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Full Length Article

Vision-based investigation of road traffic and violations at urban roundabout in India using UAV video: A case study

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ABSTRACT

In the past decade, the number of vehicles in India has increased exponentially; however, road infrastructure has not scaled proportionately. As a result, road traffic problems such as congestion on urban roads, dangerous traffic violations, and road accidents have increased significantly. Due to limited road infrastructure, traffic violations (human errors) have intensified in densely populated urban areas. This paper presents a case study (at a multi-lane urban roundabout in Ahmedabad city, India) and the methodology based on computer vision to investigate road traffic and violations using drone/UAV-based aerial video. You Only Look Once-YOLOv7 is used for vehicle detection, and Simple Online and Real Time Tracking-SORT for tracking vehicles. Our methodology divides the road scene (roundabout) into certain zones. We then formulated the dictionary, which maps the traffic violations under Motor Vehicle Driving Regulations - MVDR/ Motor Vehicle Act - MVA and the movement of the vehicle (zone traversal sequences). Using the zone-based methodology, we could also probe other road traffic data such as the count of vehicles, speed of vehicles, rate of traffic flow, and congestion. Based on our results, we also infer some of the possible causes of traffic violations in terms of problems/limitations of road infrastructure. As per our analysis, around 23.26% of vehicles committed traffic violations. We detected traffic violations related to lane indiscipline, driving against the authorized flow of traffic, parking violations, and over-speeding within the roundabout. Our methodology of investigating road traffic and violations can be used for road infrastructure improvement, law enforcement drives, and policy making, for road traffic safety, in developing and densely populated countries.

1. Introduction

India is a developing, densely populated country with a literacy rate of 77.7% [1]. The road infrastructure in India has improved in the past decade but has not scaled proportionately to match the exponential rise in vehicles and urbanization [2,3]. Road traffic and accidents have increased, so the governance procedure for obtaining a driving license in India should be more efficient at imparting proper knowledge of driving regulations [4,5]. In addition, India's socio-cultural values and socio-economic conditions are inherent "factors that influence a driver's knowledge, reaction, and practice" [6–8]. These factors combined have led to several issues related to road traffic safety, such as reduced perception of risk [9], aberrant and unnecessary movement of vehicles [10], nonchalant attitude towards other road users, lack of necessary attention towards conditions of road infrastructure, ignoring and avoiding safety measures, competitive driving (where a driver "competes for time and space on the road") and aggressive driving [11].

More than 1.5 lakh people died, and nearly 3.8 lakh people were injured in road accidents in India, as per the 2021 annual report of the Ministry of Road Transport and Highways (MoRTH), Government of India (GoI) [12,13]. The major causes of road accidents in India have been broadly categorized as human error (leading to traffic violations), conditions of road infrastructure, and vehicular condition [12]. Most accidents occurred on urban roads. "Over-speeding", "driving on wrong side" and "lane indiscipline" are the major three causes of road accidents [12], based on the movement of vehicles. Driving on "wrong side" [12, 14] or "wrong way" [15], means "driving a vehicle against the authorized flow of traffic" [16].

Contributions of various causes of road accidents in Ahmedabad city, India are shown in Fig. 1 as per state government accident investigation report [17]. As shown in Fig. 1, the major causes of road accidents are human error (46%) and the combined effect of human error and road

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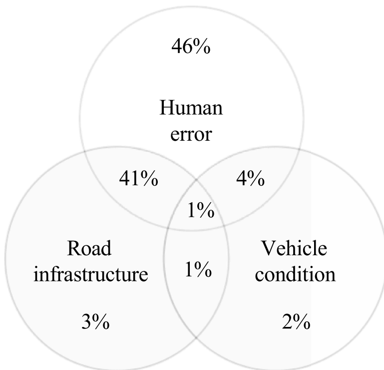


Fig. 1. Contributions of various causes in road accidents (Ahmedabad city, Gujarat, India) [17].

infrastructure (41%), which warrant further investigation.

Lane indiscipline, is also considered the leading cause of traffic bottlenecks and congestion in urban areas [18–24]. The term "lane indiscipline" represents a wide variety of incorrect driving practices pertaining to lanes, such as incessant lane change, lane swerving (abrupt lane change), driving between two lanes (squeezing between two lanes and driving on lane markings), not following the lane designated for certain class of vehicle, not following the speed limit designated for certain lane, driving slowly in rightmost lane on highways, not following the directional arrow markings, changing lane while passing through road junction, not following designated paths at roundabout [20, 25–31]. According to MoRTH [12], the top four vulnerable road users (in terms of involvement in accidents or deaths) are two- wheelers, cars/taxis/vans, pedestrians, and trucks, in that order.

Above discussed causes of road accidents and problems of road traffic are also prevalent in other developing and densely populated countries (Pakistan, Bangladesh, Nepal, and Srilanka) of the Indian subcontinent [32,33]. Hence, the work discussed in this paper easily applies to these countries. To reduce road accidents, the government of these countries focuses mainly on the following objectives for road traffic safety [32,33]:

- Obj1 Improving traffic monitoring and management [34,35].
- Obj2 Public awareness campaigns on road safety [36].
- Obj3 Investigation of road accidents [17,37].
- Obj4 Improving road infrastructure through road safety audit [15, 38,39] and road assessment programme for star ratings [40,41].
- Obj5 Localized short duration traffic law enforcement drives [42–44].
- Obj6 Amendment to transportation and urban development policies [16,45–48].

The GoI has defined the rules and regulations for driving a vehicle (for creating a "careful and competent driver" [16]), known as the Motor Vehicle Driving Regulations (MVDR) [49], listed under section 118, of Chapter VIII Control of Traffic, of the Motor Vehicles Act (MVA) 1988 (amendment 2019) [16,50]. Other sections under Chapter VIII of the MVA provide rules and regulations regarding speed limits, parking/-stopping, and obeying traffic signs/signals/instructions.

Traffic Management and Information Control Centre (TMICC) (also called Transportation Management Centres (TMC) in other countries) [34,35,45] act as the nerve centre of the transportation management system and are typically involved with several activities such as a collection of traffic data (speed, traffic volume, traffic violations).

CCTV (Closed-Circuit TeleVision) cameras play vital roles in video surveillance [51], and the majority of Indian state governments use CCTV for traffic surveillance (provision under section 136A(2) of MVA [16]), to detect red light jumping, stop line violations, and over-speeding [52–56]. These camera-based systems have several limitations: occluded view, limited area coverage, focused angled view, and limited capability to track vehicles across the complete road junction (from approach/entry point to exit point). Global Positioning System (GPS) is an alternative (non vision-based) solution for obtaining trajectories of vehicles [57–61], but there are issues such as, limited ground level visibility and coverage, limited vehicles with GPS facility in developing countries [62], and an inability to cover road infrastructure [63,64]. Due to these limitations, we are not using GPS-based trajectories for our traffic investigation.

Nowadays, Unmanned Aerial Vehicles (UAVs), especially multi-rotor drones with steady hoovering capability and stabilized 3-axis gimbal-based high-resolution cameras, are also used in video surveillance [51], traffic monitoring and management, road safety, and parking management [65,66]. Drones can provide a bird eye view, increasing the coverage area by ten folds when compared to CCTV, thus providing traffic information in multiple travel directions at the same time [65, 66].

In summary, drone/UAV [65,66] is a better option than CCTV to study the causes of road accidents (human error, road infrastructure, and the combined effect of both) [17]. Data collection through drones allows us to observe the movement of the vehicles (i.e., the tracks or trajectories of the vehicles) across the complete road junction and analyse road traffic data. Further analysis of such data can be useful [65, 66] for Obj1, Obj3, and Obj4.

This paper presents a case study and the methodology based on computer vision to study human error (traffic violations based on vehicular movement) and the combined effect of human error and road infrastructure (to infer problems or limitations). This case study is based on aerial videos (collected using a drone) of road traffic at a multi-lane urban roundabout in Ahmedabad, India. Our contributions are as mentioned below:

- Augmented the taxonomy of vision-based road traffic monitoring system, to include attributes related to traffic data analysis and violations (helps in Obj1).
  - Presented literature survey based on the attributes of augmented taxonomy.
- Proposed zone-based methodology for investigating road traffic and violations (helps in Obj1, Obj4, Obj5, and Obj6).
  - Leveraged drone technology (collected road traffic videos of a multi-lane urban roundabout).
  - Applied computer vision techniques for road users detection and tracking.
  - Formulated zone-based dictionary, which is the mapping between the traffic violations (sections of the MVDR/MVA) and the movement of the vehicle (zone traversal sequences); The dictionary is scalable and can be generalized/customized to other road junctions.
  - Codify and automate detection of traffic violations; Probe macroscopic road traffic data, identify possible causes for traffic congestion, and infer problems or limitations of road infrastructure.
- Provided suggestions for transportation and urban development policies (helps in Obj6).

The rest of the paper is organized as follows. Literature survey is presented in Section 2. Our methodology is de- scribed in Section 3. Results are discussed in Section 4. Section 5 concludes the paper. Future work is discussed in Section 6.

2. Literature survey

The basic taxonomy (tree-structure) for drone-based traffic monitoring is provided in [67]. Based on [67], we provide an expanded/augmented taxonomy more suitable for vision-based (CCTV and drone) traffic monitoring system as shown in Fig. 2. We have added several attributes related to traffic flow analysis and traffic violations (based on our work), and road safety (derived from [66]). In Fig. 2, augmented attributes are highlighted in bold. The attributes relevant to our research work are data collection (UAV), site selection (multi-lane urban roundabout), processing on (recorded video), and tasks/analysis (detection, tracking, counting, traffic flow analysis, traffic violations).

