

Article

Visualization and Analysis of Traffic Flow and Congestion in India

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Abstract: The paper takes an analysis of traffic conditions in a developing country, namely, India. India is a country with a rapidly growing economy and a large market, and it has the second largest population in the world, which was 1.3 billion in 2018. India also suffers from environmental problems, such as air pollution and global warming that is contributed by traffic CO₂ emissions from transportation. In order to analyze this problem, a particularly challenging issue in developing countries like India, is the collection of traffic data. In general, developing countries do not often have well established infrastructure such as installations of small traffic signals, they lack new road construction and public transportation, etc. This study is the first real traffic congestion analysis in India and introduces unique traffic flow analysis such as: (1) Collecting over a month of recent traffic data in a major city in India, (2) defining traffic congestion from occupancy parameter based on traffic flow theory and observation data, and (3) using geographical special analysis (GIS) for identifying traffic congestion location. These three combination analysis enables one to identify the most congested area in the city with quantitative congestion condition. This study becomes useful to other countries that have similar issues.



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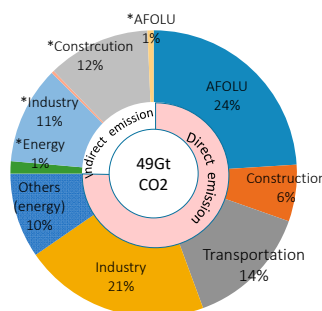
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Keywords: traffic flow analysis; traffic congestion; fundamental traffic flow characteristics

1. Introduction

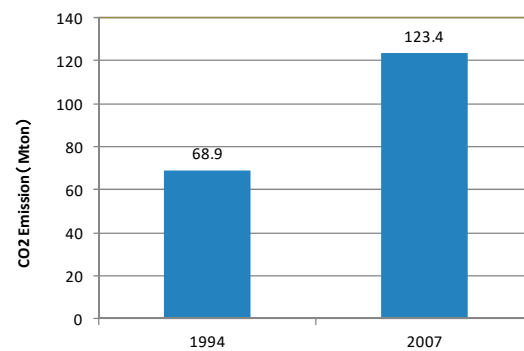
1.1. Environment

Global warming and greenhouse effects, including CO₂ emissions, have been concerns since the 1970s. Figure 1 shows that transportation accounted for 14% of CO₂ emissions worldwide in 2010, corresponding to 6.86 giga-tons [1]. Figure 2 shows that the volume of CO₂ emissions doubled and the number of vehicles tripled in India between 1994 and 2007 [2]. As for India’s traffic condition, there is a great volume of traffic growing under its poorly developed transport infrastructure, there is heavy traffic congestion as a result of crowded traffic, and traffic accidents. Therefore, it is urgent to find out the reason for traffic congestion mechanism in order to deploy a low carbon transport system.

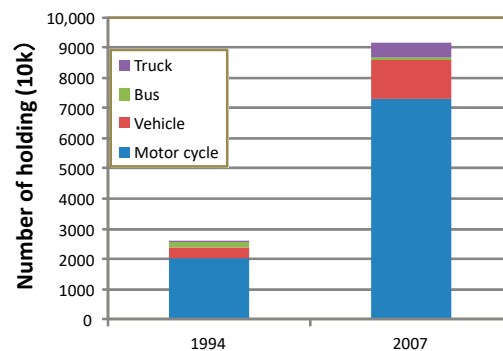


Note:
1) * Indirect emission 2) AFOLU agriculture, forestry and other land use.

Figure 1. Global CO₂ emissions.



(a) CO₂ emissions from road transportation.



(b) Number of vehicles for road transportation.

Figure 2. Indian road transportation.

Motorcycles have typically makes up the largest section of transport in India, as is still the case in 2020. This trend is typical for developing countries.

1.2. Related Work

In this study, measurement data were used to visualize actual traffic conditions, and transportation parameters were used to analyze traffic flow. The author has participated in a Japanese and Indian government project on urban transportation analysis in India since April 2017 [3]. Several studies have been performed on traffic flow research [4,5]. Studies have also been carried out specifically on Indian traffic. For example, A. Salim et al. used traffic density and space headway parameters to analyze traffic congestion [6], but measurement data were only obtained over four days in Chennai, India. M. Goutham and B. Chanda reported vehicle probe data in terms of the traffic volume and speed in Hyderabad, India, based on the Indian Road Standard IRC-106-1990 [7]. This study is a multiple-month measurement analysis of data obtained from January 2019 to August 2019 in the city of Ahmedabad in the state of Gujarat in India. This first study is the first long-span measurement analysis of traffic in India.

