Gradual sustainability approach for urban transport through subtle measures

Mukti Advani[1,*], Niraj Sharma[1], Madhu Errampalli[1], Yash Rane[2], Rajni Dhyani[1] and P. V. Pradeep Kumar[1]

[1]Central Road Research Institute, New Delhi 110 025, India
[2]Parul University, Vadodara 391 760, India

Capacity enhancement and demand reduction are the two most common approaches considered to deal with increased congestion in urban areas. The first approach involves construction of various infrastructure for providing increased capacity for motorized vehicles, whereas the second approach includes restricting movement of road users from congested area(s). Experiences from across the world have demonstrated that both the approaches have failed to resolve the problem of congestion. The present study has been carried out to assess traffic characteristics around five metro (rail) station areas in New Delhi, India, to examine the effect of subtle changes towards improvement for all road users. The impact of alternate traffic circulation plans, based on various traffic management strategies around these metro stations, has been compared using microscopic traffic simulation. The study has clearly demonstrated that parking related policies (including segregated parking lanes for cycle rickshaws and electric-rickshaws) can result in improvement in vehicular speed by 2 to 6 km/h in the influence zone of the selected metro stations for all categories of motorized vehicles. This is expected to result in total daily savings of 593 litres of petrol, 103 litres diesel and 643 kg CNG, and total CO_2e (equivalent) reduction of 3.5 tonne/day in all the five metro stations. It is evident that the sustainable scenarios (viz. segregation/shifting of on-street parking, signal design, etc.) or similar to those that have been suggested, would result in significant reduction in fuel consumption and corresponding CO_2e (equivalent) emissions. Implementing agencies can choose the scenario best suited to them, among the given options.

Keywords: Metro station, sustainability, traffic simulation, urban transport, vehicular emission.

Background

THE two possible approaches to deal with increased congestion at any location in urban areas are based on 'capacity enhancement' and 'reduction of demand'. The first approach involves construction of different infrastructure (i.e. construction of flyovers, underpasses, road widening, signal-free corridors, etc.) providing increased capacity for motorized vehicles, whereas the second approach includes restricting movement of a few (pre-identified/selected) road users from congested areas (i.e. by constructing grade separators for pedestrians restricting heavy vehicles for some duration during the day, access control corridors, banning the entry of slow-moving vehicles on major roads, etc.). However, both approaches have not completely and permanently solved the problem of congestion, even after spending huge resources in terms of money and space. Rather, the problem of traffic congestion has increased in long run after (may be) an illusionary short-term relief. This increase is a result of approaches adopted, making commuting by cars and two-wheelers easier, compared to commuting by public transport and non-motorized transport (NMT) modes. As a result, there is a rise in demand of personalized vehicles, resulting in increased levels of congestion, fuel consumption and corresponding vehicular emissions.

Realizing this, few countries have removed the capacity enhancing structures like flyovers to prioritize sustainable transport modes, whereas few other countries have dropped plans of constructing new flyovers[1]. Though the focus is shifting towards sustainable infrastructure in a few developed countries, especially the European countries, it is still a challenge for most of the developing countries which are still constructing new flyovers and similar infrastructure to provide immediate relief from the problem of motorized traffic congestion.

Since the capacity building strategies result in increased/induced demand and ultimately the same or higher level of congestion is experienced by the commuters within the duration of a few years, 'sustainable measures' (viz. separate lane for particular vehicle types, e.g. priority lane for buses and traffic signal phasing and timing to suit the needs of all road users including pedestrians, footpaths) need to be adopted. These strategies are not unknown, but usually remain at low priority as their benefits are considered to be small and usually not quantified. Due to non-quantified benefits, their implementation is generally compromised considering the limitation with respect to space availability. Non-quantified benefits, coupled with the existing level of private vehicle usage and/or taking

*For correspondence. (e-mail: mukti7@gmail.com)

