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Traffic density determination and its applications using smartphone

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Abstract Smartphone is progressively becoming a dominant platform for many transportation applications. This paper introduces a new application for using smartphones to measure traffic density and speed. The proposed system consists of two smartphones and two cars, with observer to count vehicles between the two cars. This count is utilized with tracking data to give "measured" density and "measured" speed. The travel speed and manual traffic counts were used to derive "calculated" density. Measured density was validated against calculated one, and statistical *t*-test confirmed that the mean difference between two densities is not significant at 5% level. Calculated flow rates were also comparable to actual counts, with an average error of 8.2%. The proposed system was then applied to measure density on 6 of October Elevated Road in Egypt, and the level of service was determined accordingly on 15 road sections studied on this road. Furthermore, actual speed-density data were fitted using exponential model with *R*2 of 0.85. Advantages of proposed system qualify it for potential applications in developing countries where available resources limit installation of more costly systems. The application of proposed system is limited to daytime, uninterrupted flow conditions, and traffic streams with less percentage of heavy vehicles.

1. Introduction

Traffic density is a fundamental macroscopic characteristic of traffic flow, and is used in assessing traffic performance from the point of view of users and system operators. It is also employed as the primary control variable in freeway control and surveillance systems. The difficulty in measuring density inhibited its general use until the early 1960s, when presence-type detectors were introduced [1]. Density is also an important measure of the quality of traffic flow, as it is a measure of the proximity of other vehicles, a factor which influences freedom to maneuver and the psychological comfort of drivers

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[2]. For these reasons, the Highway Capacity Manual [3] used the traffic density as the primary measure of level of service (LOS) for uninterrupted flow situations.

The measurement and analysis of density characteristics are of particular interest from a historical perspective. The stages of development of density analysis were controlled primarily by measurement techniques. Before the 1950s only photographic techniques were employed. By the early 1960s, three approaches were being undertaken in parallel: calculation of density from input–output counts, calculation of density from measured speed and flow, and measurement of percent occupancy [1]. Video filming has also been used for estimating macroscopic density where exists an elevated vantage point from which the highway section under study can be observed [4]. Recent researches have been directed to automatic extraction of traffic density characteristics from video images using detection and tracking techniques [5,6]. Other non-intrusive systems have also been used to estimate traffic density. These are highlighted in the following paragraphs.

Photographic techniques were first employed, which revealed the importance and significance of density. However, they required considerable planning and time-consuming analysis, and could not be analyzed in real time. One of the first studies reported in the literature was published in 1928 and was an aerial photographic study of traffic density along the Baltimore–Washington highway [7]. Extensive aerial photographic studies were undertaken in the early 1960s in several cities in USA [8], and resulted in the development of density contour maps.

The input–output count technique is a rather straightforward approach in concept in which an initial count is made of the number of vehicles along the roadway between two count stations, and over time the number of vehicles entering the section is continuously added and the number of vehicles leaving the section is continuously subtracted from the initial count. The problem in this approach is that section density is calculated on the basis of the difference between two large numbers (input and output counts), and detector errors (even minor) cannot be tolerated without frequent re-initialization [1]. A unique input–output count algorithm for determining density was developed by the Port of New York Authority in the 1960s in the Lincoln and Holland Tunnels [9]. Similar input–output technique was executed using automatic Metro Count devices at the beginning and end of a road section [10].

A third technique is to calculate density from speed and flow measurements. This calculation technique requires two detectors, count and speed or two closely spaced detectors with software to convert elapsed travel time to speed. The density can then be calculated as the division of flow by speed. One problem with this approach is that it uses the time-mean-speed at this measurement station instead of the space-mean-speed [1].

The most significant advance in the measurement and analysis of density, however, was due to the development of presence-type detectors and the processing of signal pulses to compute percent occupancy in the early 1960s [11]. Occupancy is defined as the proportion of time that a detector is "occupied," or covered, by a vehicle in a defined time period. The lengths of the average vehicle and the detector are needed to compute occupancy [2]. The widespread use of presence-type detectors and percent occupancy calculations has led to numerous new applications.

Although the inductive loop technique used for density measurement is not affected by weather and light conditions, it suffers from high installation and maintenance costs [12,13]. In order to overcome this limitation, vehicle tracking using image processing techniques has been adopted in traffic monitoring systems to give traffic parameters including traffic count, speed, density, vehicle classification, and incident detection [12,13]. Nowadays, detection and tracking of moving objects are becoming more essential to traffic engineers. Although all detector technologies and particular devices have certain limitations and/or capabilities, only microwave radar, active infrared, and video image processing (VIP) systems are capable of supporting multiple lane and multiple detection zone applications [14]. In comparison with all other technologies, VIP system is considered the best in terms of installation, maintenance, and future upgrade. Moreover, this technology allows users to check visually the results by watching videos previously recorded [5].

The VIP system requires higher mounting camera position allowing for better angle and wider view of lanes on the road. Lower mounting heights would not provide effective images as some vehicles may hide behind others. In this case, the video image processing recognizes overlapped vehicles as single objects [15]. There are also concerns regarding accuracy of VIP results when processing video images with lane changes, light variation, shadows, vibration due to wind, and/or trucks that obscure full view of vehicles [5].