In terms of traffic data collection technology, there are several studies that use information communication technology (ICT), such as cloud computing [8] and DSRC (V2X) technology [9]. These challenges are relatively new and their technology is not widely applicable, especially in developing countries. Therefore, it is necessary to use practical methods from a sustainable point of view. In this study, we used 31 ordinal traffic monitoring CCTV units installed in one of the major cities in India and collected traffic data every minutes over 24 h over 8 months, which became 345,600 points = 60 min × 24 h × 30 days × 8 months per CCTV. The total coverage area of this study is the center of Ahmedabad city, which a 7 km × 7 km square space range on the west side of the city.

As for road network analysis, S. Mukherjee introduced Indian road network analysis based on an urban centralization factor [10]. This research is city level road network

analysis for high way connectivity and it is not related inside traffic congestion. In terms of road infrastructure, the Indian government currently promotes new road construction and road expansion aggressively. Therefore GIS network analysis is potentially changing day by day. In this research, the author chose GIS special analysis instead of network analysis.

Traffic flow theory and the measurement procedure are described in Section 2. Then, the traffic flow analysis is described. A spatial analysis of traffic congestion is presented in Section 3. The results are discussed in Section 4, and conclusions are presented in Section 5.

2. Theory and Measurements

2.1. Traffic Flow Theory

Traffic flow theory has been developed since the 1930s. The well-known Greenshields observation model first appeared exactly 75 years ago (Proc. of the 13th Annual Meeting of the Highway Research Board, December 1933) [11].

The Greenshields equation is given by Equation (1):

$$v = v_f \left(1 - \frac{k}{k_j} \right), \tag{1}$$

where v_f is the free speed and k_j is the jam traffic density.

Equation (2) can be used to model continuous traffic flow:

$$q = k \times v, \tag{2}$$

where q is the traffic volume and v is the vehicle speed.

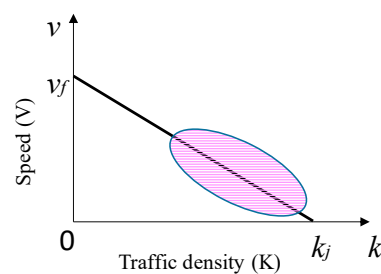
Combining Equations (1) and (2) yields Equation (3):

$$q = v_f \left(1 - \frac{k}{k_j} \right) k \tag{3}$$

Equation (3) can be transformed to Equation (4) as follows:

$$q = -\frac{v_f}{k_j} \left(k - \frac{k_j}{2} \right)^2 + \frac{v_f k_j}{4}. \tag{4}$$

Figure 3 illustrates three fundamental traffic flow characteristics obtained using the traffic flow theory presented above, where the point of traffic congestion is marked in each graph. Traffic congestion occurs in high traffic density areas, and there is a critical traffic volume that represents a threshold between no congestion and the onset of congestion.



(a) k - v curve

Figure 3. Cont.

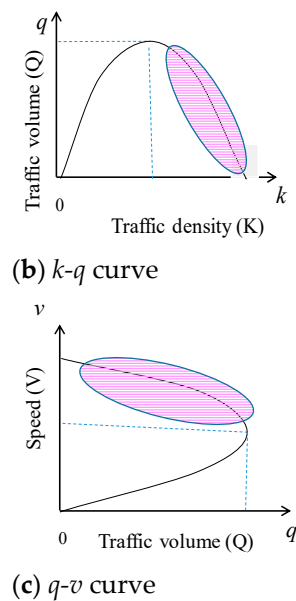


Figure 3. Theoretical fundamental traffic flow characteristics.

2.2. Traffic Flow Measurement: Step 1

2.2.1. Measurement Environment

The author has been involved in the Science and Technology Research Partnership for Sustainable Development (known as the “SATREPS” project) [12], which focuses on low-carbon urban transportation development. Under the auspices of this project, we installed traffic monitoring CCTVs and a traffic sign board, known as a variable message sign (VMS), to obtain real-time traffic conditions in the city of Ahmedabad. In 2018, Ahmedabad had a population of approximately 8 million [13], with 2.6 million four wheelers and 15.8 million two wheelers [14]. The four-wheeler growth rate was 65% more than that in 2010. Ahmedabad is an economic and industrial hub in India and the largest city in the state of Gujarat. Therefore, there is heavy traffic congestion in the city, presenting challenging conditions for urban transportation management by the local government, the Ahmedabad Municipal Corporation. We collected traffic data from 21 CCTVs out of a total of 35 CCTVs in the city (CCTV No. 1 has since been removed), the CCTV locations are shown in Figure 4. The numbers shown in Figure 4 correspond to the labels of the CCTVs used to collect traffic flow data, i.e., the number of vehicles, average vehicle speed, gap, or headway between vehicles, vehicle length, etc. All traffic flow data were measured every minute. The volume of the measurement data was 43,200 points per location for one month. We analyzed 8 months of data from January to August 2019 in this study, and we performed a one-month data analysis for June 2019 in this study.