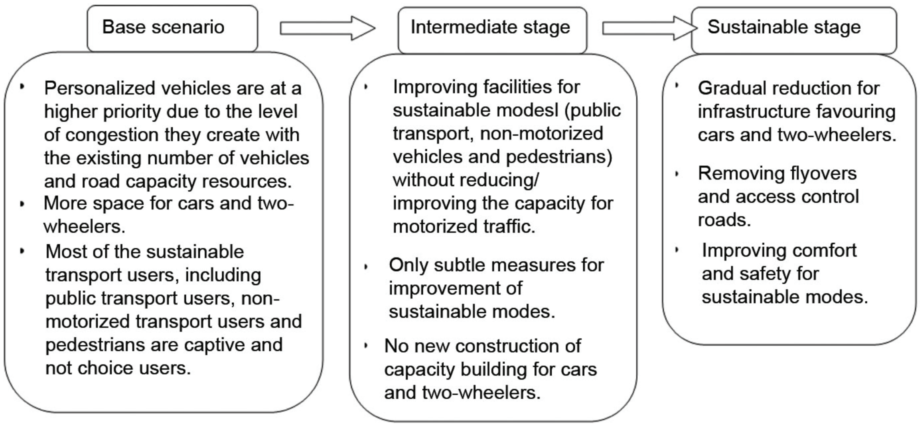

Figure 1. Concept of gradual sustainability.

away existing space from private motor vehicles for prioritizing movement of sustainable modes (viz. walking, cycling and intermediate public transport) are a challenge for traffic management agencies. Therefore, a gradual shift towards sustainability with an intermediate approach needs to be adopted (Figure 1).

We call this approach as the 'gradual sustainability (GS) approach', i.e. moving towards sustainability gradually without making drastic changes, as drastic changes may disturb the present conditions. For example, shifting commuters from personalized vehicles to public transport is sustainable, but cannot be achieved immediately. It needs a gradual strategy to cope with the infrastructure and operational challenges as well as social acceptance. Therefore, the present study proposes such a shift to be gradual. As shown in Figure 1, the base scenario represents the existing condition where personalized vehicles are operational at high priority by supported infrastructure, resulting in most of the space being occupied by cars and two-wheelers. Apart from this, the level of service provided in public transport modes is weak. As a result, most of the sustainable transport users, including public transport users, NMT users and pedestrians are captive and not choice users. Captive users are those who do not have the choice of using personalized vehicles primarily due to cost constraints. To change the scenario towards sustainability, the intermediate stage broadly includes: (1) measures to improve public transport, and (2) gradual discouragement from using personalized vehicles. Both can be done through infrastructural intervention. However, to make it gradual, only subtle measures must be adopted. Subtle measure means small changes and not the major involving construction work or demolition work. Minor changes which can be further ease out the facilities for personalized vehicles and at the same time minor and regular improvements for public transport modes. This will help in a gradual shift towards the final stage of achieving sustainability.

The proposed GS approach includes identification of existing space for better management of traffic. This approach is based on the concept of improving the congestion level for all road users without the need for more space and infrastructure requirements involving additional cost implications to the local/municipal authorities dealing with traffic management.

However, any traffic-related scenario needs to be quantified and compared for better decision-making. Any infrastructure and/or traffic management-related change affects the traffic performance (level of congestion), and this can be studied through simulation techniques.

Measuring congestion and simulation techniques

Researchers have used various methods to study transportation area/network performance considering various parameters, including travel speed, delay, level of service, connectivity, safety, link performances, volume capacity ratio, etc.[2,3]. One study had proposed a scalable time inflation performance measure that accounts for speed variations along a corridor affecting free-flow speeds and travel times[4]. Other parameters considered in studies by various researchers included time, delay, level of service, volume and speed[5,6]. The National Cooperative Highway Research Program report on right-sizing transportation investment includes a discussion on improving sustainability, rather than focusing only on vehicular congestion[7]. Several studies on the effect of traffic scenarios/strategies, including change in space utilization by adding/redesigning road space have been carried out based on the micro simulation technique[8–11]. Few studies have also examined the efficacy of traffic management tools, including traffic signal control in reducing traffic congestion and associated fuel consumption, pollution, etc. using simulation techniques[12–15].