We surveyed various vision-based research papers for road traffic monitoring and organised them into Table 1 based on the augmented taxonomy (refer Fig. 2). We now discuss Table 1 for the Indian subcontinent: ***Site:*** Majority research work is done for urban roads [68–75], but very less for road junctions. ***Computer vision techniques:*** Existing research uses, deep learning methods (mainly You Only Look Once (YOLO) family models) [68,69,71,72,76,77] for vehicle detection, Simple Online and Real Time (SORT) algorithms (SORT and deeep-SORT) [72,78], correlation tracker [76], RootSIFT and Flann index matcher [79], and centroid difference [68,71,72,79] for vehicle tracking. For object (helmet/seatbelt/talking on phone) detection [69,70,72,77,79], SIFT, HOG, Hough transform, and CNN-based models are used. The canny edge algorithm, Hough line transform and CNN-based models [74,77] are used for road marking detection. OCR [72,74,76,77,79] technique is generally used for licence plate detection. ***Modality and Traffic monitoring tasks/analysis:*** Most of the research uses CCTV-based systems [68,70–74,76,77,79] for detecting traffic violations related to safety measures (triple riding, seat belt, usage of phones, helmet) [69-72,77,79], over-speeding [71,76], red light jump [69], driving on wrong way [68,76], parking violations [72,76], solid line [74] and crosswalk [77] violations. Also, some research focuses on traffic data analysis, such as conflict analysis [78], gap acceptance analysis and driving behaviour analysis [73,75,78]. ***Goal:*** Most of the research focuses on traffic law enforcement (using e-challan) [68,70,72,74,76,77,79], through detecting and identifying (using license plate detection) peccant vehicles. Most research focuses on only a few categories of traffic violations; moreover, it does not study the impact of road infrastructure on traffic violations.

On the other hand, in developed countries, CCTV [80–86] and drones [78,87–93] both are used in traffic monitoring. Drones are generally used for road traffic data analysis (speed, density, congestion, flow rate). In contrast, CCTV-based systems are used for traffic violations related to safety measures, parking violations, over-speeding, red light jump, driving on wrong-way, wrong U-turn, solid line and crosswalk violation. Also, the variety of traffic violations occurring at road junctions in developed countries is much smaller than those in developing countries. Moreover, research in developed countries focuses more on road safety and policy making. Based on Table 1, we now summarize the shortcomings of the existing vision-based research work done in the Indian subcontinent as below:

- Have not explored traffic violations based on movement of vehicle [16,49], especially for road junctions.
- Have not established and studied the relationship/mapping between the movement of the vehicle and MVDR/MVA.
- Have not studied the combined effect of human error (traffic violations) and (infer problems or limitations related to) road infrastructure.
- Have not leveraged latest electronic technology [16] (drone) for traffic monitoring.
- Have not appropriately identified and provided suggestions for government policies.

We have addressed some of the above-mentioned shortcomings in our proposed work. The focus areas and attributes of our proposed work on road traffic investigation based on drone videos are shown with a tick mark(✓) in Table 1.

3. Proposed methodology

This section discusses the proposed methodology for road traffic investigation using drone-based aerial imagery. We have shown various steps/modules of our methodology in Fig. 3. Traffic video is taken as input, and the vehicle detection module detects all road users/vehicles in each frame. The complete track of each detected vehicle is generated, based on the relevant frames of the video, using the vehicle tracker module. We have divided the road scene(i.e., the multi-lane urban roundabout) into several fixed zones, as shown in Fig. 7. Finally, the traffic violation detection module takes violation dictionary and (zone-based) tracks of the vehicles as inputs, to check for traffic violations. In addition to traffic violations, we also probe traffic data in our work, such as traffic flow rate and speed. In the rest of this section, we describe each module separately.

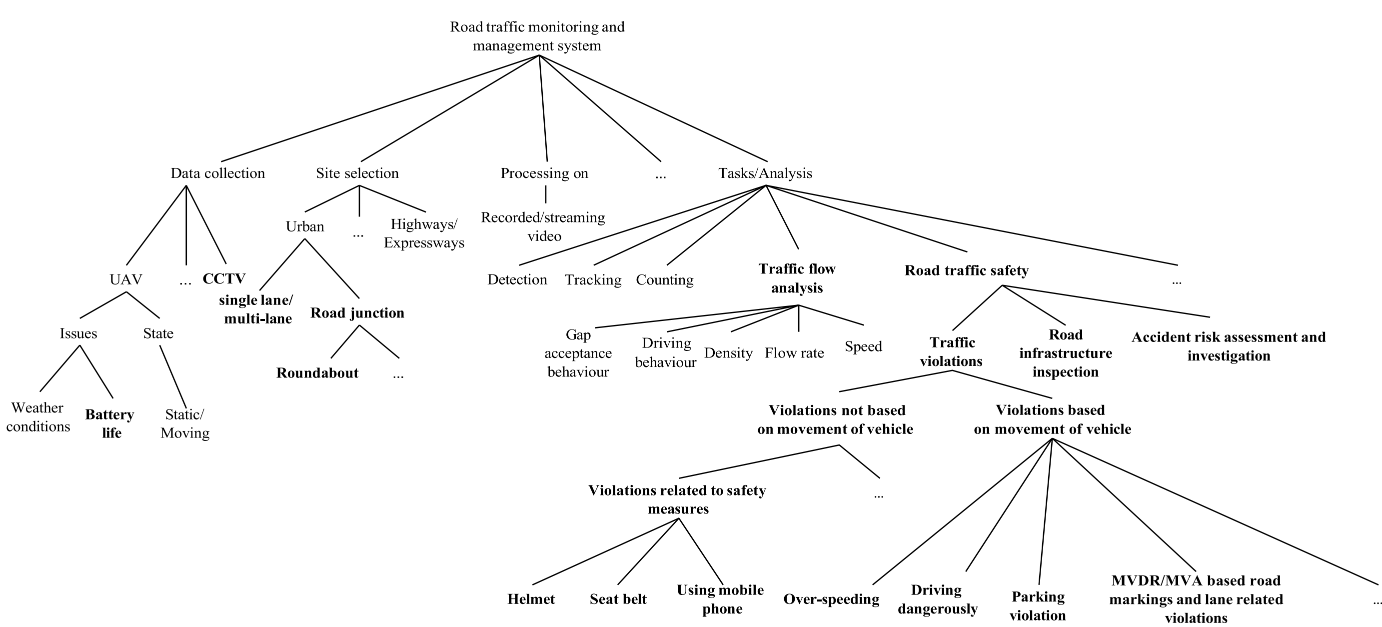


Fig. 2. Augmented(highlighted in bold) taxonomy of road traffic monitoring system.

Table 1
Summary of existing research work on road traffic monitoring using CCTV and drone/UAV(✓are covered in the proposed methodology).

Component	Attributes	References of work done in:				
		India	Bangladesh	Srilanka	Pakistan	Others
Site	Expressway/Highway/Freeway	[78,79]		[76]		[78,80,87,88]
	Urban road	[68–73]	[74]		[75]	[80-85,89-93]
	Intersection	[78]				[78,85,86]
	Roundabout	✓				[91,92]
Dataset used for deep learning model training	Visdrone	✓				
	COCO, VOC, ImageNet, IDD [94], others	[69,71]		[76]		[81,85,90]
	Custom	[70,72,77,78]				[78,80,83,85-89,93]
Trajectories dataset	Custom	[73]			[75]	[91,92]
Computer vision techniques	Vehicle detection	[79,78,68,69,70,71,72,77], ✓		[76]		[78,87,88,89,81,82,84,90,91,93,85,86],
	Object(helmet/seatbelt/talking on phone) detection	[79,69,70,72,77]				[83]
	Road marking detection	[77]	[74]			[81,88]
	License plate detection	[72,77,79]	[74]	[76]		
	Tracking	[68,71,72,78,79], ✓		[76]		[78,83-91,93]
Modality	CCTV/Mounted Camera	[68,70–73,77,79]	[74]	[76]		[80–86]
	Drone camera	[78],✓			[75]	[78,87–93]
Goal	Traffic law enforcement	[68,70,72,77,79], ✓	[74]	[76]		[80,81,84,88,89]
	Road traffic safety	[71–73,77,78],✓			[75]	[78,83,86-88,90-93]
	Policy making	✓			[75]	[85-88,90-93]
Application tested on	Recorded video	[70-73,77,78],✓	[74]	[76]	[75]	[78,80,82-84,86-88,90-93]
	Streaming video	[68,79]				[81,85,89]
System deployed on site	Yes	[68,70,79]	[74]			[81,86,89]
	No	[71–73,77,78],✓		[76]	[75]	[78,80,82-85,87,88,90-93]
Traffic data analysis (using computer vision)	Speed	[78],✓			[75]	[78,85,87,88,90,93]
	Density	✓			[75]	[85,87,88,90,92]
	Volume/Flow rate, Congestion, Capacity	✓			[75]	[86-88,90,91,93]
	Lateral and longitudinal gaps/gap acceptance behaviour	[73]			[75]	[91]
	Others	[73,78]				[78,92]
		Traffic violations not based on movement of vehicle				
Violations related to safety measures	Triple riding(on two-wheeler)	[71,72]				
	Seat belt violation	[69]				
	Usage of phones while driving	[72,79]				
	Helmet violation	[69,70,72,77]				[83,84]
		Traffic violations based on movement of vehicle				
Contravention of the speed limits	Over-speeding*,***	[71],✓		[76]		
Driving dangerously	Wheeling(of two-wheeler)	[72]				
	Red light jump*	[69]				[81]
	Driving on wrong way*	[68],✓		[76]		[80]
	Driving in anti-clockwise direction at roundabout	✓				
Parking violation	Before/After a road junction up to a distance of fifty meters from the edge of the road junction	✓				
	Others	[72]		[76]		[89]
MVDR/MVA based road markings related violations	Solid line violation		[74]			[80]
	Crosswalk violation	[77]				[82]
	Left turn from rightmost lane	✓				
	Right turn from middle lane	✓				
	Left turn from middle lane	✓				
	Right turn from leftmost lane	✓				
	Driving straight from leftmost lane	✓				
	Wrong U-turn	✓				[80]
	Lane indiscipline (Incorrect exit w.r.t designated path as per entry)	✓				
	Driving in wrong lane**	[79]				

* May also be classified as violations of road signs.
** Where a lane is marked specifically for a class of vehicles.
*** Speed within the roundabout.

