

Headway and Following Distance Estimation using a Monocular Camera and Deep Learning

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Abstract: We propose a system for monitoring the headway and following distance using a roadside camera and deep learning-based computer vision techniques. The system is composed of a vehicle detector and tracker, a speed estimator and a headway estimator. Both motion-based and appearance-based methods for vehicle detection are investigated. Appearance-based methods using convolutional neural networks are found to be most appropriate given the high detection accuracy requirements of the system. Headway estimation is then carried out using the detected vehicles on a video sequence. The following distance estimation is carried out using the headway and speed estimations. We also propose methods to assess the performance of the headway and speed estimation processes. The proposed monitoring system has been applied to data that we have collected using a roadside camera. The root mean square error of the headway estimation is found to be around 0.045 seconds.

1 INTRODUCTION

Rear-end collisions are considered one of the most common types of traffic accidents globally and lead to a significant number of injuries and fatalities. For instance, in the USA, about one-third of all crashes were rear-end crashes (NHTSA, 2003). In the Netherlands, 35% of all highways crashes are rear-ended crashes (van KAMPEN, 2000). In Japan, rear-end crashes represent about 28% of total crashes (ITARDA, 2003) (ITARDA, 1998).

Headway is usually defined as the elapsed time between the front of the leading vehicle passing a point on the roadway and the front of the following vehicle passing the same point (Michael et al., 2000). The two-second rule (RSA, 2012) is the most important guide to maintain a safe trailing distance, where the follower should stay at least two seconds behind the vehicle in front, regardless of the vehicle speed.

The authors of (Brackstone et al., 2009) and (Brackstone et al., 2002) studied the relationship between the velocity and the headway; they equipped vehicles with sensors such as a Radar Rangefinder to measure the relative distance to surrounding vehicles.

In (Robert Tscharn, 2018), (Lewis-Evans and Rothen-gatter, 2009), (Siebert et al., 2014) and (Siebert et al., 2017), the authors used a simulator to study the effects of velocity and driving environment on the headway. The authors of (Knospe et al., 2002) used two detectors, one for each direction; each detector consists of three inductive loops, one for each lane. An inductive loop is able to analyze single-vehicle data to perform classification based on the measured vehicle length; this means that the system cannot distinguish between trucks and buses as all heavy vehicles are categorized in one class.

In this paper, we present a system to monitor driving behavior data, such as the headway, the following distance, the lane occupation, the speeds of passing vehicles as well as their classification (i.e. car, truck, or bus, etc.). The measurements are performed using video traffic analysis. The system is composed of five main core components : (1) optical sensor, (2) object detection, (3) tracking, (4) speed estimation, and (5) safety distance estimation.

In order to provide an accurate estimation of the vehicle speed and safety distance, reliable vehicle detection results are needed. Many object detection methods have been proposed in the literature. They can be categorized into two classes: motion-based de-

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tection methods and appearance-based methods. The former uses a sequence of video frames to detect moving objects (i.e. vehicles) (Charouh et al., 2019). The latter uses video frame pixels to detect and recognize vehicles by analyzing contours, contrast, and other visual features. Within the second class of methods, Convolutional Neural Networks (CNNs) have been shown in recent years to provide highly accurate object detection and classification. Several improvements to the first CNN have been made to optimize run-time, such as Faster-RCNN by the introduction of Regional Proposal Network (RPN) (Ren et al., 2015). Furthermore, by combining the tasks of generating region proposals and classifying them into one network, YOLO (You Only Look Once) and YOLOv2 methods have been shown to provide better performance in terms of computational time than Faster-RCNN; in terms of accuracy, they are inferior to R-CNN family of methods. Since in our study, the accuracy is the most important metric, opted for the Faster R-CNN method for vehicle detection.

Many object tracking approaches have been proposed. They can be classified into three categories: (1) point tracking, where objects detected in consecutive frames are represented by points, and their association is based on the previous object state; (2) kernel tracking, which refers to the object shape and appearance, where the tracking is achieved by computing the motion of the kernel in consecutive frames; (3) silhouette tracking, which consists of estimating the region of the object in each frame; The silhouettes are tracked by shape matching or contour evolution (Yilmaz et al., 2006).

The safety-distance models rely on the idea that the driver of the following vehicle tends to maintain a safe distance to avoid a collision in the event of sudden braking of the lead vehicle. The Gipps model (Gipps, 1981) is a typical safety-distance model. The model includes two modes of driving: free-flow and car-following.

The remainder of the paper is organized as follows: in section II, we describe the data collection process. Section III discusses the system components and the methodology including vehicle detection, tracking, removing the projective distortion, and speed estimation. Section IV describes the headway and following distance estimation methods. Section V discusses the results. Section VI concludes the paper.



Figure 1: Example of a video frame.

2 DATA COLLECTION

We use a video system to acquire traffic data. The system is composed of a network video recorder (NVR) and an IP camera powered through PoE (Power over Ethernet). The video streams are then sent to a compact computer via Ethernet and recorded at 25 Hz with a resolution of 2560 x 1440. An example of a video frame is shown in “Fig. 1”. The system was installed at the main entrance of the International University of Rabat, where speed is limited to 40 Km/h.