The Global Positioning System (GPS) receivers have been used in many applications such as spot speed and travel speed measurements. In one of these applications, field measurements were used to analyze the location error of moving GPS receivers [16]. This error was reported to vary from 2 m in an open square to 15 m in wide streets with four story houses on both sides. The location error was analyzed into two components; longitudinal and orthogonal errors. The orthogonal (or lateral) error component constituted the major part of the total error in location. A similar study was conducted using smartphones to measure the vehicle speeds. The speed determined using smartphones was validated using radar measurements and achieved acceptable accuracy [17].

This paper presents an approach for utilization of Smartphone in measuring temporal and spatial macroscopic traffic density on road network. This approach is tested on a simple road section and then applied to a longer road corridor. In this approach, traffic density is measured using available features of handy smartphones including GPS sensor and mobile applications. Traffic data utilized in the proposed application are collected using two smartphones; each one is provided in a moving test car. In addition, the vehicles between the two test cars are counted by an observer sitting in the lag car. Measured traffic density is verified by other means to check the reliability of the proposed application. A comparison is also established between the measured and calculated densities from measured flow and travel speed. Results, applications, and general findings are presented throughout this paper.

2. Proposed technique

The proposed system consists of two moving cars, namely, lead and lag cars. Each car is provided with a Smartphone, with synchronized timing of both smartphones. Both cars move in the traffic flow within variable distance from each other according to traffic condition in such a way to maintain the lead car visible to the lag one. The observer in the lag car shall view the road segment in front up to the lead car and count all vehicles occupying the road between the two moving cars. The observer shall record the number together with the time on a tablet that is synchronized with smartphones. The length of the road segment corresponding to observer's counts can be obtained from the tracking data of smartphones. The traffic density is then calculated for each recorded count by dividing the vehicle count by the corresponding segment length. This survey is conducted along the selected road sections at least twice per hour. Tracking data for the lead car shall be used to compute the measured travel speed. Traffic flow shall be calculated by multiplying the measured density by the measured travel speed. Data collection and analysis for a simple example will be illustrated in detail in Sections 3 and 4. Furthermore, some applications for the proposed methodology are demonstrated in Section 5.

3. Data collection procedure

3.1. Selected site for traffic surveys

The traffic survey was performed on Al Ferdous Flyover, which is a 4-lane two-way bridge along Salah Salem Arterial Street in Cairo, Egypt. The survey was carried out in both directions, namely, "To Azhar" and "To Abasia" for 3 h. The flyover including approaches is about 500 m, and traffic flow is considered uninterrupted. Fig. 1 depicts the location of this site on satellite imagery.

3.2. Setup and preparation of smartphones

- The tracking application "My Track" was installed on both smartphones used in the survey and the settings were unified to record data every one second. This application has the advantage to export tracking data into an external data file.
- The tracking application was synchronized with Google maps to record coordinates that are compatible with Google maps for easy presentation on Google Earth and comparison with the road section alignment.
- The tracking application was setup on both smartphones to ensure the same recording time interval and allowable recording accuracy.
- The timer of both smartphones was synchronized up to one second accuracy.
- The time error between the two smartphones was calibrated using the synchronization mobile applications.
- The GPS sensors of both smartphones were turned-on during the whole survey period.

3.3. Test cars used in the survey

Following are the requirements of test cars and training of drivers:

- Two cars with two drivers and one observer sitting in the lag car were used in this survey.
- Two four-wheel-drive (4WD) cars with high cabin were selected for this survey so that each car both can easily be identified to driver of the other car.
- The driver of the lag car was trained to keep enough distance from the lead car while maintaining it visible at all time. The driver was advised to make a lane change, when needed, to avoid for example a vehicle in front obscuring the view of the lead car.
- The lead car moved with the average traffic speed, and both drivers were trained through a pilot survey prior to the start of the actual survey.

3.4. Observer in the lag car

- The observer, sitting in the lag car, was trained to count and record the number of vehicles between the two test cars at any time. The count was made manually by the observer and recorded using a tablet application that features recording time up to 0.01 s.
- Twenty round trips were made along the studied road section. Each car traveled about 7.5 km to make one round trip, covering both directions of the road section. This long travel distance was because U-turns were located far away from the flyover.

3.5. Traffic count on selected section

- The traffic volumes moving in each direction were counted during the survey period. Vehicle count was made for 5-min intervals.
- This vehicle count is not required for Measured density but is used with the travel speeds, obtained from tracking data of smart phones, to derive the Calculated density at any given time.

3.6. Accuracy of location provided by smartphones

The tracking data include longitude and latitude coordinates of the Smartphone. These geographic coordinates are mapped into easting and northing according to the ellipsoid considered in the tracking application. The location accuracy depends mainly on the number of visible satellites as well as their distribution. The location is determined by at least four satellites, while the location accuracy depends on the angles between the lines from the Smartphone to these satellites in which large angles give more accurate location. In addition, extra satellites are used to improve the location accuracy. The accuracy of the smartphones in determining location was evaluated during the survey based on errors reported by each device as part of the tracking data. The mean value of this error for both smartphones ranged between 5 and 15 m. This error was minimized by projecting the vehicle location on the road centerline to eliminate the lateral component of the error, which has been reported to account for most of the location error [16].