3.1. Site selection

The proposed research is focused on multi-lane urban roundabouts because the number of accidents, per- sons killed, and persons injured at roundabouts in India have increased by 18.4%, 15.4%, and 20.5% respectively, from 2020 to 2021 [12,95]. Roundabout is a "self-regulatory" road junction [96]. However, the success (self--regulation of traffic) of a roundabout is dependant on the presumption that all vehicles will obey traffic rules and regulations, such as following the directional road markings, give-way or yield to traffic already pre-sent within the roundabout, following designated lanes and paths for making various turns, drive slowly within the roundabout [49,96–100].

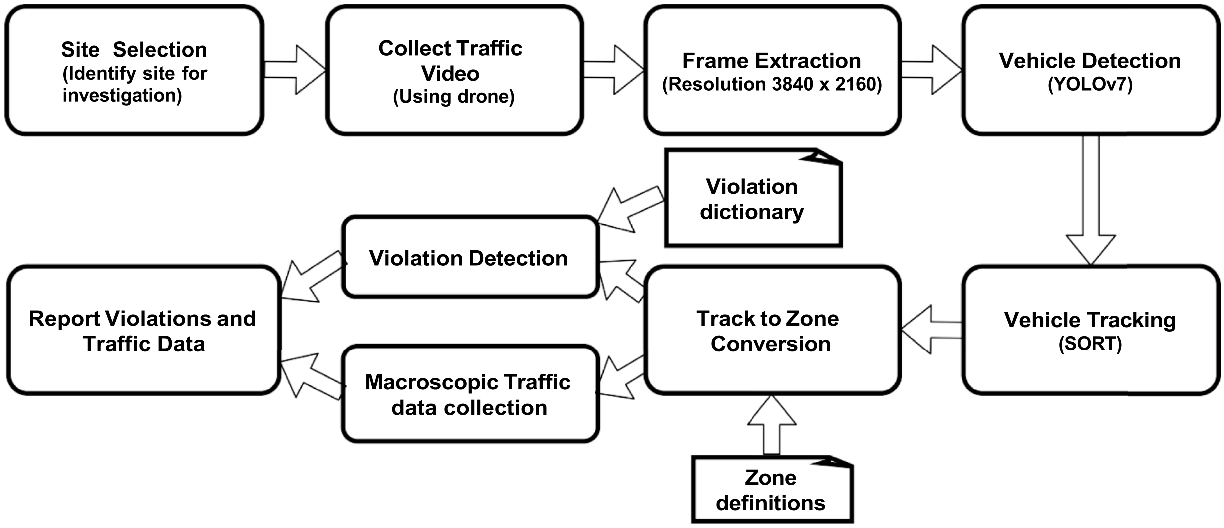


Fig. 3. Steps/modules of our proposed methodology for road traffic investigation.

Hence, a case study of a roundabout would be interesting and more suited to understanding the combined effect of human error (traffic violations) and (infer problems or limitations related to) road infrastructure.

3.2. Aerial imagery

Video surveillance using drones is emerging as the new modality [51], more suited toward understanding the traffic violations of the MVDR, many of which are based on the movement of vehicles at road junction. Hence, we collect road traffic videos (approximately 5 min) using the DJI Mavic 2 Pro-drone (gimbal 90° downwards) at a resolution of 3840 × 2160 pixels, at a multi-lane urban roundabout (lat 23°03′21.2″N, long 72°30′21.6″E), at a flight height of 80 to 85 m, in Ahmedabad city, Gujarat, India. The drone is positioned in such a way that all entry-exit points of the roundabout are visible.

3.3. Vehicle detection

In the proposed methodology, for each frame of the video, we detect all the road users/vehicles on the road. We use Visdrone 2019 [101] dataset to train the object detection model. It contains nearly 6400 images for training and 500 images for validation. Class-wise distribution of the VisDrone 2019 (training) dataset is shown in Fig. 4 (The “motor” class in [101], is referred to as “two-wheeler” in our paper). This is a skewed dataset due to the difference between the number of samples of vehicle classes (refer Fig. 4). Also, some samples have image sizes lesser than 50 × 50 (small pixel footprint) and are referred to as “small objects” [102].

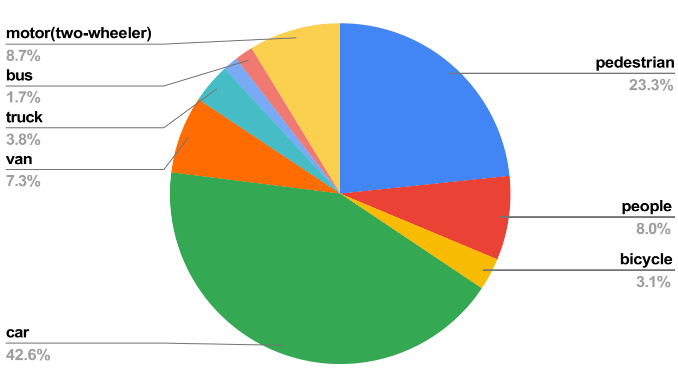


Fig. 4. Train dataset(Visdrone 2019) class-wise distribution.

YOLO is generally used as the object detection model with VisDrone dataset [103]. YOLOv7 uses Extended Efficient Layer Aggregation Networks (E-ELAN), which helps to learn better features [104]. It uses planned re-parameterized convolution, a trainable bag of freebies, to improve model performance. YOLOv7 is a concatenation-based model which concatenates feature maps from different scales and uses adaptive anchor sizes. This improvises small object detection, and hence we have used YOLOv7. We choose the YOLOv7-w6 model and set various hyper-parameters, such as input image size of 1280 × 1280 (a larger input image size helps to improve small object detection), class-agnostic Non-Max Suppression (NMS), and data augmentation (rotation, scaling, translation). Data augmentation helps to balance the training dataset. Class-agnostic NMS selects the best bounding box (with maximum confidence score) for each vehicle, which helps in vehicle tracking. The object detection model is trained on the workstation (Quadro RTX 6000/8000) for 300 epochs and achieves 60% mAP@0.5. Fig. 5 shows the result of object detection using YOLOv7 on one example frame of the video.

3.4. Vehicle tracking

The next step in our proposed methodology is to track each vehicle detected in the previous step. We use SORT [105] algorithm, which is a computationally simple and fast Multi-Object Tracker (MOT) algorithm, which uses the outputs (bounding box of vehicles) of vehicle detection module (see Fig. 3). It has two main components, motion estimation

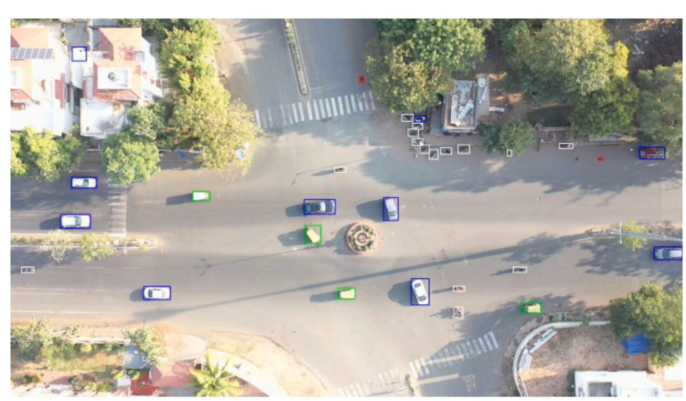


Fig. 5. An example frame showing bounding boxes for the vehicles detected using YOLOv7.

model and data association algorithm. SORT uses the Kalman Filter (KF) [106] for motion estimation and the Hungarian algorithm [107] for data association. KF [106] uses inter-frame displacement to estimate motion of the object. It requires some initial frames (defined by min_ *hits*) to fine-tune the model parameters, such as the central location of the object, aspect ratio, and scale. Intersection over Union (IoU) is used as a cost metric in the Hungarian algorithm [107] for data association (defined by *iou_threshold*). SORT can also keep a track alive to some number of consecutive frames (defined by max_*age*) when detection fails in those frames. Through experiments on our test dataset, we set hyper-parameters of SORT, such as min_*hits*=3, max_*age*=5, and *iou_threshold*=0.3. Fig. 6 shows an example of the track of a car derived using the SORT algorithm.

3.5. Formulation of traffic violations based on the movement of vehicle

According to regulation 40 of the MVDR [49], drivers should know and understand road signs, markings, traffic control signals, and traffic rules and regulations. In this paper, traffic violations are defined as “contravention of any provision/section/rule/regulation” given in Chapter-VIII Control of Traffic, under MVA [16], which includes the MVDR (section 118 of MVA) [49]. In this paper, we are interested in investigating those traffic violations that can be detected using computer vision techniques from drone video.

In transportation engineering, to carry out traffic surveys, the road is generally divided into various regions (zones)/lines [96]. Inspired by that, we have defined certain zones (superimposed on our road scene) near the roundabout, as shown in Fig. 7. The rectangular zones 1 through 24 represent the roundabout’s entry and exit points(or lanes). The rectangular zones, 25 through 28, are used to understand the movement of vehicles within the roundabout. The polygon zones 29 through 35 represent the no-parking zones of the road junction (in our case, the roundabout). The circular zone 36, shown in Fig. 7, is used for speed estimation of vehicles within the roundabout.