The most common parameters studied are speed, delay and safety. However, few studies also included aspects related to impact on fuel consumption and corresponding vehicular emissions. However, factors related to fuel consumption and emission were considered only in case of major infrastructural changes. The present study is based on subtle infrastructural changes and compares different scenarios in terms of the most common parameters, viz. speed and delay as well as fuel consumption and emission.

Objectives of the present study

Considering the proposed gradual sustainability approach, the best possible scenario for managing traffic in an area has to be identified by checking various space management and traffic circulation plans. The study areas (i.e. metro stations) considered in the present study are among the most congested locations in New Delhi, the capital city of India. The selected sites are around Delhi metro (rail) stations which always experience traffic congestion. These sites include a variety of road users, including pedestrians, cycles and electric rickshaws, autorickshaws, cars, two-wheelers and buses. The problem of congestion around these metro stations is not faced by vehicle users, but all metro riders due to increased discomforted movement and increased safety risk level.

The present study involves with the (i) preparation of various traffic circulation plans, considering subtle changes for the GS approach around the selected metro stations in New Delhi, and (ii) to quantify the benefits of the identified alternate circulation plans in terms of travel time, speed, fuel consumption and corresponding vehicular emissions.

Methodology

The study methodology has been divided into three major parts as discussed below.

(i) Identification of potential space around metro stations to be included in the traffic circulation plans. For this, all detailed geometrical data (road width, median width, etc.) were collected apart from data with respect to traffic characteristics and users' opinion through personal interviews.

(ii) Development of the microscopic traffic simulation model and extraction of various traffic parameters (speed, delay, etc.) from the base case and various traffic circulation plans. This includes capturing of 'base conditions' through road geometry, traffic characteristics, space utilization by various activities, including walking, vehicular movements, on-street parking, signal phasing and timings along with the development of a simulation model using the VISSIM software, which includes model calibration and validation for the observed traffic conditions, captured for different traffic period(s). Various traffic circulation plans were designed for different options, viz. shifting of on-street parking, signal cycle design, diverting traffic on nearby roads, moving all pedestrians walking on the road to the footpath, etc.

(iii) Estimation of fuel consumption and corresponding vehicular emission for various traffic circulation plans/scenarios as identified in (ii). The change in vehicular speed estimated for various traffic circulation plan(s) resulted in change in fuel consumption (and corresponding emission) for moving as well as idling motor vehicles at the traffic intersections, in the influence zone of the selected metro stations. Vehicular emission was estimated using fuel-based emission factors based on the quantity consumed and type of fuel[16].

Study area and primary data collection

Study area

The Delhi Metrorail network stretches across 391 km with 286 stations. The Delhi Metro Rail Corporation (DMRC) operates 2700 trips per day carrying around 2.8 million passengers (during pre-COVID period)[17]. In the present study, five metro stations were identified in Delhi to cover the range of ridership from 6000–40,000 passengers/day. The five metro stations selected were Karol Bagh, Kailash Colony, Laxmi Nagar, Lajpat Nagar and Inderlok. These have a common problem of congestion around them with a range of traffic characteristics, feeder modes, pedestrian volume, on-street parking, signal design, space availability and other aspects related to comfort and safety. Table 1 provides information regarding the selected metro stations and their characteristics with respect to average ridership and land use around them.

Data collection

Data collected at the five metro stations included (i) information related to road space/geometry and potential space around them; (ii) traffic characteristics, viz. speed, delay and classified traffic volume count; (iii) feeder modes, and (iv) opinion of road users.

Road geometry data were collected and recorded as detailed drawings, which included information on road width, median details, footpath details, area dimensions of authorized/unauthorized parking, rickshaws (cycle rickshaws, battery or electric-rickshaws, autorickshaws), bus-stop locations, pick-up/drop area, location of FOBs (foot over bridges), location of metro entry/exit gates, signals and other road side furniture/activities like poles, parkings, bus stops, hawkers area, etc.

