considering the current policy reforms. Penetration of some of these technologies is considered for different scenarios for the year 2032. To expedite clean and gasoline-free transportation option to the people, demand-side incentives to facilitate the acquisition of hybrid/electric vehicles are being considered in India (Department of Heavy Industry 2012). Indian market is already seeing the arrival of a few of the electric cars from different big car manufacturers. Electric two-wheelers have also been in existence from last 10 years, but have not made an impact due to the cheaper, less sophisticated vehicles in the market. Given the aggressive policies of the Indian government favoring electric vehicles, many automobile companies are planning to launch electric two-wheelers as well as three-wheelers in the Indian automobile market. For the purpose of the study, future technologies include electric cars, electric scooters, electric auto rickshaws, and gasoline buses with better fuel efficiency as it can be assumed that the fuel efficiency of buses in next 16 years would increase by 20%. Table 3 gives the emissions from vehicles based on new technologies. The lowered emissions from new technology come with an increased cost. Table 3 gives the cost in INR per kilometer for new technologies. These costs are according to current research standards and may improve significantly in the future as technology evolves.

Table 3: Emissions by new technologies

Means	Emission factor (g/km)	Cost INR/km)
Electric Car	125	10.5
New Bus	20	0.3
Electric 2 wheeler	30	1.4
Electric auto	34	1.0

Source: Data adapted and calculated from Cherry, Weinert, and Xinmiao (2009)

Planned interventions and policy reforms are the keys to successfully incorporate alternative fuel vehicle (AFV). For example, in China, a demonstration program of an electric vehicle was launched in 13 cities in 2009. Most of these 13 cities planned to deploy 1000–5000 electric vehicles (hybrid electric vehicles) for public service by 2012 (Zheng et al. 2012). However, it has been reported that the AFV (buses) perform considerably well in comparison to diesel buses at a low speed and full load (Zhou et al. 2016). While it has been reported that electric two-wheelers emit several times lower pollution per kilometer than motorcycles and cars (Cherry et al. 2009).

4. Methodology

To estimate the modal split that would reduce CO_2 emission, while minimizing the cost, three scenarios have been studied based on the projected demand of travel considering the passenger kilometers of travel. Scenarios have been generated to study the amount of CO_2 emission in 2032, which are as follows:

(1) business as usual,

(2) what if the current modal split remains unchanged, while new automotive technologies are introduced and

(3) and to estimate an optimal modal split while minimizing the cost.

For the purpose of optimization, a pinch analysis based approach is applied in this paper. Limiting composite curve methodology, introduced by Wang and Smith (1994) for water conservation in industries, has been adopted to find the optimal solution. In this method, a limiting composite curve (LCC) is plotted including all the sources and the demand. A resource line can be drawn to minimize the resource utilization. LCC is made by plotting quality (emission factor in g/pkm) on the Y-axis and cumulative quality load (total emission in million ton of CO_2) on the X-axis. LCC is obtained algebraically by using the composite table algorithm (CTA) developed by Agrawal and Shenoy (2005) and Shenoy (2010). While the context of transportation planning in developing nations might vary significantly, similar optimization is applied to the Indian healthcare sector (Basu et al. 2017) as well as to the power system planning for Indian sector (Krishna Priya and Bandyopadhyay 2013). It may be noted that the LCA based approach can be directly adopted for system level optimization level with a single resource (for a single mode for the present case). However, in case of transport sector planning, various new modes need to be optimized. For multiple modes, the important question is to determine their appropriate sequence for the optimisation. Mode with least emission may not be the vehicle with the least cost and vice versa. To solve this dilemma, a concept of prioritized cost can be used which was introduced by Shenoy and Bandyopadhyay (2007). Prioritized cost is calculated taken into consideration the emission level as well as the cost of the resource. Krishna Priya and Bandyopadhyay (2013) applied the concept of prioritization of the new power plants to account for the emission constraint as well as to minimize the total cost for the power plants. Similar methodology is adopted in this paper and details are not discussed for brevity. Applicability of the proposed pinch analysis methodology is illustrated with the help of a case study on Indian passenger transport sector. In the case study, one of the scenarios is solved in detail by the limiting composite curve method of pinch analysis to illustrate the calculations.

Estimating the Carbon dioxide emission

The unit 'grams of CO_2/km' is not comparable with respect to the different modes of transport, since different modes of transportation have different occupancy. Occupancy is defined as the average number of people carried by a particular mode of transport. For example, in the case of two-wheelers, the occupancy is 2 people for 50% instances and an occupancy of one person for the other 50% instances. Thus the occupancy is the average number of people for all times, which comes out to be 1.5 in the above case. Table 4 gives the average occupancy level for different modes of transport and emission per passenger km.