3.7. Collected data

The data collected in these surveys consist of the following:

- Data of counted vehicles by the observer sitting in lag car. This data is in the form of observer's counts and time of each count for 40 data points collected during the survey.

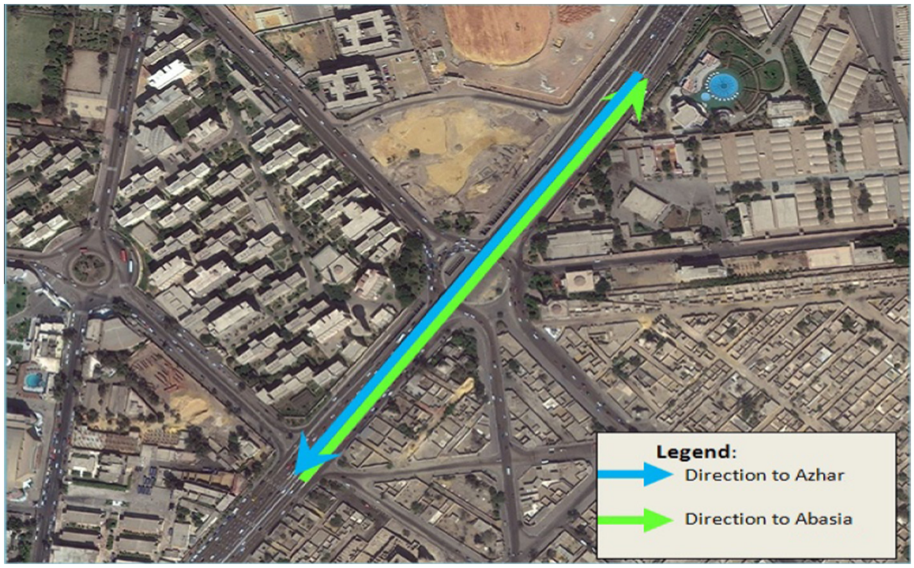

Figure 1 Layout of Al Ferdous Flyover/Salah Salem Road.

- Tracking data of both smartphones for the whole survey period. Each mobile has recorded about 8400 records including the geographic coordinates, location accuracy, spot speed, and the time in 0.01 s tolerance. Table 1 shows a sample of key data records captured by the Smartphone during the survey.
- Traffic volume counts for both directions every 5 min during the survey period for use in validation purposes.

Collected data were analyzed for each direction separately and also combined for overall analysis as presented in the next section.

Table 1 Sample of key records of raw data.

Time	Latitude (deg)	Longitude (deg)	Accuracy (m)	Speed (m/s)
2015-07-24T14:20:00.895Z	30.055006	31.279395	4	12.8945
2015-07-24T14:20:01.853Z	30.055101	31.279472	4	13.0741
2015-07-24T14:20:02.853Z	30.055198	31.279551	4	13.0503
2015-07-24T14:20:03.854Z	30.055293	31.279629	4	13.1131
2015-07-24T14:20:04.851Z	30.055392	31.279714	6	13.3916

4. Data compilation and analysis

4.1. Spatial road segment length

The location of each Smartphone at given time (T_i) was computed from the tracking data of the Smartphone. This location was projected along the road centerline and corresponding station was determined according to the road alignment. The road segment length (L_i) between the two smartphones at time (T_i) was then determined by subtracting the stations corresponding to the two smartphones. This spatial segment length ranged between 30.78 m and 266.26 m, with a mean value of 83.67 m.

4.2. Measured macroscopic traffic density

At first, the segment density (K_i) of a road spatial segment at time (T_i) was calculated using the following equation:

$$K_i = \frac{N_i}{L_i} \tag{1}$$

where variables are as defined earlier.

Second, the section density (K_p) was aggregated for each trip using all densities computed in Eq. (1) for all road spatial segments observed along this trip using the following equation:

$$K_p = \frac{\sum_1^n K_i}{n} \tag{2}$$

where (n) is the number of the observed spatial segments during one trip and K_p is section density for the time of same trip.

Finally, the Measured density for certain time interval (t) was computed by aggregating all section densities within the same time interval as follows:

$$K_M = \frac{\sum_1^m K_p}{m} \tag{3}$$

where (m) is the number of trips covered in the time interval (t) and KM is the Measured section density for the same interval time (t).

It is worth pointing out that all densities presented in Section 4 are the number of vehicles in the two lanes per km. The Measured density obtained from Eq. (3) has a mean and standard deviation of 36.82 veh/km and 12.54 veh/km, respectively. Fig. 2 depicts all measured densities for both directions of the study section.

4.3. Measured travel speed and flow

Beside the measured density, the travel speed was obtained from the same survey measurements.

The tracking data of the lead car Smartphone were analyzed to determine travel distance (L_p) and travel time (T_p) along the road section for each trip. Then, the section travel speed (V_p) is computed using the following equation:

$$V_p = \frac{L_p}{T_p} \tag{4}$$

Furthermore, the measured travel speed (V_M) at certain time interval (t) is computed by aggregating all section travel speeds within the same time interval as follows:

$$V_M = \frac{\sum_1^m V_p}{m} \tag{5}$$

where (m) is the number of trips covered in the time interval (t) and (V_M) is the measured section travel speed for the same interval time (t).