Traffic characteristics captured in the present study included classified traffic volume count (CTVC) data on a typical working day, i.e. July 2019 for 15 h duration (from 7:00 am to 10:00 pm) and speed data using the VBOX equipment. The CTVC data were collected through video recording covering all vehicular movements around each metro station area. The road user classification considered for extraction included: cars, two-wheelers (TWs); autorickshaws, including electric-rickshaws (autos); buses; light commercial vehicles (LCVs), including goods auto; two- and/or three-axle trucks; multi-axle trucks;

Table 1. Selected metro stations and their characteristics

Metro station	Average ridership (commuters/day)	Land use around metro stations	Congestion level
Karol Bagh	~40,000	Mixed, residential and commercial	High
Kailash Colony	~6,000	Residential	Medium
Laxmi Nagar	~40,000	Mixed, residential and commercial	High
Lajpat Nagar	~15,000	Mixed, residential and commercial	High
Inderlok	~6,000	Residential	Medium

Table 2. Observed journey speed data from V-BOX at the five metro stations

Metro station	Location/direction	Journey speed (kmph)
Karol Bagh	Jhandewalan to Rajendra Place	24.67
	Rajendra Place to Jhandewalan	11.33
Kailash Colony	Nehru Place to Moolchand	16.45
	Moolchand to Nehru Place	15.31
	Shakarpur	21.06
Laxmi Nagar	ITO	23.09
	Nirman Vihar	17.46
	Jangpura	24.69
Lajpat Nagar	Moolchand	22.20
	Vinobapuri	25.91
	Shastri Nagar	17.78
Inderlok	Ashok Park	15.04
	Maharaja Nahar Singh Marg	11.40
	Haji Abdul Salam Qureshi Marg	14.40

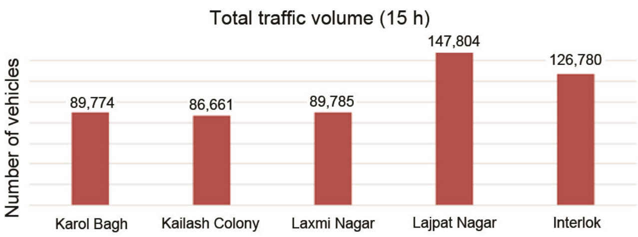

Figure 2. Total number of vehicles around the five selected metro stations.

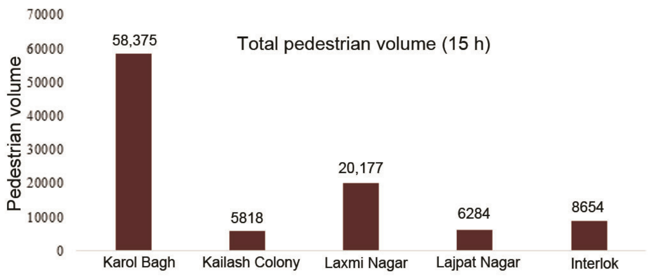

Figure 3. Total number of pedestrians around the five metro stations.

cycle rickshaws; bicycles and pedestrians. Traffic video data collected using multiple cameras were processed through semi-automatic method to count the number of moving vehicles. Further, pedestrian data were extracted with respect to the number of pedestrians walking/crossing and the number of pedestrians walking on footpath and/or road (i.e. vehicle-path/carriageway).

Speed data was collected by performing multiple rounds on roads around metro stations using VBOX with 0.1 sec precision. Data were collected by setting up the VBOX in the subject vehicle (car), which was made to travel on all the approach roads and the road network around the selected metro stations with 3–6 runs during 7 am to 10 pm.

Analysis, results and discussion

Identification of potential spaces around metro stations

Existing spaces around the selected metro stations were considered for developing traffic circulation plans to accommodate all existing road users. Additional space around these metro stations was identified, which is currently used for unorganized activities and has the potential to be included in the circulation plans. This comprises space under metro station structure/flyover/FOBs, space used for parking vehicles, unauthorized parking, etc.

Traffic volume and speed

Figures 2 and 3 show the total number of vehicles and pedestrians respectively, observed around the five metro stations during 15 h duration of a day.

The maximum number of pedestrians (58,375 was observed at the Karol Bagh metro station). The observed traffic speed around the five selected metro stations ranged from 11.33 to 25.91 kmph (Table 2).