Figure 4 shows the three segments used for traffic data measurement. The left side of the group lies along a major road, 132 Feet Ring Road, which is monitored by CCTV No. 2 to 14. New shopping malls, restaurants, and business offices in this area are monitored by CCTV No. 1001 to 1018. A second group of CCTVs is located near the river area—the Sabarmati Riverfront. A third group of CCTVs is located at a major junction, namely, the Paldi Junction (CCTV No. 2001 to 2004), which is the end point of a flyover starting near CCTV No. 11. A metro is being constructed in Ahmedabad that comprises a north-south line and an east-west line. The partial operation of metro services began in March 2019, and phase 1 of the north-south line will be completed by 2023 [15]. Ahmedabad has had a dedicated bus rapid transit service or BRT since 2009, which has a 101-km operation with 275 buses [16].



Figure 4. Traffic measurement environment in Ahmedabad city (the number is defined each CCTV installed location. Blue line and red line are the Metro line which is under development).

2.2.2. Traffic Data Measurement

Figure 5 shows an example of fundamental traffic flow characteristics obtained from CCTV No. 2 for June 2019. It is difficult to determine traffic congestion from these curves. The traffic data presented in each graph are based on lanes, for example, a 100-vehicles/km (veh/km) traffic density corresponds to a 100 veh/km lane. CCTV No. 2 monitors two lanes.

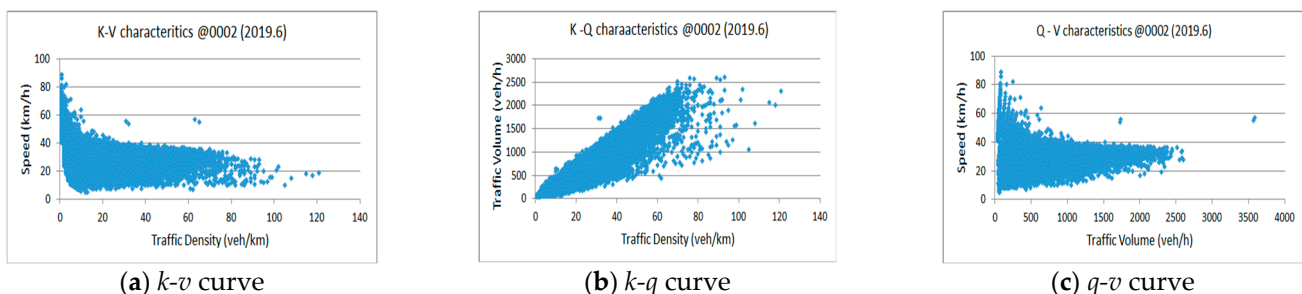


Figure 5. Example of fundamental traffic flow characteristics monitored by CCTV No. 2.

Figure 6 shows the variation in the traffic volume and average vehicle speed with time. The traffic volume peaks twice, in the morning and evening. Traffic congestion is clearly reflected in the vehicle speed. The traffic speed is lower in the evening than in the morning, indicating that traffic congestion is heavier in the evening than in the morning. Similar trends in the traffic flow characteristics are obtained at other locations.

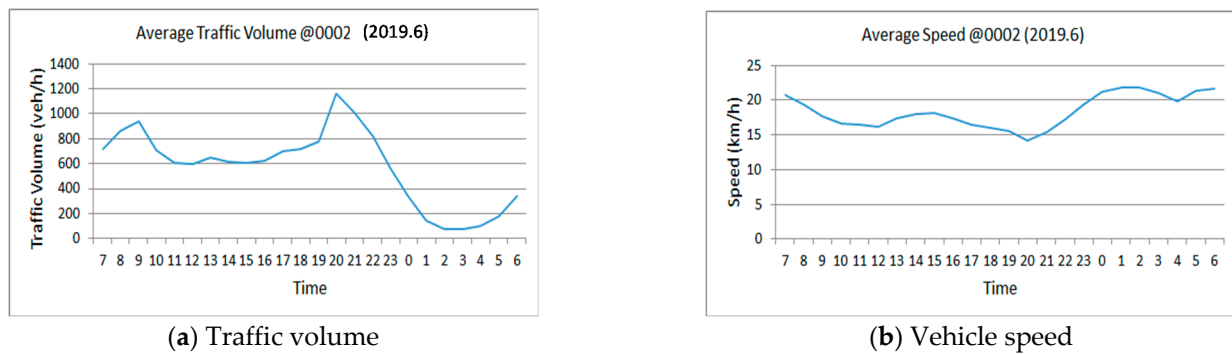


Figure 6. Example of daily traffic flow characteristics at CCTV No. 2.

The occupancy (OC) is generally used to measure traffic congestion and is defined as the percentage ratio of the total measurement time (t) of vehicles for a given block of a road section at a given time, as shown in Equation (5):

$$OC = \frac{1}{T} \sum_i t_i \times 100 (\%), \tag{5}$$

where T is the time of measurement and t_i is the time of detection of vehicle i [17].