These zones must be customized to the specific road scene/segment/junction (visible in the road traffic video) we are investigating. The number of zones needed would depend on the number of lanes, road junction, and the types of traffic violations we want to detect. In our proposed methodology, these zones help define the traffic violations in terms of the zone traversal sequence corresponding to the track of a vehicle (i.e., the sequence of zones that a vehicle crosses when it moves through the round- about). In India, according to IRC:35–2015 manual [100], directional arrow markings should be present on multi-lane urban roads. However, the survey in [3] suggests that road markings are mostly absent/faded at roundabouts in India. In our traffic video, road markings are absent/faded, but we have to assume them for our investigation of traffic violations. In Fig. 7, we have shown the assumed directional arrow markings (superimposed) at all the entry points for a better understanding of lane indiscipline- related violations, as per [100]. Fig. 7 also shows (in green colour) the designated paths (for vehicles entering from the west) that should be followed by the vehicles to avoid bottleneck or congestion. These designated paths originate from the west entry point, and end at either the north exit or east exit or south exit or west exit, depending on the intended movement of the vehicle, left turn, go straight, right turn, U-turn, respectively. These paths provide a better understanding of lane indiscipline related violations. Similarly, designated paths must be assumed from other entry points (north, south, and east).

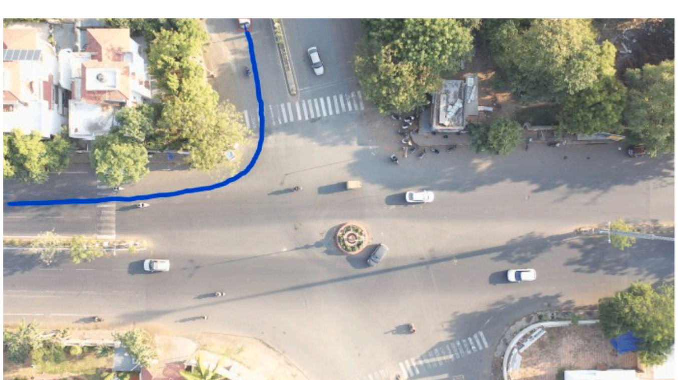


Fig. 6. An example of vehicle tracking using SORT.

In this paper, zones 1 through 24 are also further referred to as rightmost (R), middle (M), and leftmost (L) lanes from the perspective of the designated paths originating from a particular entry point. For example, zones 19, 20, and 21 can also be referred to as rightmost (R), middle (M), and leftmost (L) lanes, respectively, for west entry, and zones 6, 5, and 4 can also be referred to as rightmost (R), middle (M), and leftmost (L) lanes, respectively, for east exit.

Table 2 depicts a dictionary that shows the mapping between the traffic violations (sections of the MVDR/MVA) and the movement of the vehicle (in terms of zone traversal sequences). In Table 2, the dictionary ID is used only as a serial/index number for further discussions in this paper. Other fields of Table 2 are used to provide more details related to the category of violation, a description of the violation, and an exemplar image of the violation (to visualize the movement of the vehicle). For example, the dictionary IDs 86, 87, and 88 are represented as the zone traversal sequences “2,26,27,16/17/18″, are sequences of length = 4, and indicates the traffic violation: taking right turn from middle lane, and either of these sequences, “2,26,27,16″ or “2,26,27,17″ or “2,26,27,18″ indicates this particular traffic violation, corresponding to dictionary IDs 86, 87, and 88, respectively. We have studied various driving manuals [108–111], driving guidelines [97,98,112,113] and, GoI driving rules and regulations [15,16,49] to define traffic violations at a roundabout. Finally, we have compiled 131 different zone traversal sequences, defining various traffic violations in the dictionary. We believe the paper is the first attempt to map, codify and automate the detection of traffic violations as per MVDR/MVA for roundabouts. The dictionary is scalable and can be generalized/customized to other road junctions.

3.6. Detecting traffic violations

For traffic violation detection, our methodology takes the tracks of vehicles and the dictionary of traffic violations act as inputs (see Fig. 3). Each track is converted into corresponding zone traversal sequence based on its IoU[$] with predefined zones. ([$]In the context of this discussion, IoU means non-zero overlap between the predefined zone and bounding box of the vehicle). This zone traversal sequence is matched to zone traversal sequences defined in the dictionary of traffic violations (Ref. Table 2). If any traffic violation is found, it will be reported.

3.7. Probe traffic data

Road traffic data is very important for traffic analyses and is mostly used by government agencies (policy-makers) for urban planning and improvising road infrastructure [34,45]. In addition to traffic violations, our methodology is also capable of probing macroscopic traffic data (based on zones defined in Fig. 7), such as the count of the vehicles, speed of vehicles, and rate of traffic flow. These data are helpful in flow analysis (using Origin-Destination (OD) matrix) and congestion analysis. The method of probing such data is based on the IoU of tracks of vehicles with the corresponding zones (that we wish to study) in the road scene (see Fig. 7).

3.7.1. Traffic data estimation

We have generated the OD matrix data using IoU of zones 1 through 24, with tracks of all the vehicles. We have captured lane usage data using IoU of zones 1 through 24, with tracks of all the vehicles. The rate

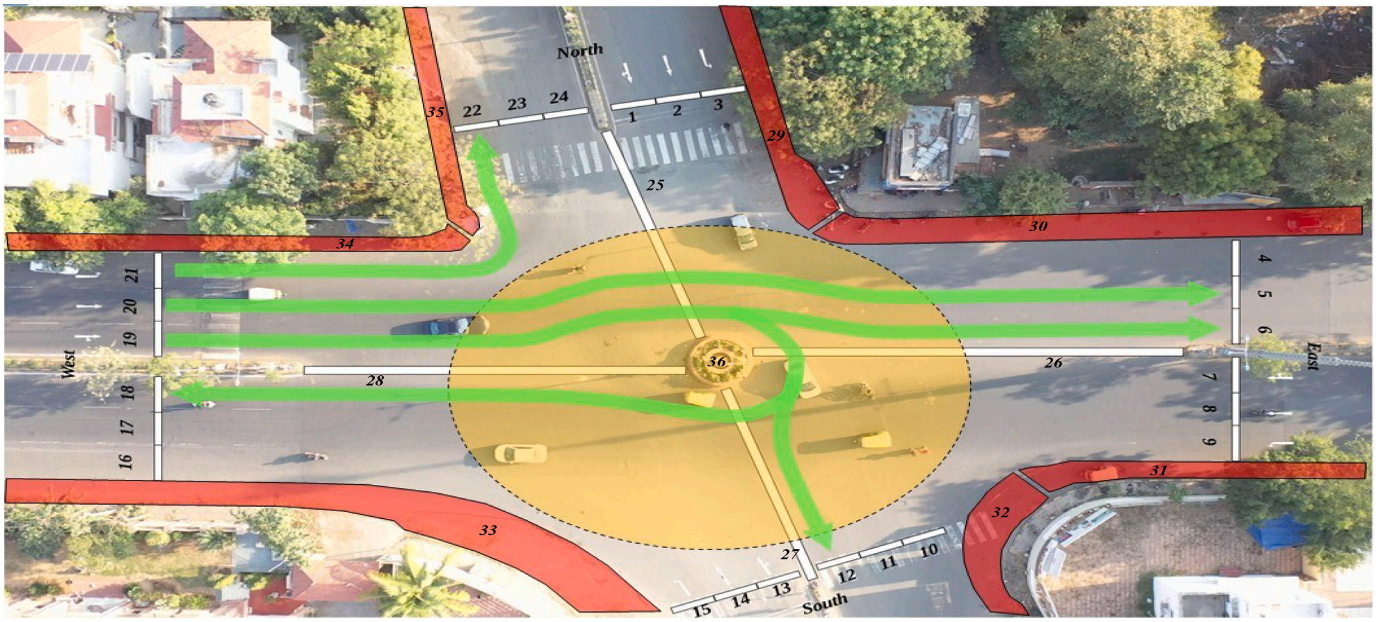


Fig. 7. Road scene with defined zones at every entry-exit point and near a multi-lane urban roundabout.(Best-viewed as colour image).

of the traffic flow at entry points can be captured using IoU of zones 1–3, 7–9, 13–15, and 19–21 with tracks of all the vehicles.

3.7.2. Vehicle speed estimation

Vehicle speed estimation in drone video requires pixel-to-actual distance relationship [114–119], known as Ground Sample Distance (GSD). We use the flight height of the drone and camera sensor size to establish this relationship based on Field Of View (FOV) (see Fig. 8).

GSD is derived as below:

$$GSD = \frac{Sensor\ width \times Flight\ height}{Focal\ length \times Image\ width} \tag{1}$$

In our case, drone *flight height* is in the range of 80 to 85 m and for our drone (DJI Mavic 2 Pro) *sensor width*=13.2 mm, *focal length*=10.3 mm, and *image width*=3840 pixels.

Error in the estimation of size (diagonal length) of various vehicles according to our GSD Eq. (1) is shown in Table 3. When using Eq. (1), for the speed estimation of a vehicle, the error in speed estimation will be significantly less because the movement of a vehicle in two consecutive frames is very small.

A difference in the centroid points (x_i,y_i) of bounding boxes between two frames is calculated for each vehicle. Then, the time (t_i) difference is the reciprocal of frames per second (fps) of video. In our case, the fps is 30. The speed of the vehicle is then estimated using Eqs. (2)–(4).

$$V_x = \frac{(x_2 - x_1) \times GSD}{(t_2 - t_1)} \tag{2}$$

$$V_y = \frac{(y_2 - y_1) \times GSD}{(t_2 - t_1)} \tag{3}$$

$$V = \sqrt{V_x^2 + V_y^2} \tag{4}$$

We are estimating the speed of vehicles (within the roundabout), using IoU of circular zone 36 with tracks of all the vehicles.