Pedestrians' facilities, their choices and opinions

At none of the five selected metro stations is a continuous, good quality footpath available to pedestrians for walking. Footpaths were not only encroached by temporary and removable obstructions like hawkers, parked vehicle, etc. but occasionally were found to be encroached by permanent structures (e.g. concrete pillars). Thus, pedestrians were observed to walk on the footpath as well as on the road. Pedestrians' decision to walk on the footpath or on the road depends on the quality of the footpath and traffic characteristics on the road. Nearly 30–70% of pedestrians were observed to be walking on the roads, in the presence of footpaths for their full or partial trip length. It was observed that poorer quality of footpaths resulted in more number of pedestrians sharing space with vehicles on the roads, resulting in reduced space for vehicular movement as well as conflicts between pedestrians and vehicles. To reduce congestion on the roads and to increase the safety of pedestrians good-quality footpaths are essential. Good-quality footpaths in full length (without any missing links) should be considered on priority for immediate and long-term benefits[18].

The following five possible approaches/solutions to remove the obstruction(s) in walking on footpaths were discussed with pedestrians through personal interviews. (i) Removal/relocation of all temporary obstructions (dustbins, garbage, parked vehicles, hawkers, etc.). (ii) Designing 'safe pedestrian bay' around permanent obstructions. (iii) Signal phasing and timings for comfortable crossings. (iv) Sufficiently wide zebra crossing at locations with large pedestrian crossings. (v) Evaluating single/two-stage road crossings and their suitability with median space and signal timings.

Further, to gather opinions on safety and comfort around metro stations, road users were interviewed through a prepared questionnaire. Out of the total 1200 personal interviews, 10% were female commuters and the remaining 90% were male commuters. All interviewed commuters were found in the age group between 16 and 60 years, and 737 (66%) were metro users while the remaining 379 commuters (34%) were non-metro users. Further, out of 737 metro users, 287 commuters (~39%) reached the metro station by walk, 258 commuters (35%) reached by cycle rickshaws or electric rickshaws, 103 commuters (~14%) by personalized cars or app-based taxis, 59 commuters (~8%) by buses and the remaining 30 commuters (~4%) reached the metro station by two-wheelers. Of the 379 were non-metro users, 153 were pedestrians, 89 were cycle rickshaw users, 43 electric rickshaw users, 58 two-wheeler users and 36 car users. In response to the question – 'what kind of crossing arrangement would you feel safe and comfortable' 90% pedestrians considered 'at-grade separation from vehicles' as their most preferred response.

Estimation of delay for alternate traffic circulations plans using VISSIM simulation

Traffic micro-simulation models represent the interaction of different components such as transportation systems, and the users such as vehicles and pedestrians at an individual level. Each vehicle that enters a road network is stochastically assigned a unique set of operational characteristics, which it maintains as it travels through the network. The interactions among system entities, whether vehicle–vehicle, vehicle–roadway or vehicle–control device are modelled based on specific road-user behaviour models, namely car-following and lane-changing models.

As explained earlier, the VISSIM software was used in the present study and traffic characteristics of one location, i.e. Laxmi Nagar metro station area were considered to calibrate the simulation model and validate it with the observed data. The developed simulation model was then extended to other metro stations to estimate vehicular movements at the respective stations. The calibration was done by trial and error method by changing the model parameters and comparing the simulation output with observed data, namely traffic volume, journey speed and time headway. For validating the model, GEH (Geoffrey E. Havers) values of volume and the 'absolute percentage error' of travel time and average headway were considered (Table 3).

As mentioned in Table 3, GEH values are less than 5.0 and therefore the simulation model could predict vehicular movement with the requisite accuracy. Further, the estimated error was less than 10% for speed and headway, which indicated that the model must be properly calibrated to predict vehicular movement with reasonable accuracy. The validated model was then extended to simulate vehicular movement at the other selected metro stations. The results for the base case, i.e. existing traffic condition were then estimated utilizing the developed simulation model (Table 4).

Various traffic circulation plans were conceptualized to be implemented at the selected metro stations based on the observed conditions. A description of the conceived scenarios (traffic circulation plans) considered in the present study is given below.