Equation (6) can be written considering that the number of existing vehicles in a given section is N , and the average length of the vehicle is \bar{l} :

$$OC = 100 \frac{q \bar{l}}{v} = 100 k \bar{l}. \tag{6}$$

Therefore, (OC) is proportional to the traffic density (k) and traffic volume (q).

From Figure 6, traffic congestion in CCTV No. 2 occurs at the maximum traffic volume at 20:00, which is also understandable by Equation (6). However, this condition is not always correct. When we take all other 34 CCTV data in June 2019, we see different results as follows.

Figure 7 shows the hourly traffic characteristics of the average traffic volume and average occupancy time trend of all CCTV data in June 2019. From the traffic volume graph, the maximum peak occurs at 10:00, and the second peak occurs at 18:00. On the other hand, from the occupancy graph, the maximum peak occurs at 20:00, and the second peak occurs at 10:00. This means that the maximum traffic volume does not always create traffic congestion. This point is another particular point about the peak timing of traffic volume, and occupancy does not always occur at the same time. In the morning at 10:00, the peak of both traffic volume and occupancy occurs at the same time, and there is no time gap. However, in the evening, the peak traffic volume occurs at 18:00, but that of occupancy occurs at 20:00, and there is a two-hour time gap. This means that there is some reason for traffic congestion aside from a large traffic volume. This situation occurs for 8 months of traffic flow observations in this study. In general, this type of traffic congestion is not seen in advanced countries, at least not in Japan today.

In the next section, detailed traffic congestion analysis is described.

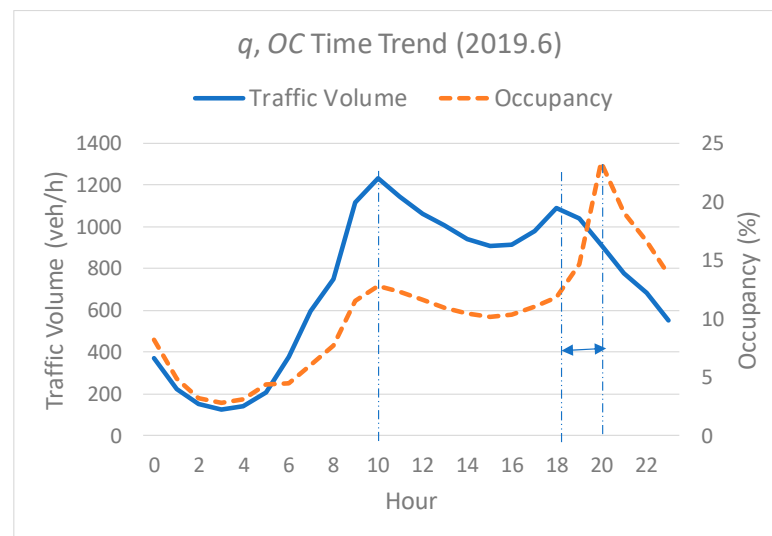


Figure 7. Hourly traffic comparison between traffic volume and occupancy.

3. Congestion Analysis

3.1. Congestion Time Analysis: Step 2

In the previous section, we see that there are some different condition changes between traffic volume and occupancy from Figure 7. This section describes a more detailed traffic congestion analysis, especially the difference between traffic volume and occupancy. Figure 8 describes the dispersion between traffic volume and occupancy. The number in the graph shows the hourly time when each traffic volume and occupancy are measured. Traffic congestion normally occurs at the over 15% occupancy level, and congestion occurs at the time frame between 20:00 and 22:00. In the morning, the relationship between traffic volume and occupancy is linear along the line from 03:00 to 10:00 in Figure 8. After 18:00, the q -OC relationship starts to change its stage, and traffic congestion occurs from 22:00. Figure 8 uses average traffic volume and occupancy data. To check real measurement data, actual measured data are plotted based on the time zone, which is divided into 6 time zones. F1 ranges from 00:00 to 03:59, F2 ranges from 04:00 to 07:59, F3 ranges from 08:00 to 11:59, F4 ranges from 12:00 to 15:59, F5 ranges from 16:00 to 19:59, and F6 ranges from 20:00 to 23:59. Figure 9 shows the time zone-based q -OC dispersion against Figure 8. This was named “traffic congestion triangle” in a previous study [18].

In summary, in this section, there are two types of traffic congestion. One is large traffic volume congestion, which is an ordinal traffic congestion condition that occurs in the morning. The other is a relatively small traffic volume congestion, which is unique in Ahmedabad and occurs in the evening. It is necessary to take another approach to determine why there are two types of traffic congestion in Ahmedabad. The next section describes the geographical congestion analysis for this question.