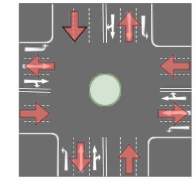
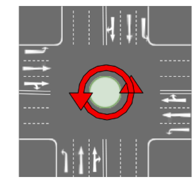
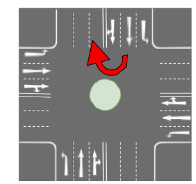
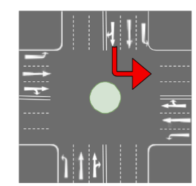
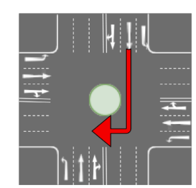
4. Results and discussion

We tested and validated our methodology on the traffic video of a multi-lane urban roundabout in Ahmedabad, India, consisting of 7136 frames (average of 33 objects per frame). We obtained 786 trajectories of road users/vehicles. Class-wise distribution of (786 trajectories) test data is given in Fig. 9, which shows that most of the vehicles in our test data fall under the classes two-wheeler and car.

4.1. Initial observations

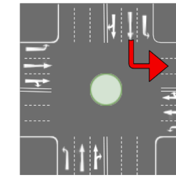
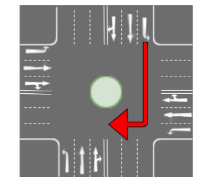
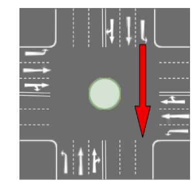
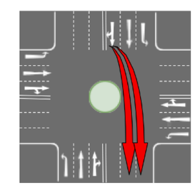
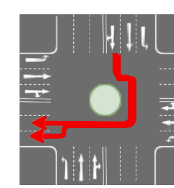
In drone-based aerial imagery, we can observe the entire roundabout (refer Fig. 10). We can easily inspect that road markings are absent/ faded, and splitter islands are absent at every arm of the roundabout. Also, vehicles are parked at the road corners near the roundabout. Note that if we were using CCTV-based imagery, capturing the entire roundabout (i.e., the entire road junction) would have been difficult, as discussed in section 1 of this paper. As per the guidelines IRC:35–2015 [100] and IRC:65–2017 [15], a multi-lane urban roundabout must have longitudinal markings (dotted/solid lane markings), transverse markings (pedestrian crossings and stop line markings), and directional arrow markings. Unfortunately, these markings are faded/absent in our roundabout, and this is a contravention of the “code of practice for road markings” [100] and roundabout design guidelines pre- scribed by the IRC [15]. Refer to annotated Fig. 10, indicating the missing road markings. The survey [3] of urban roundabouts in India also corroborates that road markings are mostly absent/faded. We measured the diameter of the central circular island of our road scene using the *GSD* mapping (derived in section 3.7.2). The measured diameter of the central island turns out to be 4.5 m, which is unfortunately similar to the standard diameter (4 m) of a mini urban roundabout [39]. It is much smaller than the desired standard diameter (at least 25 m) of a multi-lane urban roundabout [39]. This is a contravention of the roundabout design guidelines prescribed by the IRC [15,39]. The current central island of diameter 4.5 m is not suitable for a multi-lane urban roundabout. Also, the absence of splitter islands is contravention of the design guidelines, particularly section 6.4 of the IRC:65–2017 [15]. As per IRC, the absence of splitter islands leads to “dangerous wrong way shortcut right turn movements through the roundabout” [15]. Our results, Fig. 11(a) (driving against the authorized flow of traffic) and Fig. 11(b) (disobeying roundabout), corroborates the same. In summary, we can see several problems/limitations of the road infrastructure under investigation [99].

Table 2
Dictionary of traffic violations based on the movement of the vehicles in terms of zone traversal sequences with examples.

Category	Description	Dictionary ID	Zone traversal seq	Rules and Regulations	Example*
Driving against the authorized flow of the traffic	Wrong way driving	9 10 11 12 13,14,15 16,17,18 19,20,21 22,23,24	16/17/18,X 10/11/12,X 4/5/6,X 22/23/24,X X,19/20/21 X,1/2/3 X,7/8/9 X,13/14/15	MVA Sec. 184(E), MVDR 4(7)	
	Driving in anti-clockwise direction at roundabout	5 6 7 8	X,25,28,X X,28,27,X X,27,26,X X,26,25,X	MVA Sec. 184 (E), MVDR 4(7), Khanna 5.4.2, IRC 65–2017	
	Wrong U-turn	1 2 3 4	1/2/3,25,22/23/24 7/8/9,26,4/5/6 13/14/15,27,10/11/12 19/20/21,28,16/17/18	MVA Sec. 184 (E), MVDR 8(3(D)), MVDR 24(2), MVDR 4(7), Khanna 5.4.2, IRC 65–2017	
Lane indiscipline (Lane violations of directional arrow markings** or Not following designated path as per entry)	Left turn from rightmost lane	65,66,67 80,81,82 95,96,97 110,111,112	19,22/23/24 1,4/5/6 7,10/11/12 13,16/17/18	MVDR 8(1(C)), MVDR 24(2), MVDR 10(2), MVDR 6(1)	
	Right turn from middle lane	71,72,73 86,87,88 101,102,103 116,117,118	20,25,26,10/11/12 2,26,27,16/17/18 8,27,28,22/23/24 14,28,25,4/5/6	MVDR 8(2(C)), MVDR 24(2), MVDR 10(2), MVDR 6(1)	

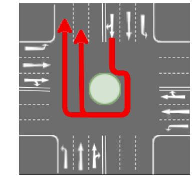
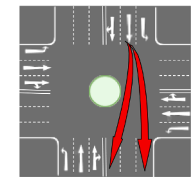
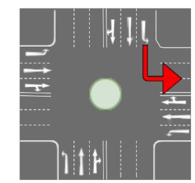
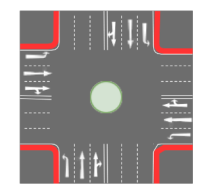
(continued on next page)

Table 2 (*continued*)

Category	Description	Dictionary ID	Zone traversal seq	Rules and Regulations	Example*
	Left turn from middle lane	68,69,70 83,84,85 98,99,100 113,114,115	20,22/23/24 2,4/5/6 8,10/11/12 14,16/17/18	MVDR 8(1(C)), MVDR 24(2), MVDR 10(2), MVDR 6(1)	
	Right turn from leftmost lane	74,75,76 89,90,91 104,105,106 119,120,121	21,25,26,X 3,26,27,X 9,27,28,X 15,28,25,X	MVDR 8(2(C)), MVDR 24(2), MVDR 10(2), MVDR 6(1)	
	Driving straight from leftmost lane	77,78,79 92,93,94 107,108,109 122,123,124	21,25,4/5/6 3,26,10/11/12 9,27,16/17/18 15,28,22/23/24	MVDR 24(2), MVDR 10(2), MVDR 6(1)	
Lane indiscipline (Incorrect exit w.r.t designated path as per entry)	Incorrect(L or M) exit w.r.t designated path as per (R) entry	25,26 35,36 45,46 55,56	19,25,4/5 7,27,17/18 1,26,10/11 13,28,22/23	MVDR 14(5(E)), MVDR 10(2), MVDR 6(1), MVDR 3, ODM 3	
		27,28 37,38 47,48 57,58	19,25,26,10/11 7,27,28,22/23 1,26,27,16/17 13,28,25,4/5		

(*continued on next page*)

Table 2 (*continued*)

Category	Description	Dictionary ID	Zone traversal seq	Rules and Regulations	Example*
		29,30 39,40 49,50 59,60	19,25,26,27,16/17 7,27,28,25,4/5 1,26,27,28,22/23 13,28,25,26,10/11		
	Incorrect(L or R) exit w.r.t designated path as per (M) entry	31,32 41,42 51,52 61,62	20,25,4/6 8,27,16/18 2,26,10/12 14,28,22/24	MVDR 14(5(E)), MVDR 10(2), MVDR 6(1), MVDR 3, ODM 3	
	Incorrect(R or M) exit w.r.t designated path as per (L) entry	33,34 43,44 53,54 63,64	21,23/24 9,11/12 3,5/6 15,17/18	MVDR 14(5(E)), MVDR 10(2), MVDR 6(1), MVDR 3, ODM 3	
Parking violation	Before/After an intersection or a junction up to a distance of fifty meters from the edge of the intersection or junction	125 126 127 128 129 130 131	29 30 31 32 33 34 35	MVDR 22(2(D)), MVDR 22(2(M)), HDM 6.9	

* Example is shown here only for North entry-exit point. It applies to other entry-exit points similarly.
** Road markings are defined in [100]
ODM- Ref. [108], HDM- Ref. [109], IRC 65–2017- Ref. [15], Khanna- Refer [96], MVA- Ref. [16], MVDR- Ref. [49].

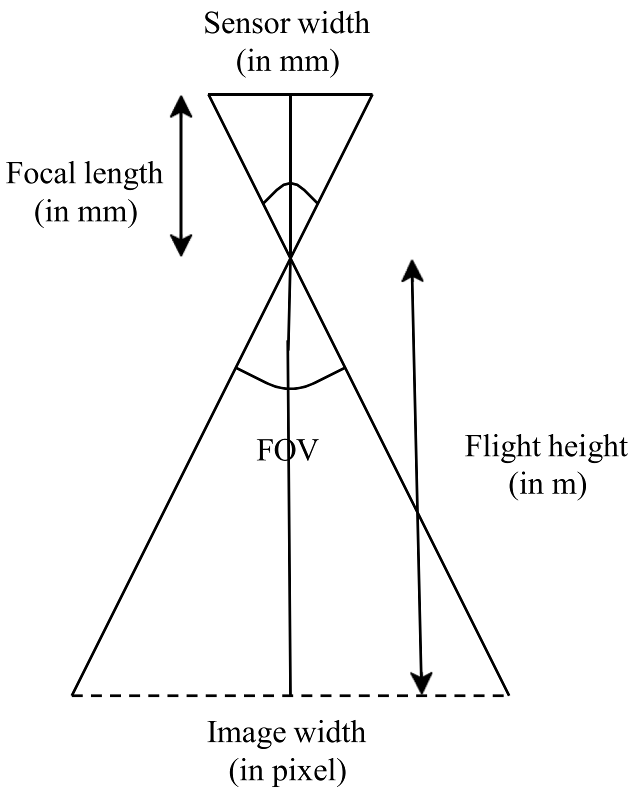


Fig. 8. Field of view of a drone camera.