The traffic volume counts made on both directions of the road section were used to give flow rates on each direction. The flow rates were interpolated to give the values corresponding to the same time used for the travel speed. Fig. 3 depicts the measured flow rates and travel speeds. The data presented in this figure show that Direction to Abasia had generally high traffic flow and relatively low speed compared with the other direction; To Azhar.

4.4. Calculated macroscopic traffic density

The "Calculated" density was then computed from flow rate and travel speed using the following equation:

$$K_C = \frac{Q_i}{V_M} \tag{6}$$

where Q_i is the hourly flow rate in vph at specific point of time (i) and the V_M is the average travel speed in km/h at the same point of time. This calculated speed corresponds to the same time used for the measured density. The Calculated density has a mean value of 37.0 veh/km and standard deviation of 7.11 veh/km. These calculated densities are depicted in Fig. 4, which shows a narrow range of the density except for two points on the direction to Abasia.

4.5. Comparison of measured and calculated densities

Table 2 gives a summary of statistical inferences on the measured and calculated densities obtained through the traffic survey, which confirms very close mean values for the two densities. However, the results show that the measured density experiences high range and high variation when compared with its counterparts of the calculated density.

It is worth pointing out that the calculated density (K_C) is considered more accurate because the measured travel speed and volume counts were made with reasonable accuracy. In particular, the travel speed was computed from the tracking data as discussed above. The volume count was also made by trained surveyors assigned to each direction. Thus, the difference between the two densities may be attributed to errors in estimating the Measured density.

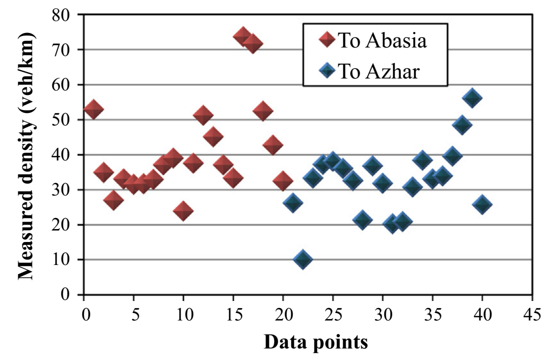

Figure 2 Measured density on both directions.

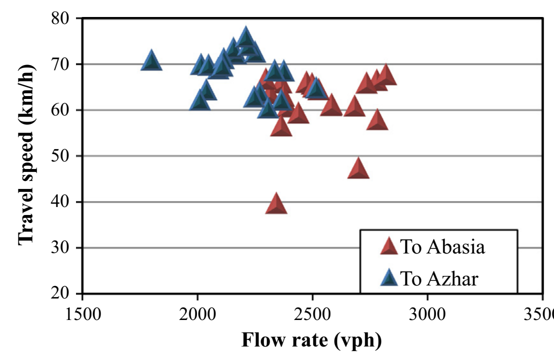

Figure 3 Measured flow rate and speed.

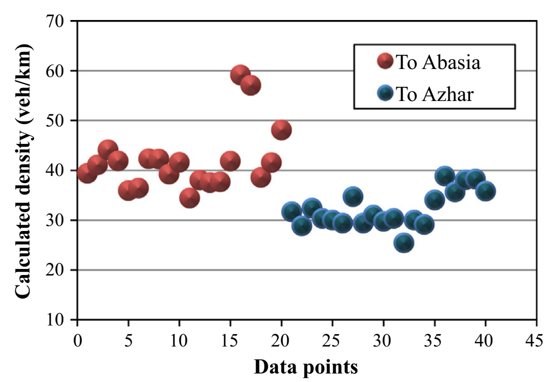

Figure 4 Calculated density for both directions.

Table 2 Descriptive statistics of both types of densities.

Variable	N	Min.	Max.	Mean	Std. dev.	Skewness	
						Statistic	Std. error
Measured density (veh/km)	40	10	73.7	36.8	12.54	1.03	0.374
Calculated density (veh/km)	40	25	59.1	37.0	7.11	1.17	0.374

On the other hand, there is a potential of possible errors that might be encountered while acquiring the measured density (K_M). One source of these errors is the possible error by the observer sitting in the lag car while counting cars between the two test cars. This error can be minimized if the observer was trained to consider fractions of a vehicle when that vehicle is located partially between the two test cars. Another source of the error is the possible error in estimating the length of road segment that corresponds to the counted cars by the observer. This depends on the accuracy of the smartphones in recording the car location in the tracking data. Attempts were made to minimize this type of error by projecting the car locations on the road centerline and measuring the distance between the two cars along the road centerline; hence neglecting error due to lateral position.

This error, however, is not significant since it affects both measured and calculated densities in the same way. This is because the length of road segment is used for estimating measured density and measured travel speed, and the latter is used to compute the calculated density. In other words, an overestimation of the segment length leads to underestimation of measured density and overestimation of travel speed, which in turn leads to underestimation of calculated density (Q_i/V_M).