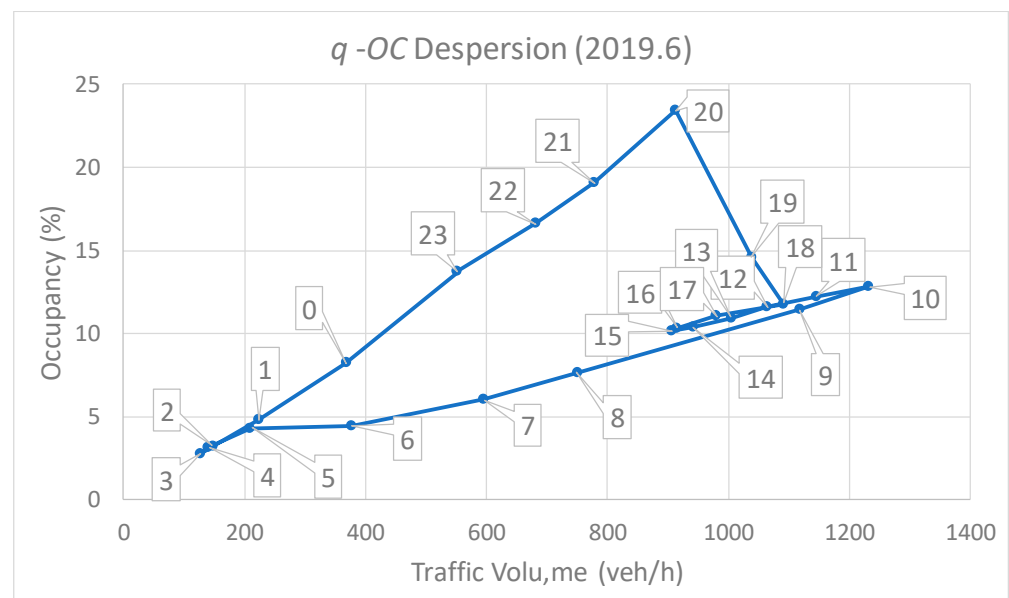


Figure 8. Average traffic volume and occupancy in June 2019 (the number of inside graph shows time frame in day e.g., 22 means the hour from 22:00 to 22:59).

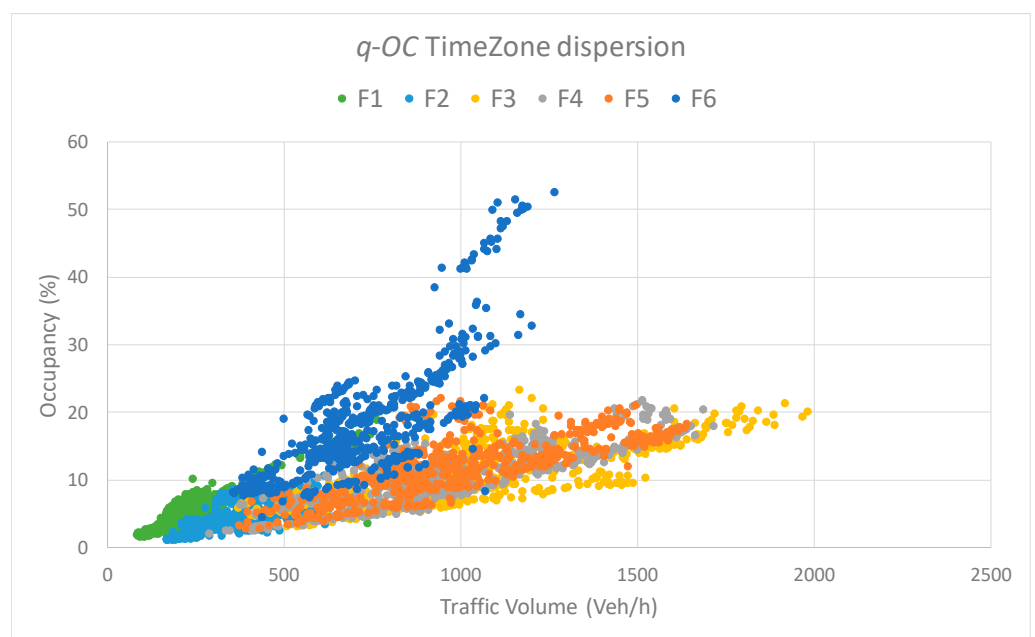


Figure 9. Time zone-based traffic volume and occupancy dispersion in June 2019.

3.2. Congestion Spatial Analysis: Step 3

First, the spatial traffic congestion in each different time frame is shown via occupancy. In terms of spatial analysis, inverse distance weight (IDW) interpolation among measurement points is used. Therefore the occupancy or congestion spatial level does not present the real traffic congestion condition. In the case of detailed congestion analysis, it is necessary to compare with all related road measurement. The GIS tool in this research is ArcGIS and ArcGIS Pro from Esri (Environmental Systems Research Institute). Figure 10 shows four different hourly traffic congestion conditions by occupancy level between 0% and 60% occupancy from white to a dark color. From Figure 10d, the most congested area is near the CCTV No. 2 location. The subsequent Discussion section describes a detailed congestion analysis, especially at the CCTV No. 2 location.