Table 3
Error in GSD estimation.

Class of vehicle	Actual Size (in cm)	Error (%)
Car	371	6.00
Two-wheeler	223	8.60
Three-wheeler	286	8.44
Mini-bus	583	9.12

4.2. Traffic violations

Our methodology detects 131 (refer Fig. 16) different traffic violations on the test data, which is 16.67% of the total 786 vehicles. Fig. 11 (a) shows an example of a two-wheeler that seems to be going towards the east but takes a U-turn at the east exit and then proceeds towards the south exit. The track of this vehicle has IoU with zones 25, 4, 6, 26, 10, which is detected as dictionary ID 11 (zone traversal sequence 4/5/6, X),

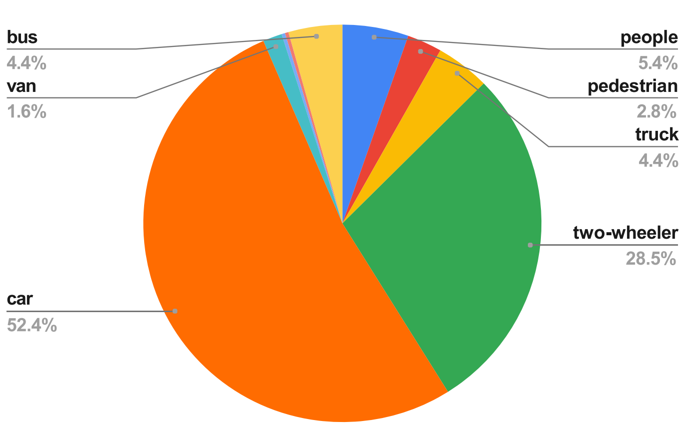


Fig. 9. Test data class-wise distribution.

under violation "Wrong way driving" (Ref. Table 2). Fig. 11(b) shows an example of a car going from the north entry to the west exit. The track of this vehicle has IoU with zones 2, 25, 28, and 18, which is detected as dictionary ID 5 (zone traversal sequence X,25,28,X), under violation "Driving in anti-clockwise direction at the roundabout" (Ref. Table 2). This is due to the absence of splitter islands, which leads to "dangerous wrong way short cut right turn movements through the roundabout" as stated by IRC [15].

Also, it is observed that pedestrians/people are not using zebra crossing (pedestrian crossing) and are instead found walking within the roundabout. For example, in Fig. 12, a pedestrian is seen near the central island (of the roundabout). Also, people are seen walking to/from the grocery store near the northeast corner. In Fig. 16, we can see pedestrian/people under dictionary IDs 9, 10, 17, 19, which means pedestrians are walking dangerously within the roundabout (walking through zones 26 or 27), making them vulnerable to road accidents [12].

The maximum allowable speed of a vehicle within a multi-lane urban roundabout is 40 kmph, as per the design guidelines for urban roundabouts [39]. In Fig. 13, it is observed that 6.6% vehicles (out of the 786 vehicles) are not following the designated speed limit within the roundabout (i.e., within the circular zone 36), which is a traffic violation (section 112 of MVA [16]).

Class-wise traffic violations are shown in Fig. 14. Two- wheelers commit the highest number of traffic violations, and the same is corroborated in the report by MoRTH [12].

Overall category-wise traffic violations are shown in Fig. 15. Majority (74.8%) of the traffic violations are related to lane indiscipline (not following designated paths/not following directional arrow markings), which could lead to traffic congestion [18]. 15.3% of the traffic violations are related to vehicles driven against the authorized flow of the traffic, which is very dangerous and can have serious consequences [14,16,120]. 9.9% of the traffic violations are related to parking violations near the road junction (roundabout).

Fig. 16 shows the count and class of vehicles for the various traffic violations (refer to dictionary IDs in Table 2). More traffic violations correspond to dictionary IDs 32, 25, and 41, which indicates lane indiscipline (Incorrect exit w.r.t designated path as per entry).

Vehicles are parked near the roundabout (within the road junction). This is because of a grocery store in the northeast corner of the roundabout (refer Fig. 19). In the section 4.1, we already discussed that splitter islands are absent; hence, some vehicles are taking the wrong U-turns (refer to dictionary ID 4 in Fig. 16.).

4.3. Traffic data analysis

Our methodology is also capable of probing various traffic data as discussed in section 3.7, such as count of vehicles, lane usage, the speed of vehicles near/within the roundabout, and flow rate. Fig. 17 shows the trajectories of all vehicles.

4.3.1. OD matrix for the roundabout

OD matrix generally represents the count of vehicles that passes from each origin (entry) to destination (exit). OD matrix gives an abstract idea about the traffic flow at the roundabout. We have shown the percentage of flow in each direction in Table 4. In our case, the majority of the traffic moves from the west to the east direction (refer Table 4).

For further analysis related to congestion (as we have observed more violations related to lane indiscipline in section 4.2) in the direction of majority traffic flow, we have shown the lane-wise distribution of traffic in Table 5 (each row of this table represents the traffic distribution of respective lane/zone(R/M/L) of east and west entries). We observed that for west entry, out of the total vehicles entering from (R) entry (lane/zone 19), **42.86%** vehicles are exited in (R) exit (lane/zone 6) of the east (means they are driving in their designated path), but **35.71%** vehicles exited in (M) exit (lane/zone 5) (means they deviated from their designated path), which indirectly forces vehicles entering from (M)

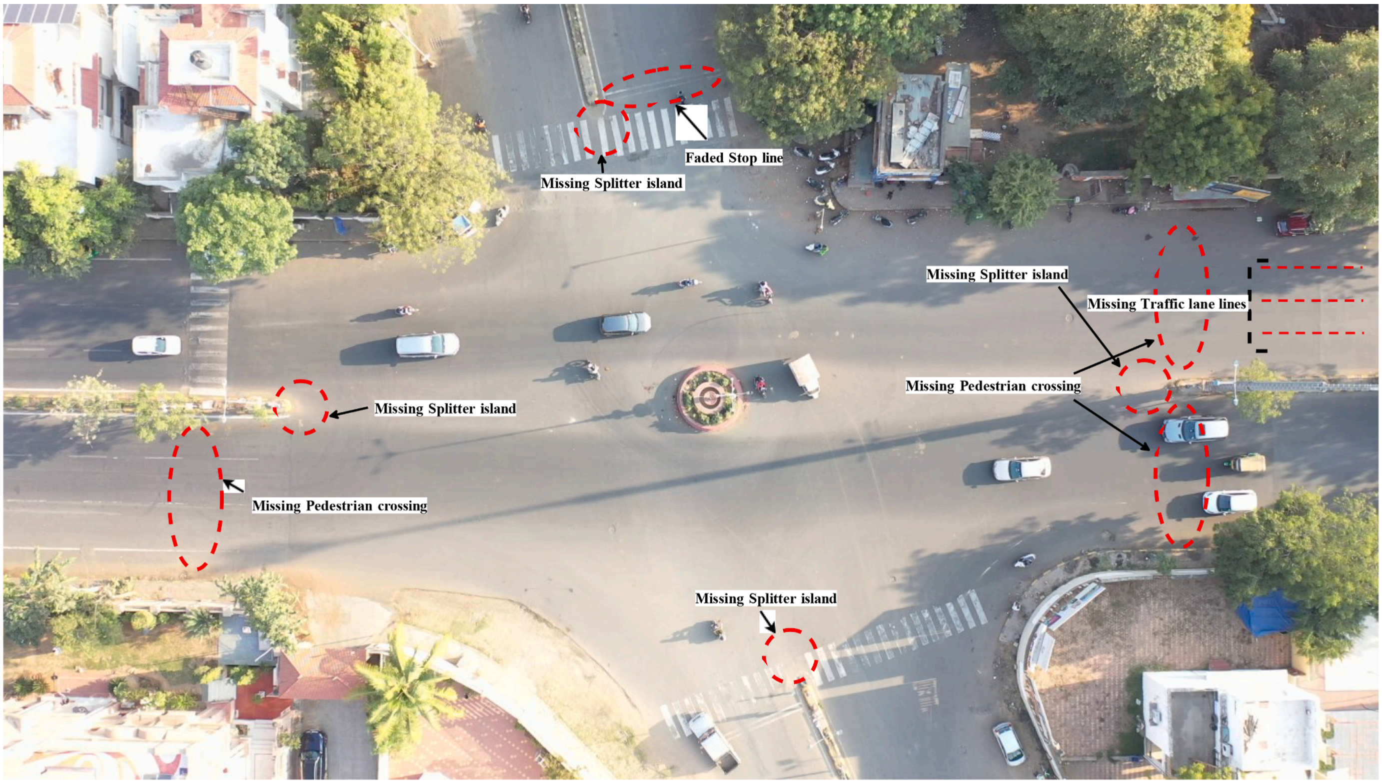


Fig. 10. Aerial image of the multi-lane urban roundabout.

(a) Two-wheeler entering from exit point (dictionary ID 11). (b) Car disobeying roundabout (dictionary ID 5).

Fig. 11. Examples of traffic violations(vehicles).

entry (lane/zone 20) of west entry to deviate from their designated path. This congestion-causing phenomenon can be easily verified with the fact that, out of total vehicles entering from (M) entry (lane/zone 20), **36.07%** vehicles deviated from their designated path and were forced to exit in (L) exit (lane/zone 4). Also, **22.22%** vehicles (out of total entering from (L) entry (lane/zone 21)) exited in (L) exit (lane/zone 4), which is a directional arrow marking traffic violation. All these will cause overuse of (L) exit (lane/zone 4) and (M) exit (lane/zone 5) (refer Fig. 18), eventually creating a bottleneck at the east exit (refer Fig. 17). Also, these cause inconvenience for vehicles entering from (L) entry (lane/zone 3) of the north (refer Fig. 17). Similarly, vehicles entering from the east have deviated from their designated paths, causing a bottleneck at the west exit.