Scenario 1: Segregation and shifting of on-street parking to minor roads/appropriate locations.
Scenario 2: Shifting bus stops and reduction of dwell time for mini buses.
Scenario 3: Introducing all red phase in existing signal/installation of new pedestrian signal to enhance pedestrian safety.
Scenario 4: Signal redesign for major intersections.
Scenario 5: Diversion of traffic partially to alternative route.
Scenario 6: Segregated pick-up/drop-off lanes on major roads.
Scenario 7: Setting-up exclusive pick-up/drop-off areas away from major roads.
Scenario 8: Using the bicycle lane for cycle rickshaw parking/waiting.

The above scenarios were created in the developed VISSIM simulation model and the parameters similar to the base case conditions were estimated. From the estimated speed, it can be inferred that at the Karol Bagh metro station, scenario 1 was able to best improve the traffic situation maximum (speed increase by 27%), followed by scenarios 4 and 2. This scenario 1 alone was able to improve traffic conditions significantly. In the case of Kailash Colony metro station also, scenario 1 was best able to improve the traffic situation (speed increase by 13%). However, scenario 3 was basically related to signal redesign

Table 3. Comparison of observed and simulated traffic volume

Location/direction	Traffic volume (veh/h)			Journey speed (kmph)		
	Observed	VISSIM	GEH value	Observed	VISSIM	Error (%)
Shakarpur	2394	2325	1.42	21.06	21.18	0.53
ITO	3158	3154	0.07	23.09	24.71	7.0
Nirman Vihar	3774	3736	0.62	17.46	17.62	0.93

Table 4. Estimated results for base condition for different metro stations

Parameter	Karol Bagh	Kailash Colony	Laxmi Nagar	Lajpat Nagar	Inderlok
Average delay time per vehicle (sec)	149	31	42	9	94
Average speed (kmph)	10.3	14.1	14.8	33.5	14.6
Average stopped delay per vehicle (sec)	70	15	22	1	71
Total delay time (h)	3855.3	678.8	1486.9	375.5	3203.8
Total distance travelled (km)	55,465.9	20,265.3	92,343	58,535.6	91,081.2
Total stopped delay (h)	1816.8	321.8	773.7	50.6	2429.5
Total travel time (h)	5366.0	1438.2	6257.6	1748.1	6251.9

by introducing all red phase to enhance pedestrian safety, which increased delays and reduced the speed of vehicular traffic slightly (speed decrease by 4%) than the base condition. This scenario estimated increased traffic delay; however, it improved the safety of pedestrians.

For Laxmi Nagar, scenarios 2 and 1 were best improve the traffic situation (speed increase is 45%), followed by scenario 4 (speed increase by 7%). Scenario 6 reduced speed by 8% compared to the base case. For the Lajpat Nagar metro station, scenario 7 was best able to improve the traffic situation (speed increase around 10%), followed by scenarios 1 (speed increase of around 7%) and 8. However, scenario 3 impacted the vehicular speed insignificantly (only 1% reduction in speed). At Inderlok, scenario 1 was best able to improve the traffic situation (approximately 45% speed increase), followed by scenario 2 (speed increase around 5%), whereas scenario 3 reduced the speed by 26%, which however enhanced pedestrian safety compared to the other scenarios.

Estimation of fuel consumption savings and corresponding vehicular emission: The methodology for estimation of savings in fuel consumption has two components: (i) Fuel savings corresponding to improvement (i.e. reduction) in traffic/time delays at various traffic signals in the influence zone (i.e. fuel consumption estimation during idling of motor vehicles at the traffic intersection). (ii) Fuel savings due to improvement of traffic speed, i.e. reduction in congestion in and around the metro stations or in its influence zone (i.e. savings in running fuel consumption of motor vehicles).