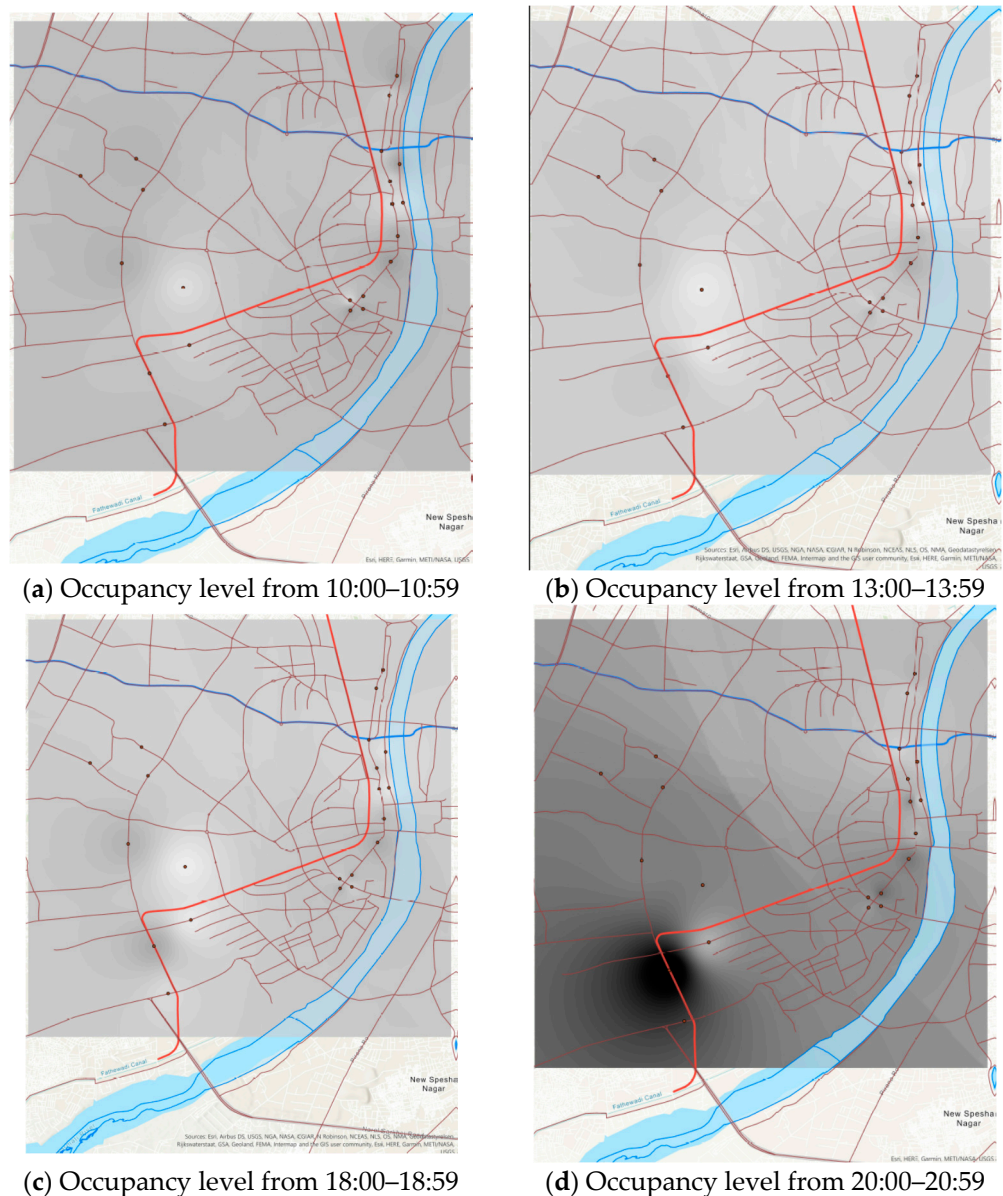


Figure 10. Spatial congestion analysis for different time frames.

4. Discussion

For traffic congestion to occur near the CCTV No. 2 location, it is necessary to check the traffic measurement environment. Figure 11 shows the CCTV installation position, and its arrow shows the CCTV face direction. For example, CCTV No. 2 measures traffic flow data from south to north, and CCTV No. 4 measures traffic flow data from north to south. CCTV No. 3 measures traffic flow data from west to east. The traffic flow from CCTV No. 2 and CCTV No. 4 goes to the center point among CCTV No. 2, CCTV No. 3, and CCTV No. 4. From this CCTV position, traffic flow at CCTV No. 3 means a reduction of its traffic from the center point.