4.3.2. Lane usage

Fig. 18 shows lane usage by vehicles. The rightmost lane on the south entry (lane/zone 13) and the leftmost lane on the north exit (lane/zone 22) are rarely used. We found a very interesting reason for the lack of use of the leftmost lane on the north exit (lane/zone 22), which is the presence of a hawker (with a push cart) standing at the northwest corner of the roundabout (refer Fig. 19).

4.3.3. Rate of traffic flow at entry points

In Table 6, we have shown the rate of the traffic flow at entry points. More vehicles are entering from the east and west than vehicles from the north and south.

4.3.4. Speed estimation of vehicles

We have estimated the speed of vehicles using Eqs. (2)–(4). Here, we are using the estimated speed of vehicles to detect over-speeding within the roundabout. The maximum allowable speed of vehicles within a multi-lane urban roundabout is 40 kmph, but 6.6% vehicles (out of the 786 vehicles) were found to be over-speeding (refer Fig. 13).

Fig. 12. Pedestrian walking within the roundabout.

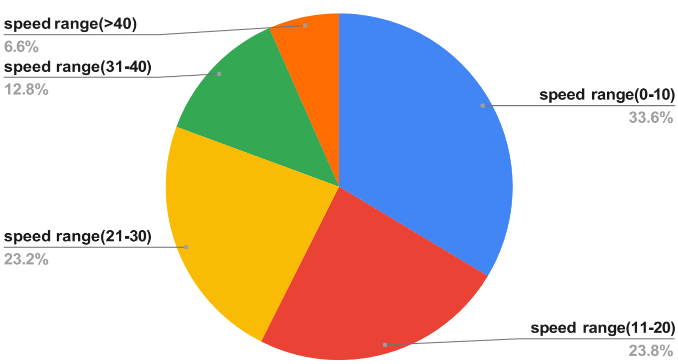


Fig. 13. Speed profile within roundabout(in kmph).

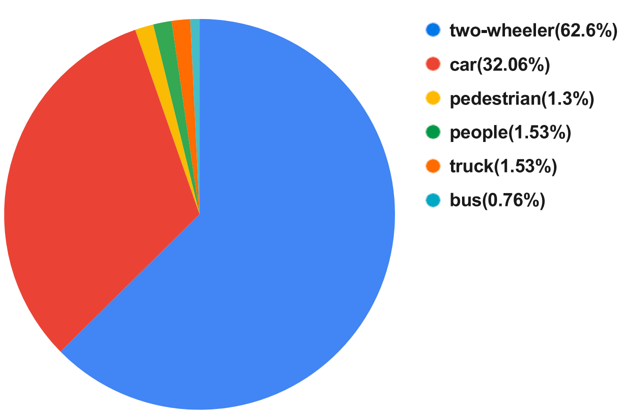


Fig. 14. Class-wise traffic violations.

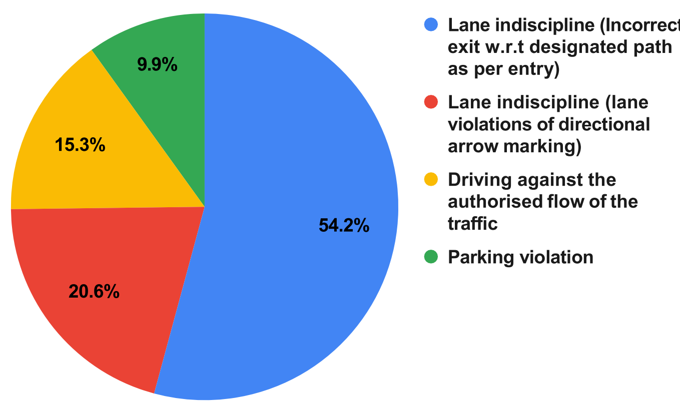


Fig. 15. Category-wise distribution of traffic violations.

4.4. *Comparison, advantages, and limitations*

The qualitative comparison of our proposed methodology with other research works done for the Indian subcontinent is given in Table 7 . The columns (Input, Computer Vision (CV) techniques, Out-comes, and Applicability) of Table 7 indicates: type of traffic video/image used as input to methodology, various CV techniques used in sub-modules of methodology, results of the methodology (traffic data and violations), and applicability of results of the methodology, respectively. Our proposed zone-based methodology uses recorded UAV video as input. We believe our methodology is the first to formulate MVDR based traffic violation dictionary (mapping between sections of MVDR and the movement of vehicles) for a roundabout. Our methodology has captured several categories of traffic violations based on movement of vehicles, as opposed to other works that mostly focuses on traffic law enforcement of safety measures (Triple riding on two-wheeler, seat belt, usage of phones

Class	Dictionary ID																																															
	4	5	6	7	8	9	10	11	12	14	17	19	25	27	28	29	30	31	32	33	34	35	37	41	42	45	47	52	54	57	61	64	69	70	72	77	78	84	87	88	98	99	107	108	125	126	128	130	Grand Total
bus																																							1										1
car	1	2			1	1							9	1		1		1	3	2	1	1	1	5			1			1			2						1	1	1	1		1		1	1	1	42
pedestrian						1	1																																										2
people											1	1																																					2
truck																										1							1																2
two-wheeler	2	4	1	1		2		2	1	1			1		1	1	1		13		3	6		5	6		1	2	1		1	1	4	1	2	1	1	2	2				2		5	5			82
Grand Total	3	6	1	1	1	4	1	2	1	1	1	1	10	1	1	2	1	1	16	2	4	7	1	10	6	1	2	2	1	1	1	1	7	1	2	1	1	2	4	1	1	1	2	1	5	6	1	1	131

Fig. 16. Heat map of traffic violations w.r.t. vehicle class and their count.

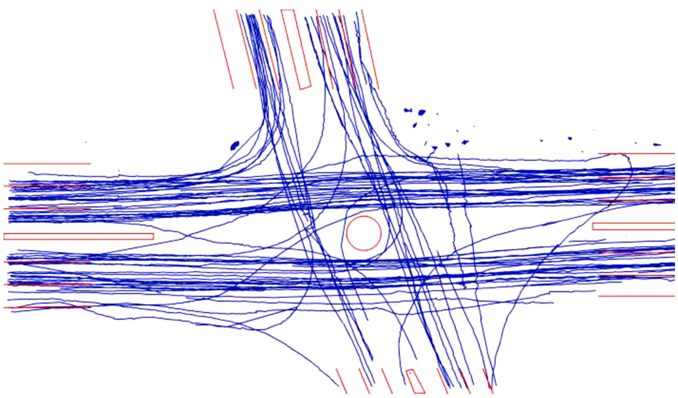


Fig. 17. Trajectory map of all entry points.

Table 4
Origin-destination matrix (in percentage).

		Destinations			
		East	South	West	North
Origins	North	1.50	6.00	4.50	0
	East	0	3.00	42.00	0.75
	South	0.75	0	3.00	1.90
	West	27.34	1.50	1.50	6.40

while driving, and helmet) related violations. Results (traffic data, violations, and inferences) of our methodology helps to under- stand linkages in traffic violations and road infrastructure, and provides suggestions for law enforcement drives and policy making.

We now discuss advantages and limitations (including limitations of UAV itself) of our methodology.

4.4.1. Advantages

(a) Cost effective solution because a single drone can be re-used at various sites (as opposed to mounting numerous CCTVs) to investigate road traffic and violations. Also, the flight height of drone is adjustable to capture a complete road junction. Top-view (gimbal 90° downwards) from the drone provides non-occluded view; (b) Traffic violation dictionary is expandable and customizable. Zones can be customized to the specific road scene (lane/segment/junction) and the types of traffic violations that we want to detect; (c) Any traffic violations based on the movement of vehicles can be detected; (d) Zone-based approach to capture road traffic data around any road junction/segment; (e) Identify causes of traffic congestion using traffic data analysis; (f) Helps to study the combined effect of human error and road infrastructure. Hence, it helps to study the causes of road accidents; (g) Could give suggestions to transportation and urban development policies.

4.4.2. Limitations

(a) Site selection could be a problem because of airspace regulations and privacy of citizens [66]; (b) In our methodology, to observe a road junction, it is required to fly the drone at a higher height. Hence, two-wheelers and pedestrians become small objects. Sometimes tracking algorithm fails for these small objects leading to multiple broken tracks for a vehicle/pedestrian. Possible reasons for such failure are objects missed during detection (YOLOv7) for a few consecutive frames and insufficient IoU between bounding boxes from detection and KF estimation. Such few tracks have to be interpolated and merged using semi-automatic script based on spatio-temporal proximity; (c) Additional or different zones need to be defined for investigating other types of road junction/segment and traffic violations; (d) Our methodology cannot detect traffic violations, which are not based on movement of vehicle; (e) Our methodology currently works on recorded UAV video; (f) Road traffic monitoring based on UAV is limited by its battery life [66].

4.5. Policy related suggestions

Results (traffic data, violations and inferences) obtained through our methodology could be used to amend transportation and urban development policies and initiate law enforcement drives. Few suggestions/examples are given below:

- In the street vendors act 2014 [48], chapter III (rights and obligations of street vendors), the following should be added: Vendors/Hawkers cannot cause any impediment to the flow of traffic or cause hazardous conditions and congestion near roundabout.
- MVA [16], section 201, should also include regulations for non-motorised objects (hawkers and push carts) causing impediment to the flow of traffic and should be punishable offence under section 283, IPC (Indian Penal Code).
- In the National Urban Transport Policy 2014 [45,47] and National Urban Policy Framework 2018 [46], in the parking section, the

Table 5
Lane-wise distribution of traffic w.r.t east and west entries(in percentage).