To validate our speed estimation method, the ground truth vehicle’s speed is extracted using the On-Board Diagnostics 2 protocol (OBD-II) over the CAN (i.e. Controller Area Network) bus and transferred for storage to the driver’s smartphone using a Bluetooth connection.

To validate our headway estimation technique, the ground truth headway is obtained using the video recording system of a smartphone placed beside the road; the videos are analyzed to measure the timestamps of vehicles passing a region of interest, and the headway is determined as the difference between two consecutive timestamps. The videos are recorded at 30 Hz with a resolution of 1920 x 1080.

3 METHODOLOGY

As mentioned above, the proposed system is composed of four components: a detector, a tracker, a speed estimator, and a following-distance estimator. The detector represents the main component of the system. Before applying the detection method, the video frames are pre-processed to select only the region of interest covering the road. The detector and tracker operate as follows: the video sequence is processed frame by frame, each frame is fed to the detector, the detector then outputs all vehicles present in the scene, specifying their positions and types. To

improve performance, the tracker combines detection and prediction of vehicles' positions on the next frame.

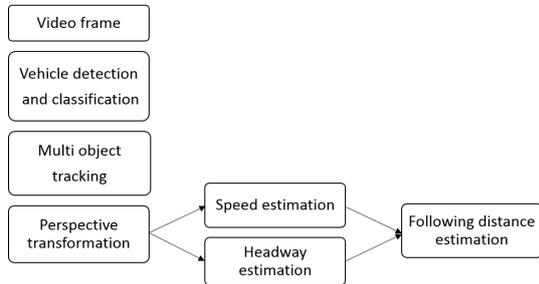


Figure 2: The proposed methodology.

3.1 Object Detection

We use the Faster RCNN algorithm as a detector. It is composed of two modules. The first module is a Region Proposal Network (RPN) which takes an image as input and proposes regions with a wide range of scales and aspect ratios. The second module is a classifier, which takes as input the proposed regions and returns the positions and the types of vehicles (Ren et al., 2015). In this work, the Faster R-CNN uses the intermediate features of ResNet-50 to aid in the region proposal task.

In our study, the vehicles appear in some specific shapes, which is due to the fact that our cameras were oriented to capture the rear-ends of vehicles, and also to the dimensions of the heavy vehicles. So we modified some scales and aspect ratios which influence the RPN, so that the proposed regions match all of the vehicle types that we can observe in the scene.

The video frames are captured with a camera placed on an 8m-high highway bridge. The camera is oriented so that it captures the rear-ends of the passing vehicles. To train the vehicle detector in this setting, we generated a dataset of frames containing vehicles that we have labeled by specifying their types and positions. We generated 925 images, including 1226 vehicles, 323 trucks, 858 cars, and 45 buses. To increase the dataset size, we applied the following data augmentation techniques: horizontal flip, adding of a Gaussian Noise, and adding of a salt-and-pepper noise. Thus, the detector was trained using 7400 frames.

3.2 Tracker

The detector and tracker are applied to every frame. The result of this operation gives one of the following 4 cases: (1) a tracked vehicle which is detected in the

current frame, (2) a new vehicle is detected but not yet tracked, (3) a tracked vehicle which is not detected in the current frame (this is referred to as a predicted vehicle), and (4) a predicted vehicle which was not detected.

The tracker has two sources of information: predicted vehicles and detected vehicles. We use the Munkres algorithm (Munkres, 1957) to assign each detection to the appropriate tracked vehicle. The algorithm takes as input the prediction and detection results and measures the cost of associating each detection to a tracked vehicle. The cost is calculated using the sum of distances between the centroids of the predicted and detected vehicles.

To predict new positions of vehicles, we assume that the vehicle speed does not significantly vary from one frame to the next, so we use a simplified version of the Kalman filter to construct our predictor. The state vector consists of the centroids' coordinates and velocities along the 2 axes. The coordinates are obtained directly from the detector, whereas the velocity is calculated using the previous and the current centroid's positions.

When a new vehicle is detected, we start to track it; but as it can be a false positive detection, we consider it as a temporary vehicle until we succeed to consistently track it over a determined number of successive frames, in which case it is considered a real tracked vehicle.

We predict the next positions of tracked vehicles using the last velocity and the last position. In some cases, the detector can fail in detecting the vehicle in the scene, (e.g. occluded vehicle), so the predicted position will be used as the real positions of the tracked vehicle, and the velocity will no be updated. This prediction in the absence of detection will continue over a number of frames beyond which the vehicle is considered to be lost and thus removed from the list of tracked vehicles. We also remove from this list the tracked vehicles whose coordinates go beyond the region of interest.

3.3 Removing the Projective Distortion

Vehicle detection and tracking are essential in many road traffic applications, such as vehicle counting, speed estimation, lane occupation estimation, headway estimation, etc.. Counting vehicles does not require precise positioning of the vehicles on the road. However, to estimate lane occupations, speeds, and headways, we need to estimate the vehicles' positions accurately, and we need to be able to measure real distances, i.e. values must be converted from the pixel domain to the real-world domain.