In Figures 10 and 11, the red line is the Metro line which is under development and its operation will begin by 2023. There is a potential for reduction of traffic congestion when the Metro operation starts because the most congested location is near the CCTV No. 2 area (refer to Figure 10d). Therefore, this part of congestion analysis becomes important for future traffic design.

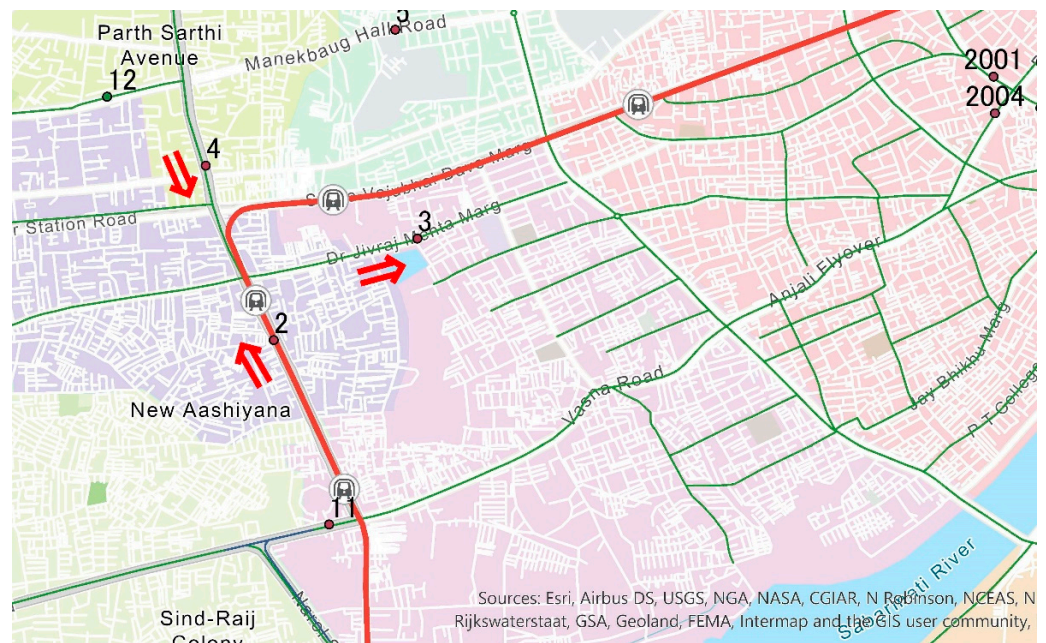
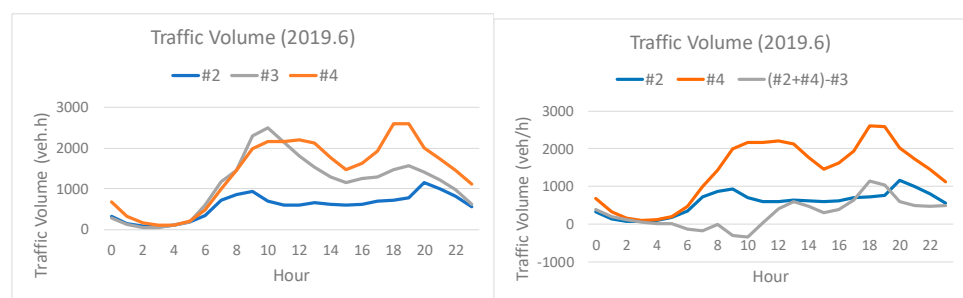


Figure 11. Relationship between traffic volume and occupancy in Ahmedabad (red line is under development for the first Metro in Ahmedabad and the train mark is the Metro station).

In Figure 12a, each traffic volume of CCTV No. 2, No. 3, and No. 4 is shown. When the traffic volume of CCTV No. 3 is subtracted from the total accumulated traffic volume of CCTV No. 2 and CCTV No. 4, the traffic volume curve (= No. 2 + No. 4 – No. 3) means the total traffic volume condition at the center among CCTV No. 2, No. 3, and No. 4. From Figure 12b, there is a large difference in traffic volume conditions at 10:00 and 18:00 to 20:00. These traffic volume changes cause traffic congestion conditions in the evening. From this analysis, some number of vehicle coming from CCTV No. 2 and No. 4 in the evening seems to stay around this location. There is no other information from this observation but it should have some reason for the evening traffic congestion. It is necessary to have on-site observation in future.



(a) Each CCTV location traffic volume

(b) Subtraction of CCTV No. 3 traffic volume

Figure 12. Traffic volume near the CCTV No. 2 location.

5. Conclusions

We visualized actual traffic conditions and identified traffic congestion patterns by the combination of traffic flow and geographic analysis based on long term collecting data in the city of Ahmedabad in India.