			Exit											
			East			South			West			North		
			4(L)	5(M)	6(R)	10(L)	11(M)	12(R)	16(L)	17(M)	18(R)	22(L)	23(M)	24(R)
Entry	East	7(R)	0	0	0	0	0	0	0	20.51	74.36	0	2.56	2.56
		8(M)	0	0	0	1.37	1.37	0	12.33	71.23	13.70	0	0	0
		9(L)	0	0	0	60.00	0	0	30.00	10.00	0	0	0	0
	West	19(R)	0	**35.71**	**42.86**	3.57	3.57	0	3.57	10.71	0	0	0	0
		20(M)	**36.07**	40.98	1.64	0	3.28	0	0	0	0	0	14.75	3.28
		21(L)	**22.22**	11.11	0	0	0	0	0	0	0	0	44.44	22.22

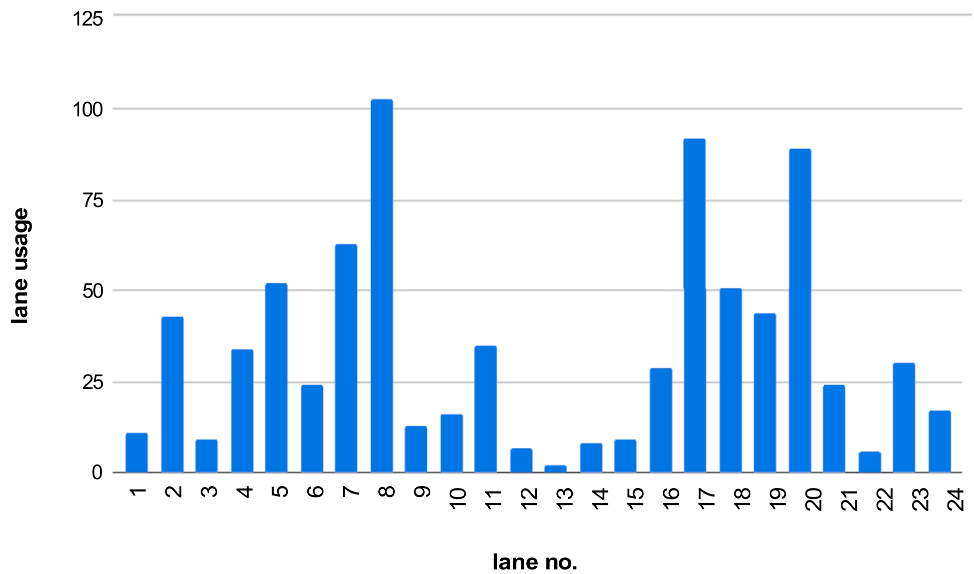


Fig. 18. Lane usage by vehicles.

Fig. 19. Hawker standing at the northwest corner and Grocery store at northeast corner.

Table 6
Rate of traffic flow for all entry points.

Entry Point	Rate of flow(vehicles/hour)
North	480
East	1830
East	225
West	1470

following should be added: Construction plans for commercial and residential buildings near roundabout should have off-street parking facilities and are not allowed to have provision/interface for road-side parking, and such buildings cannot have shops/businesses with high pedestrian footfalls and two-wheeler stoppages (such as tea-stalls, small grocery stores, auto garages, and auto dealerships).

- Detailed instructions (similar to those in developed countries [111]) for manoeuvring across roundabout should be added in MVDR/MVA [16] and driving manuals, and should be incorporated in driving test procedures (section 15 of CMVR [121]) of issuing driving licenses.
- The state governments, under sections 138 and 210A of MVA [16] should notify and initiate traffic law enforcement drives, especially for urban roundabouts.
- Traffic data collected and generated through our methodology supports the operations ("Data Repository and Analysis") [35] of TMICC under the national urban transportation policy [34].

Table 7
Comparison of our proposed methodology with other work.

Ref	Input	Computer vision techniques used	Outcomes	Applicability
[74]	Recorded CCTV video	Gaussian blur, Canny edge, and Hough line transform for lane detection; Auto- matic licence plate recognition system	Solid line violation; SMS to peccant road user	Traffic law enforcement
[68]	Streaming CCTV video	TensorFlow object detection model; Centroid difference is used for tracking	Driving on wrong way violation	Traffic monitoring
[76]	Recorded CCTV video	Haar classifier, Single Shot multi-box detector, and YOLOv3 for vehicle detection; correlation tracker for vehicle tracking; OCR for licence plate recognition	Over-speeding, parking, and driving on wrong-way violations	Traffic monitoring
[69]	Recorded CCTV video	YOLOv3 for vehicle detection	Red light jump, Safety measures (helmet, seat belt), and stop line violations	Traffic law enforcement
[79]	Recorded CCTV video	Grab cut and Hough transform for lane detection; RootSIFT and Flann-index matcher for vehicle tracking; Harr cascade algorithm for open mouth detection; Automatic licence plate recognition system	Safety measure (using mobile phone while driving) violation; Send e-challan over phone and mail	Traffic law enforcement
[77]	Recorded CCTV video	YOLO for vehicle detection; CNN for helmet detection; Mark R-CNN for crosswalk detection; OCR for licence plate recognition	Safety measure (helmet) and crosswalk violations; Send e-challan over phone and mail	Traffic law enforcement
[70]	Recorded CCTV video	Background subtraction; HOG, SIFT, and LBP feature extractors for two- wheeler and helmet; SVM classifier as binary classifier for two-wheeler and helmet detection	Safety measure (helmet) violation	Traffic law enforcement
[71]	Recorded CCTV video	Triple riding detection using YOLO	Safety measure (triple riding on two- wheeler) violation	Traffic law enforcement
[72]	Streaming CCTV video	YOLOv4 for violation detection; DeepSORT for violation tracking; OCR for licence plate recognition	Safety measure (helmet, triple riding, using mobile phone while driving), wheeling, and parking violations; Ticket generating	Traffic law enforcement
[75]	Recorded UAV video	Vehicle trajectories manually extracted using ClickCounter software	Traffic data (flow, density, speed, longitudinal, and lateral gaps) extraction	Study driving (gap acceptance) behaviour
[78]	Recorded UAV image sequences	HOG and SVM for vehicle detection; Kalman filter for vehicle tracking	Vehicle class, position, velocity, and trajectory extraction; Determine safety space of two-wheeler	Traffic conflict analysis
[73]	Recorded Mounted camera video	Vehicle trajectories semi-automatically extracted using Trajectory Extractor software	Vehicle class, position, velocity, and trajectory extraction; longitudinal and lateral gaps extraction	Study vehicle following behaviour (car following, staggered following, following between two vehicles)
Our work	Recorded UAV video	YOLOv7 for vehicle detection; SORT for vehicle tracking; Developed zone traversal sequence based method for violation detection and traffic data collection	Formulated zone-based traffic violation dictionary based on MVDR/MVA for roundabout; Traffic violations based on the movement of vehicle at roundabout; over-speeding, driving on wrong way, driving against the authorised flow of the traffic at roundabout, parking violations near a roundabout, left turn from rightmost lane, right/left turn from middle lane, right turn/driving straight from leftmost lane, wrong U-turn, and lane indiscipline (incorrect exit w.r.t designated path as per entry)	Traffic monitoring (supports the TMICC operations); Suggestions for transportation and urban development policies

- Contraventions of road design guidelines of IRC [15,38,100] observed through our methodology supports the operation ("Road construction and maintenance") of TMICC, which are punishable under section 166 of CMVR [121].

5. Conclusions

This paper presents a case study (and the methodology) for drone/UAV video-based investigation of road traffic and violations at a multi-lane urban roundabout in India. The computer vision techniques used in our work are YOLOv7 for vehicle detection and SORT-based tracking of vehicles. Our methodology divides the road scene (roundabout) into specific zones. We then formulated the dictionary, which is the mapping between the traffic violations (sections of the MVDR/MVA) and the movement of the vehicle (zone traversal sequences). Using the zone-based methodology, we could also probe other road traffic data such as the count of vehicles, speed of vehicles near a roundabout, rate of traffic flow, and congestion. Based on our results, we also infer some of the possible causes of traffic violations in terms of problems/limitations of road infrastructure. Our methodology can also be easily applied to other road junctions/segments by appropriately defining custom zones for the required study of road traffic.

We have investigated a multi-lane urban roundabout (in Ahmedabad city). Around 23.26% of vehicles committed violations (including over-speeding within the roundabout). We detected traffic violations related to lane indiscipline, driving against the authorized flow of the traffic, parking violations, and over-speeding within roundabout. The central island diameter is extremely small, and splitter islands are absent, which could be the reason for the violations: Driving in the wrong way, driving in anti- clockwise direction at the roundabout, and wrong U-turn. Zebra crossings (road markings) are absent and the location of a grocery store (at the northeast corner) could be the reason for pedestrians walking dangerously within the roundabout. The grocery store is also the reason for parking violations. Directional arrow markings are absent, which could be the major cause for lane indiscipline (one of the causes for congestion) related traffic violations. The hawker, located at the northwest corner, is the reason for the lack of use of the leftmost lane of the north exit.

Results (traffic data, violations, and inferences) obtained through our methodology could be used for (Obj1, Obj4, Obj5, and Obj6) road infrastructure improvement, law enforcement drives, and policy making, for road traffic safety.

Future work

Although our proposed methodology has covered many aspects of investigating road traffic and violations using drone videos, there is scope to improvise this computer vision-based investigation. The sites for investigation can be selected based on historical data (of violations or accidents) available with local authorities. Machine Learning (ML) and Computer Vision (CV) techniques can be used to automatically identify/detect/predict the various zones in the road scene (road junction/segment), such as entry-exit points and lanes, lane markings, zebra crossing markings, and directional arrow markings. The problem of multiple broken tracks of small objects may be solved using a tiling approach for object detection and a feature-based data association algorithm in tracking. Some violations of the MVDR/MVA require spatio-temporal modelling of multiple road users, which is a more complex problem and can be attempted to be solved using augmented ML and CV techniques.

Declaration of Competing Interest

None.

Data availability

We will share data on request.

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