A comparison of individual values of both densities is also depicted in Fig. 5. The figure shows the line of equality. In addition, a trendline was also generated for zero intercept, which resulted in the following form:

$$K_C = 0.931 K_M \tag{7}$$

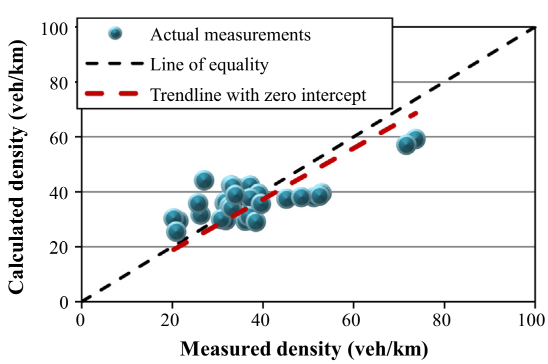

Figure 5 Comparison of measured and calculated densities.

This relationship is very close to the equality line. The comparison in this figure shows that the measured density is relatively less than the calculated one for densities less than 30 veh/km. For densities greater than 50 veh/km, the measured density is relatively higher than calculated density.

4.6. Testing the difference between measured and calculated densities

Although the general comparison in the previous section shows close relationship of both measured and calculated densities, it was necessary to use statistical tests to examine the difference between the two densities. For this purpose, the correlation between both densities was determined as 0.64 confirming the significance of this relationship at the 0.01 level.

The next step was to perform the t-test on two data sets of densities to examine the difference between the mean values of the two densities. The SPSS Package [18] was utilized in this analysis. Results are shown in Table 3.

The t-test confirms that there is no significant difference between the two mean values of measured and calculated densities at the 5% significance level. Furthermore, the 95% confidence intervals established for both density means indicate that the whole range of calculated density overlaps entirely with the limits of the measured density.

In view of the above results, it was concluded that the system of the two smartphones was successfully utilized to measure macroscopic traffic density on the road. The statistical tests confirmed the validation of the density measurements, yielding potential of valuable utilization of measured density in numerous applications as discussed in the following sections. Furthermore, this will also encourage development of further research to expand the scope of this survey and enhance the accuracy of its results.

5. Applications of the proposed technique

5.1. Traffic flow determination

As demonstrated above, the proposed system of two smartphones provides traffic density with reasonable accuracy. In addition, the travel speed is also measured from tracking data. Having both measured density and travel speed, one can easily calculate the flow rate (Q_c) as the multiplication of density and speed. This means that the use of two smartphones and crew of

Table 3 *T*-test for equal means of the two samples.

Criteria	Measured density	Calculated density
Mean	36.82	37.01
Variance	157.15	50.71
Observations	40	40
Lower limit of 95% confidence interval	32.81	34.73
Upper limit of 95% confidence interval	40.83	39.28
Hypothesized mean difference	0	
Degree of freedom	78	
t-Stat	−0.080	
$P\ (T \leqslant t)$ two-tail	0.936	
t Critical two-tail	1.991	

Table 4 Comparison of actual and calculated traffic flow.

Period	Traffic flow rate (v/h)					
	AbasiaDir			AzharDir		
	Q_A	Q_C	Abs. error (%)	Q_A	Q_C	Abs. error (%)
16:30–17:00	2573	2283	11.3	2039	1760	13.7
17:00–17:30	2461	2094	14.9	2187	2269	3.7
17:30–18:00	2535	2501	1.3	2068	1958	5.3
18:00–18:30	2389	2531	5.9	2321	2417	4.1
18:30–19:00	2680	2874	7.2	2297	2636	14.8
Average			8.1			8.3

two drivers and an observer can provide data of, the three main macroscopic parameters of the traffic stream, namely, speed, flow, and density.

As previously explained, the actual flow rate (Q_A) was counted manually in a parallel survey. Table 4 depicts a comparison between the calculated traffic flow Q_c based on the proposed technique and the actual traffic flow Q_A obtained through the manual count.

The error in calculated traffic flow ranges between 1.3% and 15%, with an average value of 8%. This error may be tolerated for many applications, especially in the absence of actual counts.

5.2. Traffic assessment and surveillance

The availability of the main macroscopic traffic parameters is a key element in traffic management and other applications of intelligent transportation systems (ITS). As such, most of traffic operation centers (TOCs) use the speed on road sections to present the traffic conditions and mobility on the road section using certain coloring scheme that shows Red color at very low speeds. Furthermore, the 2010 HCM [3], utilizes the traffic density in determining the level of service (LOS) on road sections of uninterrupted flow conditions. With the current, or most recent, data of any road network available, an appropriate action can be taken to divert traffic in case of an incident occurring on one section of the road network. Hence, the proposed system is a valuable tool for traffic surveillance on small size networks. For small size networks, in the order of 10–20 km long, one crew can cover the network and traffic data become available in less than one hour. For larger scale networks, additional crews can be dispatched to limit the coverage time of the road network to one hour. The processing time of collected data can significantly be reduced if the collected data at site are transferred online to a workstation computer with software prepared to automate all computations and report results. In fact, this is possible nowadays with the amazing applications and communication features of smartphones. In this way, the assessment of traffic conditions on the road network can nearly be achieved online.