- Long term observation data: Actual traffic data collection comes from 8 months of traffic data observation in 34 traffic monitoring cameras in the city. The pattern of traffic during the 8 months was the same trend by monthly, weekly, and daily

basis, which means the traffic condition is stable under the current condition and it is necessary to change this traffic condition through certain transportation policy;

- Time-based traffic flow analysis: Occupancy provides better traffic congestion condition than the traffic volume and speed. There is some unique pattern between occupancy and traffic volume which is defined as the traffic congestion triangle phenomenon. The traffic congestion mechanism was not only caused by heavy traffic volume. There appears to be a special environmental condition in evening traffic congestion;
- Geographic traffic analysis: Traffic congestion in Ahmedabad occurred from 18:00 to 20:00 in the evening near the CCTV No. 2 location by GIS spatial analysis. The area around CCTV No. 2 is a commercial zone with shops, restaurants, and other market place businesses. It is necessary to undertake more investigation about the location and time frame.

From these combination analysis, we achieved identifying the most congested location and traffic condition. This result shows that maximum traffic volume does not always generate traffic congestion. During 8 months of traffic analysis, the area of CCTV No. 2 was seen to be always congested around the 20:00 time frame.

As for future work, it is necessary to find out the reason for a particular area and particular time frame congestion. We expect there are other reasons for Ahmedabad traffic congestion, such as infrastructure issues and parking space. A detailed study will be performed, such as on-site observation at the congested area and congested time. Traffic is not always congested in Ahmedabad, which means there is some solution for the reduction of traffic congestion in future. In addition, there is one more uniqueness of this study based on the PPP business. It is important as a sustainable traffic management system (refer to the Appendix A). This kind of traffic study has the potential for traffic studies in other developing countries. The first Metro in Ahmedabad is currently under development, which will be completed by 2023 and a partial operation has begun. Therefore the effect of public transportation will be considered in future work. It is also worth noting some kind of traffic study in other major cities in India.

This study introduced a new style of traffic congestion analysis in India and we expect that there is potential to have this kind of traffic analysis in other developing countries because of a similar condition and background.

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Informed Consent Statement: This is for studies not involving humans.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

This study began as a joint research between the Japanese and Indian government in 2014 and focused on sustainability for traffic management. In October 2014, we started the project, which was able to provide motorists with real-time traffic information at key decision-making points of their journey through information boards, i.e., “VMSs”, enabling

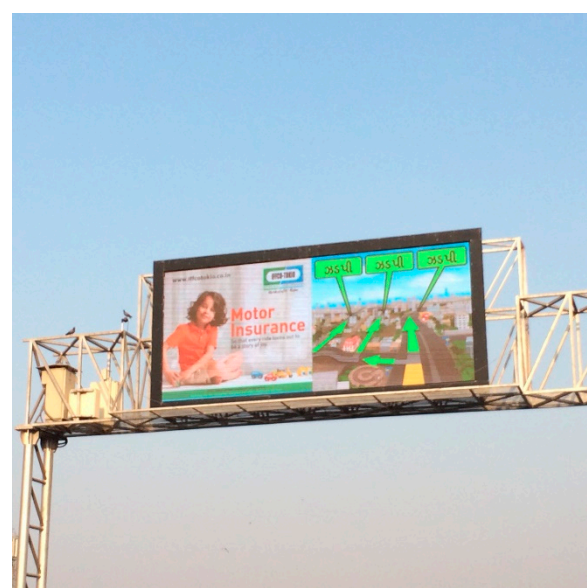
them to choose the best route to their destination, saving both time and money [19]. The information boards showed not only traffic information but also digital ad signage by private companies. The boards will provide both public information (traffic information) and private information (commercial) to motorists. Advertisement revenue from the display of digital ad signage helps cover the maintenance and operation costs of the system. This idea brings smart mobility solutions to address current traffic problems in India and can act as a driver towards implementing a new and sustainable business model for smart cities.

Through this basic public and private partnership or PPP business model, maintenance and operational costs are covered therefore, it is not necessary to obtain extra funding for the maintenance and operation of the solution. One typical VMS in Ahmedabad is shown in Figure A1. The right side of the display shows the traffic condition and the left side shows a commercial.

In terms of traffic congestion, the right side of the display shows the current traffic condition based on traffic occupancy analysis by three levels of congestion condition. When (OC) is less than 10%, the traffic condition is smooth (green arrow symbol in the display). When the OC is between 10% and 20%, the traffic becomes lightly congested (yellow arrow symbol), and when the (OC) is larger than 20%, the traffic becomes heavily congested (red arrow symbol).



(a) VMS examples at CCTV No. 1018



(b) VMS example at CCTV No. 4

Figure A1. Example of variable message sign (VMS) in Ahmedabad city.

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