The idling fuel consumption/loss at various traffic intersections in the zone of influence of the metro stations was estimated using information related to number, type and category of idling vehicles, idling fuel consumption values of different vehicle categories and observed time delays at these traffic intersection, etc.[19]. The running fuel consumption by motor vehicles in the influence zone was estimated using various vehicle speed-based equations which are a function of type category of vehicles and their fuel type[20]. The estimated fuel consumption under both conditions (i.e. idling and running) was converted to the corresponding emission in terms of direct green house gases (GHGs; viz. CO_2, CH_4 and N_2O) and indirect GHGs (viz. CO, NO_x and non-methane volatile organic compounds (NMVOC)) using fuel-based IPCC emission factors. However, for better representation and comparison, the results have been represented in CO_2e (equivalent) terms. The fuel consumption and corresponding emission at the selected metro stations were estimated for base/existing scenarios and various traffic plans. Table 5 presents the results of fuel consumption and CO_2e (CO_s equivalent) emission for running and idling vehicles. Vehicular emission was estimated using IPCC pollutant- specific emission factors (kg/TJ) for each fuel type used as shown in eq. (1), and by various categories of vehicles as given in eq. (2).

$$E = \sum (FC_a * EF_a), \quad (1)$$

where E is the emission of gases (e.g. CO_2, CH_4, N_2O, CO, NO_x and NMVOC (kg); direct and indirect GHG emissions). EF is the emission factor (kg/TJ) by IPCC, FC the fuel consumption activity as energy input (TJ; determined from net calorific value(s) of the corresponding fuel(s)) and a is the fuel type.

$$E_i = \left[\sum V_j(k_y) * FC(j, f, k_y) * D_f T(j, f, k_y) * NCV_f * EF_{(f,i)} \right], \quad (2)$$

where E_i is the total emission of pollutants of type i (g), $V_j(k_y)$ the vehicle type j of vintage k_y (no. of vehicles), FC (j, f, k_y) the fuel consumption during idling by vehicle

Table 5. Impact of fuel consumption and corresponding vehicular emissions from best scenarios at different metro stations

(Metro station) scenario	Petrol (litre)	Diesel (litre)	CNG (kg)	Emission (kg/day) CO_2	CH_4	N_2O	CO	NO_x	NMVOC	CO_{2e} (tonnes/day)
Karol Bagh										
Base case	1164	218	1125	6284	6	0.3	338	62	60	6.5
Scenario 1	942	175	939	5158	5	0.2	274	51	48	5.3
Kailash Colony										
Base case	371	72	231	1666	1	0.1	105	16	19	1.7
Scenario 1	329	62	214	1498	1	0.1	94	14	17	1.5
Laxmi Nagar										
Base case	1147	214	858	5517	5	0.2	328	54	59	5.7
Combined scenario (1, 2 and 6)	1091	208	725	5014	4	0.2	311	49	56	5.2
Lajpat Nagar										
Base case	910	185	436	3757	3	0.1	256	36	47	3.9
Scenario 8	879	170	408	3571	2	0.1	247	34	45	3.7
Inderlok										
Base case	1387	351	1643	8545	8	0.4	412	85	72	8.8
Combined scenario (1 and 2)	1140	308	1228	6745	6	0.3	337	67	59	7.0

type *j* using fuel type *f* of vintage k_y (ml/sec), D_f the density of fuel *f* (g/ml), T (j, f, k_y) the time delay at traffic intersections by vehicle type *j* of fuel type *f* of vintage k_y (sec), NCV_f the net calorific value for fuel type *f* ((TJ/t)) and $EF_{(f,i)}$ is the emission factor for fuel type *f* of pollutant type *i* (t/TJ).

The fuel consumption and corresponding vehicular emission from different scenarios at all the five selected metro stations were estimated. In order to assess the benefits generated by each of the traffic circulation plans/scenarios, the best plan was selected after combining various scenarios and presented for each of the selected metro station (Table 5).