The approach described and validated throughout this paper was applied to gather macroscopic traffic data from a major arterial road in Cairo. The collected data through this technique were investigated to see whether it can serve in traffic surveillance and reporting some sort of live traffic reports. This is discussed in detail in the following subsections.

5.2.1. Studied road corridor

The 6 of October Road was selected for this study. It is an elevated road and crosses the Greater Cairo for more than 12 km. This main arterial road is a multilane highway consisting of 2–3 lanes per direction. It runs almost in the east–west direction and connects Cairo Governorate (on eastside) with Giza Governorate (on Westside) across the Nile River. Because it is elevated above the ground, the road is considered full access control with interface with surface road network at entrance and exit ramps. Due to space limitation on Greater Cairo streets, the road and ramp alignments do not have homogeneous or standard geometry. As such, main road experiences some relatively sharp bends, and ramps do not have proper acceleration or deceleration lanes and some are linked to local streets in congested areas. Fig. 6 shows the general layout of this road on Google image.

A segment of about 9 km long of this road was selected for this application. The start and end of this segment are shown in Fig. 6. The segment starts at Al Nasr cross road on the eastside and ends at Abdel Monem Riyad Square on the Westside. Both directions of the road segment were considered in this study. The westbound direction was divided into eight sections whereas the eastbound direction was divided into seven sections. Each section was bounded by the location of an exit or entrance ramp and has a constant number of lanes. The average section length is about 1.2 km, with maximum and minimum values of 2.8 km and 1/4 km, respectively.

5.2.2. Traffic survey for application

The traffic survey was conducted using the proposed methodology to collect traffic data from the mentioned road on Saturday August 8, 2015 between 9:30 am and 12:30 pm. The purpose of this survey was to collect traffic density and speed data for all sections covering the 18-km directional road.

In this survey, two test cars and two smartphones; one in each car, were used. The lag vehicle was also equipped with one tablet. The timers of the two smartphones and tablet were synchronized. A total of 12 trips were carried out during the survey period, covering each direction with 6 trips. The same procedure of data collection presented in this paper was applied in this survey. The total number of observed counts made by the observer during the survey period is 735, with an average time interval of about 15 s.

5.2.3. Summary of collected data

The collected data were utilized to compute the macroscopic traffic density and speed for each road section using the methodology explained earlier in this paper. Data were aggregated for each hour of the survey to represent the average traffic conditions on each section during that hour. Table 5 summarizes the aggregated data for the three hours covered in this survey.

5.2.4. Utilization of collected data in traffic surveillance

The online traffic condition is reported as part of the traffic management system in urban areas. At almost all traffic control centers, this traffic condition is presented live on the road network map using a coloring scheme to differentiate between traffic conditions along the road network segments. The review of real time traffic information provided on road network maps revealed that almost all agencies use the speed,

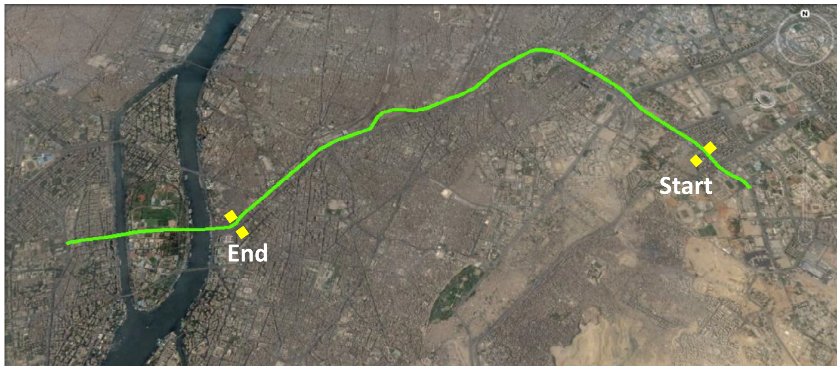

Figure 6 Layout of 6 of October Elevated Road.

Table 5 Average Traffic Conditions during Survey Period.

Road sec.	No. of lanes	Density (veh/km/lane)			Speed (km/h)		
		9:30 am–10:30 am	10:30 am–11:30 am	11:30 am–12:30 pm	9:30 am–10:30 am	10:30 am–11:30 am	11:30 am–12:30 pm
1	2	12.4	12.8	11.4	80.5	73.4	85.5
2	2	12.1	15.8	50.8	73.1	69.4	50.4
3	2	28.1	22.8	39.5	62.2	57.6	48.5
4	3	41.4	59.6	34.3	31.7	25.1	45.1
5	2	17	108.9	32.4	65.5	10	60.1
6	3	21	57.8	39.8	66.7	28.2	54.8
7	3	15.4	56.8	13.1	54.2	40.3	67.3
8	2	21.8	23.1	7.7	63.1	55.6	78.8
9	3	14.4	47.2	67.1	67.6	31.9	22.2
10	2	17.6	22.4	28.5	64.9	55.8	54.1
11	3	18.6	27.8	59.8	64.4	55.2	43.4
12	2	24.5	29.9	48.4	57.8	51.9	45
13	2	26	23	30.2	68.5	66.7	55.8
14	2	19.5	23.7	24.7	66.7	67.5	65.8
15	2	12.6	9.8	16.8	78.7	88.5	76.9

rather than density, to indicate the condition of uninterrupted traffic flow on the road. However, the highway capacity manual (HCM 2010) uses the lane density as the main criteria to determine the level of service (LOS) and hence traffic condition on a given road section. Fig. 7 illustrates the level of service (LOS) on the surveyed road based on the measured lane density as per HCM 2010 [3].