Table 4: Occupancy level for different modes of transport

Means	Occupancy Level	Emissions (g/passenger km)
Car (Petrol/Diesel/CNG)	1.2[a]	198.3
Bus	41.6[b]	24.0
2 Wheelers	1.5[b]	36.7
3 Wheelers	1.76[b]	62.5
Walking	1	0
Cycling	1	0

Source: Data compiled from [a]Badami, Tiwari, and Mohan (2004)and [b]S. K. Singh (2006)

Scenarios: Estimation of Demand

For building scenarios, the data of 2016 travel demand is analyzed. On the basis of people's current behavior and preferences for different modes of transport, future scenarios are built. New modes of transport which may be added in the future are electric cars, electric two-wheelers, electric three-wheelers, and buses with better fuel efficiency. It is assumed that the number of vehicles based on old technologies would be roughly the same number in the future as well. The additional demand would be satisfied by newer means of transport. For example, an increase in the demand for four-wheelers, it would be satisfied by electric cars and not with petrol/ diesel cars.

Scenario I: Business as Usual (BAU)

In the business as usual scenario, demand bifurcation into different means currently is extrapolated to future demand levels for this scenario. Table 4 shows the passenger means split for 2032 demand for the BAU scenario. In BAU we considered the current modal split as well as current automotive technologies.

Scenario II: Cutting down CO_2 emission while the modal split remains unchanged

In this scenario, the current modal split is considered, while introducing new technologies that would curb down emissions and improve fuel efficiencies. In this scenario, people's preferences have not been altered. Only technological changes are made for the additional vehicles required in this scenario. For example, the percentage of demand satisfied by cars has been kept the same (see Table 1) but the new cars added are assumed to run on electricity.

Scenario III: Cutting down CO_2 emission while minimizing the cost.

The objective of this scenario is to find an optimal mix of modes for future passenger transportation demand in 2032. Optimization was done with a constraint on carbon emission level while satisfying the forecasted demand and minimizing the cost incurred to achieve the target emissions level. Two different sub scenarios have been presented with varied constraints to elucidate the impact on the modal split with respect to the reduction.

Based on the several assumptions (Table 6), a combinatorial framework (Figure 1) has been designed considering existing vehicles based on conventional technologies and modes which might be introduced to cater to the passenger demand in future (FY 2032). Detailed mathematical structure is similar to the one presented in Krishna Priya and Bandyopadhyay (2013) and hence, not reported for brevity.

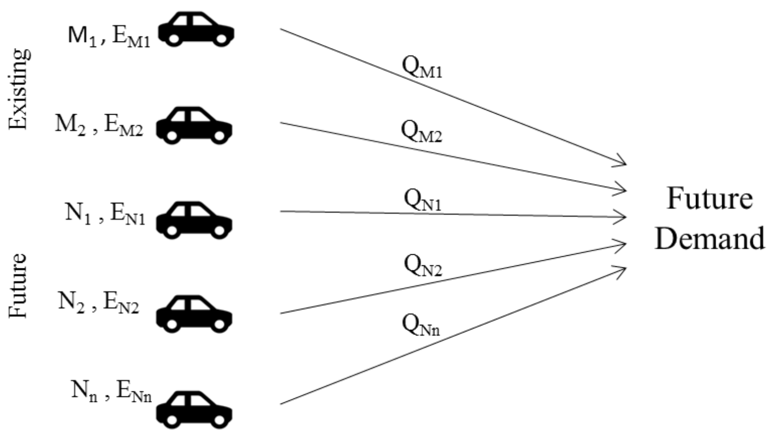

Fig. 1. Conceptual framework of the scenario III: cutting down CO_2 emission while minimizing the cost.

5. Results:

5.1. Scenario I

In this scenario, approximately five billion ton of CO_2 is estimated to be emitted in 2032, if the modal split remains the same, while new technologies are not considered introduced.

Table 4: Scenario I: Business as Usual (If modal split and technology unchanged at 2032)

Modes	Contribution towards demand (bpkm)	CO_2 Emissions (*million tons*)
O - Car (Petrol/Diesel)	11,068	2,195
O - Bus	83,941	2,015
O - 2 Wheelers	16,310	599
O - 3 Wheelers	4,411	276
O - Walking + Cycling	12,582 + 14,715	0
Total	143,027	5,084

5.2. Scenario II

In this scenario, 3.78 billion ton of CO_2 is estimated to be emitted in 2032. This would be just around 74.5 percent of scenario I. However, this would skyrocket the cost to a humongous amount (see table 5).