Table 5 indicated that in almost all the different scenarios suggested, there is less fuel consumption and corresponding emission as compared to the base case. From the results it can be concluded that parking-related policies (which include segregated parking lane for cycle rickshaws and electric-rickshaws) can result in total daily savings of petrol of 593 litres, diesel of 103 litres and CNG of 643 kg, and total CO_2 reduction of 3.5 tonne/day at all five metro stations. Similarly, bus stop location-based strategies may result in total daily savings of petrol of 165 litres, diesel of 36 litres and CNG of 265 kg, and total CO_2 reduction of 1.3 tonne/day at three metro stations (Karol Bagh, Laxmi Nagar and Inderlok). Further, segregated pick-up/drop-off facilities could generate total daily savings of petrol of 3 litres, diesel of 1 litre and CNG of 9 kg, and total CO_2 reduction of 0.1 tonne/day at two metro stations, namely Laxmi Nagar and Lajpat Nagar. However, signal redesign considering pedestrians resulted in increase in total consumption of petrol of 327 litres, diesel of 103 litres and CNG of 625 kg and total CO_2 increase of 2.8 tonne/day at four metro stations (Karol Bagh, Kailash Colony, Lajpat Nagar and Inderlok). From the results it can be concluded that the best scenario can result in total daily savings of petrol of 598 litres, diesel of 117 litres and CNG of 779 kg, and total CO_{2e} reduction of 3.9 tonne/day at all five metro stations. Implementing agencies can choose a particular scenario best suited to them within the given options, or they can consider a new scenario and its implications can be compared with other scenarios prior to selecting the best option.

Conclusion and recommendations

The widely accepted and implemented approach in developing countries like India, to deal with congestion, is to provide additional space (addition in road width or right of way or with provision of underpass or flyover). Within a few years of construction, these approaches mostly result in additional number of personalized vehicles on the road corridor/area without reducing congestion. This approach has worsened the sustainability with more number of personalized vehicles on the roads. The present study proposes the 'gradual sustainability approach', i.e. a gradual change from unsustainability to sustainability. This can be achieved through subtle measures (enough space for circulation of feeder modes serving bus/metro stations around public transport stops/stations, good walking and bicycling facilities connecting to public transport stops/stations, safe and comfortable at-grade crossing facilities, etc.) and their quantification for making the 'right' and 'well-informed' decisions.

The present study has clearly demonstrated that parking-related policies (including segregated parking lanes for cycle rickshaws and electric-rickshaws) can result in improvement in vehicular speed by 2–6 km/h in the influence zone around the selected metro stations for all the vehicle categories. This is expected to result in total daily savings of 593 litres of petrol, 103 litres of diesel and 643 kg of CNG, and total CO_{2e} (equivalent) reduction of

3.5 tonne/day at all five metro stations. It is also evident that the sustainable scenarios (viz. segregation/shifting of on-street parking, signal design, etc.) or those similar to what has been suggested here, would result in significant reduction in fuel consumption and corresponding CO_2e (equivalent) emission. Further, it is also suggested that for effective improvement measures (covered through alternate scenarios), the following areas need to be addressed while preparing traffic circulation plans: (i) On-street parking needs to be channelized and preferably on minor roads. (ii) Segregated parking lane for cycle rickshaws and e-rickshaws. (iii) Redesign of signals, including 'no free left' turn and 'all red' phase around metro stations. (iv) Pedestrian crossing at-grade as well as through metro stations. (v) Alternative bus stops locations suited to traffic and road users. (vi) Providing bus stops with 'bus bays' only for roads with less than two-lane carriageway. (vii) Possibility to provide segregated pick-up/drop off zones underneath metro stations for taxis, private vehicles and autos. (viii) Explore potential spaces for utilization of different road users, metro commuters, etc.

The impact of these parameters on traffic circulation plans differs based on the traffic characteristics (including traffic volume, speed, etc.), on-street activities (i.e. parking, encroachment, etc.) and the adopted traffic management strategies (i.e. traffic signal and free-left turning vehicles).

The recommended improvement measures are subtle and provide a gradual shift towards sustainability. Quantified changes/improvements in terms of traffic delay, traffic speed, fuel consumption and vehicular emission presented in the study are location-specific, but provide an insight to the possible benefits. Moreover, any other traffic circulation plans, if and whenever suggested by local municipal or regulatory authorities, can be easily evaluated and compared with the scenarios as discussed above, in terms of improvement in traffic speed, pedestrian safety, fuel saving and the corresponding vehicular emission.

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