Fig. 7 is very helpful in monitoring the traffic conditions on 15 road sections. Furthermore, traffic conditions can also be represented using traffic speed which is also available from this survey. Although the conditions in Fig. 7 cannot be considered an online report, processing data can be made in parallel to data collection and reports can be made more frequent, say, every 15 or 30 min. Furthermore, the size of road network can be increased by deploying two or more teams to work simultaneously as needed. Reducing data collection and coverage time and increasing the size of road network can serve in establishing a primitive traffic management for simple road networks in developing countries where available funds limit the use of costly management systems.

5.3. Speed–density relationship

As previously pointed out, the traffic density is computed from observed counts collected during the survey, and values are shown in Table 5. The traffic density was found to be in good correlation with the speed and hence either characteristic can be used to describe the traffic condition. The relationship between measured speed and density was modeled using regression analysis and the best fit was achieved using the exponential model given in Eq. (8) and depicted in Fig. 8. The figure also depicts the linear fit which has the form in Eq. (9):

$$V = 93.35e^{-0.0177k} \quad (R2 = 85\%) \tag{8}$$

$$V = 81.32 - 0.7884K \quad (R2 = 81.4\%) \tag{9}$$

As also noted, the exponential model has a better fit to data than the linear model. Furthermore, the free flow speed determined from the exponential model (93.4 km/h) is very reasonable compared with the actual measurements. In

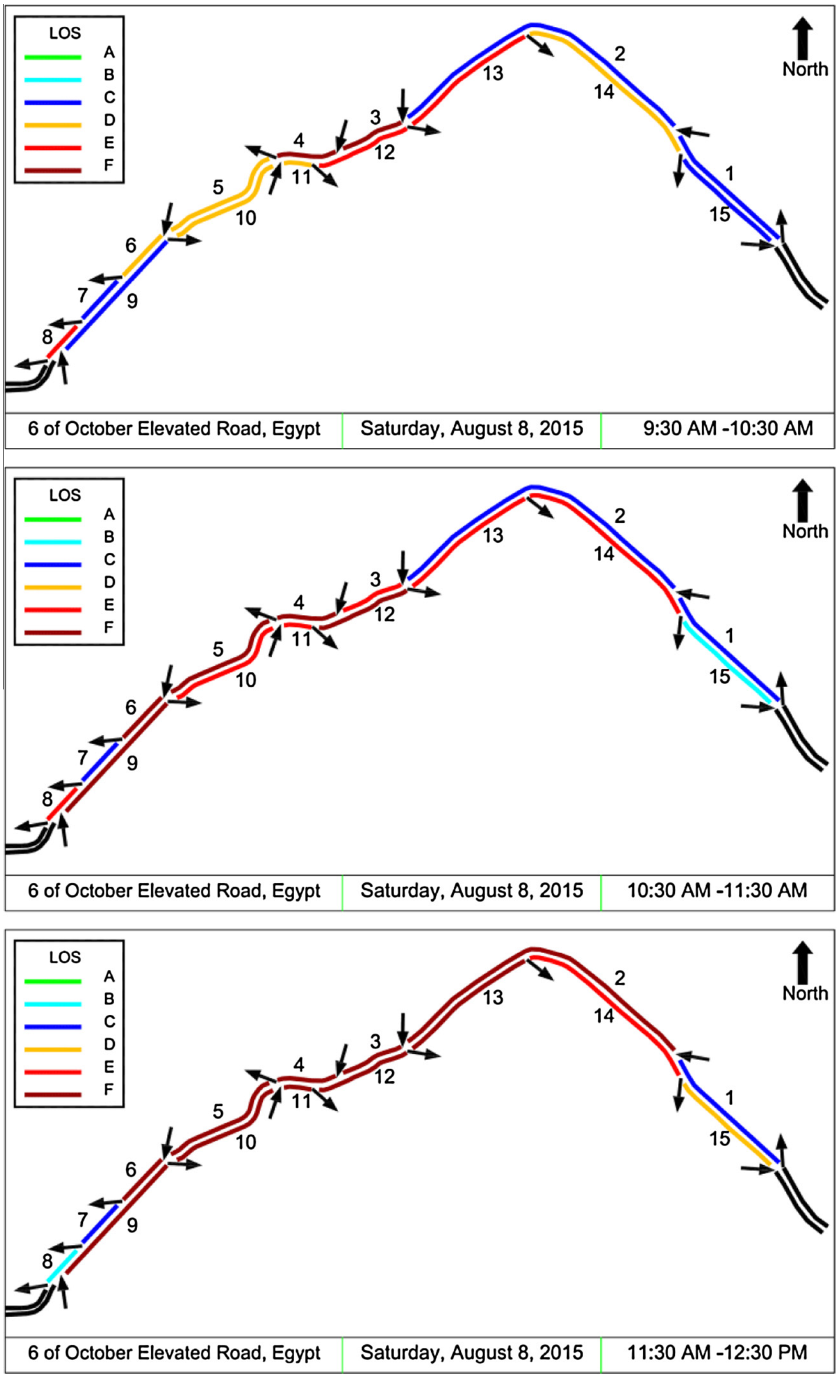

Figure 7 LOS on road sections between 9:30 am and 12:30 pm.