Table 5: Scenario II: Cutting down CO2 emission while the modal split remains unchanged

Modes	Contribution towards demand	CO_2 Emissions	Cost	CO_2 Emissions	Cost
	bpkm	*g/pkm*	*INR/pkm*	*million tons*	*Billion INR*
Existing technology					
Car (Petrol/Diesel/CNG)	680	198.3	0	134.8	0
Bus	5,157	24	0	123.8	0
2 Wheelers	1,002	36.7	0	36.8	0
3 Wheelers	271	62.5	0	16.9	0
Walking & Cycling	1,677	0	0	0.0	0

Introduction of the new technologies					
Electric Car	10,388	125	10.5	1298.6	109078.55
New Bus	78,784	20	0.3	1575.7	23635.21
Electric 2 wheeler	15,308	30	1.4	459.2	21430.73
Electric 3W	4,140	34	1	140.8	4140.10
Walking & Cycling	25,620	0	0	0.0	0.00
Total	143,027			3786.6	158284.59

5.3. Scenario III

Based on the constraints defined in the previous section, table 6 depicts the resultant optimum modal split in terms of billion passenger kilometers. The scenario IIIA depicts a reduction of 25 % in terms of CO_2 emission. In this scenario, results could vary considerably owing to the difference in ownership of vehicles. As we minimized the cost function, additional constraints of minimum personal mobility in term of cars was imposed.

Table 6: Scenario III: Cutting down CO_2 emission while minimizing the cost.

	Model IIIA			Model IIIB		
Constraints	1. The current share of bus transport which is 50% is allowed to increase up to a maximum of 60% 2. The current share of walking and cycling which is 19.2% is kept unchanged in 2032. 3. Electric cars are expected to have a maximum share of 10%, with a constraint that there would be a minimum share of 7.7% of personal mobility in terms of cars. 4. Electric three-wheelers to have a maximum share of 5% 5. Conventional two-wheelers are assumed to have a maximum share of 10 percent with an additional share of 10per cent allocated to electric two-wheelers			1. The current share of bus transport which is 50% is allowed to increase up to a maximum of 60% 2. The current share of walking and cycling which is 19.2% is expected to have a maximum share of 25%. 3. Electric cars are expected to have a minimum share of 5%. 4. Electric three-wheelers to have a maximum share of 5% 5. Conventional two-wheelers are assumed to have a maximum share of 10 percent with an additional share of 10per cent allocated to electric two-wheelers		
Modes	Contribution towards demand	CO_2 Emissions	Cost	Contribution towards demand	CO_2 Emissions	Cost
	bpkm	*million tons*	*Billion INR*	*bpkm*	*million tons*	*Billion INR*
Existing technology						
Car (Petrol/Diesel/CNG)	530	105	0	680	134.84	0
Bus	5,157	123.8	0	5,157	123.77	0
2 Wheelers	1,002	36.8	0	1,002	36.77	0
3 Wheelers	271	16.9	0	271	16.94	0
Walking & Cycling	1,677	0	0	1,677	0	0
Introduction of the new technologies						
Electric Car	11,013	1377	115637	7,151	893.9	75089
New Bus	80,659	1613	24198	80,659	1613.2	24198
Electric 2 wheeler	10,218	307	14305	5,469	164.1	7657
Electric 3W	6,880	234	6880	6,880	233.9	6880
Walking & Cycling	25,620	0	0	25,620	0	0
Total	143,027	3,814	161,021	143,027	3217.4	113,824

Model IIIA and IIIB depict the likely impact on the modal split based on the prioritized cost of emission per kilometer. In Model IIIA, the maximum share of walking and cycling is kept as per the base year 2012, however in Model IIIB, we increased the limit to 25% (see table 6). It is prudent to mention here that higher emphasis is given for the public transportation system in terms of share of bus and end to end connectivity and last mile connectivity through induction of three wheelers (auto rickshaw). Moreover, there has been studies that established incorporation of ICT enabled services in public transportation systems might influence the value of travel time savings, perhaps making buses and other public modes of transportation more attractive (Varghese and Jana 2018). A reduction of 37% of CO_2 emission is possible if walkability and pedestrian and cyclist friendly neighborhoods are conceived, which would also full the needs of the healthy city and healthy living.