addition, the optimum density obtained from the exponential model is 56.6 (1/0.0177) veh/km/lane, which is close to that obtained from the Greenshield model (51.6 veh/km/lane). The lane capacities obtained from the exponential and linear models are 1944 vph and 2097 vph, respectively. Similarly, the optimum speeds obtained from the two models are 34.3 km/h and 40.6 km/h, respectively.

5.4. Potential applications of the proposed system

In addition to the above-mentioned potential application, the available data on a given road network can be utilized in many aspects such as estimation of fuel consumption, road pricing, road user cost, and planning and feasibility studies of improvements on such road network.

Furthermore, the traffic flows computed for the road network sections can be utilized to generate the origin–destination (O–D) matrix. The review of the literature revealed that there are some techniques that can estimate this O–D matrix from the simultaneous traffic counts such as the T-Flow Fuzzy algorithm adopted in PTV VISUM software [19].

It is worth pointing out that the proposed system devices have low cost (capital, operation, and maintenance) and are portable, and non-intrusive. These facts qualify the system

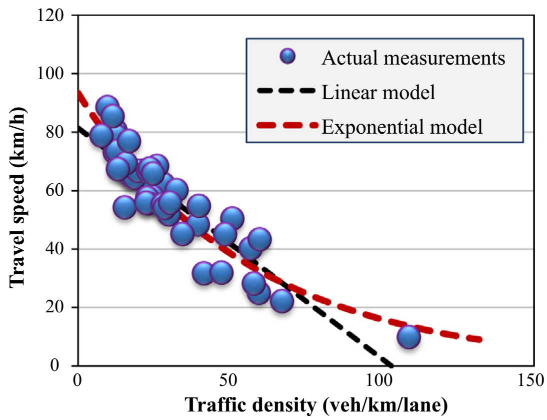

Figure 8 Speed–density relationship.

for potential applications in developing countries where limited resources cannot afford using more costly systems such as inductive loops, smart video cameras, and other non-intrusive devices.

6. Suggestions for future enhancement

Following are some suggestions that may be considered in further research for improving the efficiency and accuracy of the proposed technique:

- Mobile application can be used to send real-time data from the two smartphones and tablet to an equipped laboratory where traffic flow characteristics can be obtained online.
- Mobile video applications can be used in recording the traffic stream between the two test cars. This will facilitate the counting process and improve the accuracy of density measurements.
- The number of vehicles between the two test cars can be counted manually by replaying the video film or using video image processing applications.

7. Limitations of the proposed technique

The application of the proposed system with its current setup is limited to situations of low percentages of heavy vehicles and buses. This is because such vehicles may block the scene in front of the observer sitting in the lag car, which may result in errors in counting the number of vehicles on the road between the two test cars. The application is also limited to the daytime and also in nighttime situation with proper street lighting. The system was tested on multi-lane road of 2 lanes per direction, and, hence, its application may not be generalized for wider carriageways without further verification. Finally, the system was validated for uninterrupted flow conditions and, therefore, cannot be applied to intersections or other interrupted flow conditions without further validation.

8. Conclusions and recommendations for future work

A new technique is proposed in this paper to utilize capabilities of smartphones and measure actual densities on road segments. The proposed system consists of two smartphones, two test cars, and an observer to count the vehicles lying between the two test cars. The measured densities were validated against densities calculated from travel speeds and counted flows. Statistical *t*-tests on the means of the two densities confirmed that there is no significant difference between both means at the 5% significance level. In addition, the traffic flow rate can also be calculated using the measured density and travel speed and then compared with actual vehicle counts. The error in calculated traffic flow ranges between 1.3% and 15%, with an average value of 8%. This error may be accepted in many applications, especially when actual counts are not available.

On the other hand, the proposed methodology was applied to assess the dynamic traffic condition for a long road consisting of 15 sections. Furthermore, speed-density relationship of data collected on this long road was obtained at 0.85 coefficient of determination.

The fact that the proposed system is of low cost (capital, operation, and maintenance), portable, and non-intrusive qualifies its potential applications in developing countries where available resources do not allow for using more costly systems such as inductive loops, smart video cameras, and other non-intrusive devices. Furthermore, the system has the advantage of being flexible for possible upgrade in future to cope with advanced mobile applications and video image processing tools. On the other hand, the proposed system in its current setup is limited to traffic streams of low percentage of heavy vehicles and also to daytime or to nighttime of proper street lighting. The proposed system applications are also limited to uninterrupted flow conditions on multilane roads. Issues related to possible enhancement of the proposed system were addressed in this paper and relevant suggestions were highlighted.

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