Various models illustrated in scenario III owing to different constraints in terms of permissible limits of demand to be catered by a particular typology of mode, clearly illustrates the need for policies that would govern the following:

- Subsidies to introduce electric vehicles as a public transportation mode
- Policy to phase out old vehicles and technologies
- Decentralized urban transportation policies to cater to the needs and demand of people with respect to different tiers of cities

Policies need to be strategized based on the target of CO_2 emission reductions.

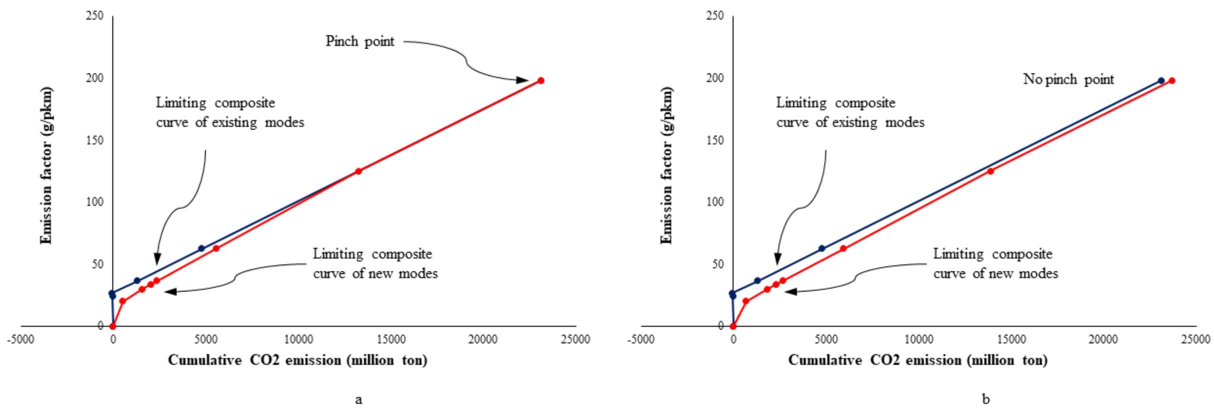

Fig. 2. Pinch analysis (a) Model IIIA; (b) Model IIIB.

Figure 2a shows that the conventional cars needs to be dissuaded significantly in 2032 to achieve the emission targets (25%), hence pinch point is observed. If the share of cycling and walking is improved considerably, emission targets can be achieved, in fact higher targets can be achieved beyond 25%, therefore pinch point is not observed.

6. Discussion and Conclusion

This paper introduces pinch analysis to optimize the distribution of demand for passenger transportation modes in future, while attempting to curb down the emission in India, this research focuses on the estimating appropriate mix of modes that might aid to achieve such feat in India. Pinch points might enable us to identify the mode of transportation that might need to be dissuaded or identification of mode that might enable policy makers to achieve emission targets in future.

Satisfying the increasing demand and reducing the emission level is indeed a big challenge for the transport sector of current times. The study takes into account a particular case of India to demonstrate the optimization methodology. The demand for Indian transport sector is expected to increase to 168,875 billion passenger-km. Three different scenarios were hypothesised for the Indian case of 2032. The major factor which is changed to develop the scenario is the emission level. The total cost that might be incurred and demand distribution for each scenario was estimated.

Using pinch analysis, the solutions were counterintuitive as the cost incurred should increase when the emission level is decreased. However, the demand distribution for future passenger might hold the key to the reduction, especially considering the non-motorized transport. However, considering the upsurge of purchasing capacity in India, limits have been assigned to estimate realistic modal split in the year 2032. When the emission level is decreased the demand for cheaper means of transport like walking and cycling increases thus reducing the total cost. The scenarios can be made more urbane by introducing more constraints considering passenger comfort and convenience that might affect the choice of the people in future.

This study can be further developed in various ways to improve the accuracy of the results obtained. In this study, only carbon dioxide emissions are considered on the basis of the emission constraint level. A comprehensive index including other pollutants from the vehicle can give a better picture of the harm done to the environment. The study qualitatively discusses a little about the people's comfort and choice. Moreover, there can be various factors by which demand can be reduced like better city planning, co-existence of workspace and residential complex, technological use to cut on the necessity to travel for example video conferencing for corporate meetings. With the advent of the concept of the smart city, the potential for the demand reduction can be studied to be included in this study. This way a varied demand level can be used to cut down on emissions apart from the ways use in this study.

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