As described in 3a, parallel lines on the scene plane (i.e. the real world) are not parallel on the image; see Fig. 1. This is known as perspective distortion. To remove this, we used a planar projective transformation (Hartley and Zisserman, 2003) also called Homography, which is a mapping between the two planes. We randomly selected a set of points on the road, and measured their coordinates using a laser distance measurer and a reference point on the road. The coordinates of the corresponding points in the pixel domain are obtained from an image of the scene, as shown in Fig. 3a. More details are given next.

Let the coordinates of points p and p' in the image and the real-world be (x, y) and (x', y') , respectively. The mapping may be expressed by

$$x' = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \quad (1)$$

$$y' = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \quad (2)$$

where the coefficients $\{h_{i,j}\}$ are to be estimated. Each point correspondence generates two equations:

$$x'(h_{31}x + h_{32}y + h_{33}) = h_{11}x + h_{12}y + h_{13} \quad (3)$$

$$y'(h_{31}x + h_{32}y + h_{33}) = h_{21}x + h_{22}y + h_{23}. \quad (4)$$

Four-point correspondences are sufficient to estimate all parameters. In our study, we used 16 points, and obtain the following a non-singular 3 by 3 matrix

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} = \begin{bmatrix} 1.23 & 1.14 & -1629.28 \\ -0.69 & 24.54 & -885.28 \\ -0.00046 & 0.015 & 1 \end{bmatrix}$$

Fig. 3b validates this estimation as in the transformed image, the lines appear parallel and the road appears to have its true geometric shape.

3.4 Speed Estimation

To estimate the vehicle speed, we extract its real position at every frame, and use the video frame rate (i.e the number of frames per second). The average speed is calculated using kinematics. In our study, we calculate the distance traveled during 1 second.



Figure 3: A) Preparing the mapping between pixel domain and real world. (b) The synthesized image using Homography.

4 HEADWAY AND FOLLOWING DISTANCE ESTIMATION

Tailgating can cause rear-end collisions, which are one of the most common types of traffic accidents.

To make safety distance measurement, the vehicles should be in a vehicle following situation. The latter is defined here as a situation where the following vehicle is within a 150m range of the car in front (Wiedemann and Reiter, 1992), and the headway is less than 5 seconds (TRBNR, 2000).

We focus on estimating the headway as the following distance can be obtained from the headway estimate and vehicle speed estimate.

To measure the headway, we set a virtual line and a timer. When the front of the vehicle passes on the line, the timer starts running until another vehicle passes or a five seconds duration expires. The following vehicle situation assumes that the two vehicles are on the same lane. Since vehicles may not respect the lane boundaries, some vehicles may be detected to be present on two lanes, thus implying sometimes a false following situation. To solve this, we used thresholds to verify the presence of vehicles on the lane.

5 TEST AND RESULTS

To assess the reliability of the proposed system, we evaluate its overall performance instead of measuring each component's effectiveness. The ground truth on vehicle speed is obtained from the CAN bus, through

OBD-II (On-Board Diagnostics 2), of the vehicle that we have used for testing. The speeds are sent to a smartphone using a Bluetooth connection. To avoid a-synchronization issues between the OBD and the smartphone application, we have asked the volunteering drivers to maintain a constant speed using cruise control. We have evaluated our system by analyzing the mean squared error, which was found to be around given 0.92 km/h. A comparison between the speeds measured by the OBD-II and speeds estimated by our system are shown in Table. 1.

Table 1: Results of speed estimation.

Estimated speed	OBD-II-based speed
33.5	32.37
52	51.49
39.60	40
57.2	56.55
60.7	59.68
42.3	41.88
65.4	66.1
68.90	70.55
46.2	46.55
30.1	31.68

The headway and distance estimation tests are done using a fixed camera that we have placed beside the road, visualizing and capturing line crossings of vehicles as shown in Fig. 4'. We have asked drivers to use the same lane, so that the vehicles can be a vehicle following situations. The videos are recorded at 30 Hz. We have added a virtual line to the frames and observed the video sequences frame by frame to obtain the 'true' headway, which is estimates using the number of the frame from the moment a vehicle passed on the line and the moment the following vehicle does.

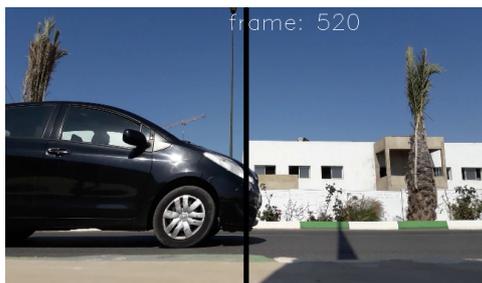


Figure 4: Experimental setup to manually measure the headway.

Using the ground truth values described above, we have evaluated the performance of our headway estimation method. The corresponding mean squared error is found to be around 0.002 second. A comparison

between the measured and estimated headways is shown in Table. 2.

Table 2: Comparison of the measured and estimated headways.

Estimated headway	Measured headway
3.1	3
2.7	2.7
2.16	2.2
2.8	2.8
3.5	3.47
1.7	1.73
2	2.07
2.22	2.23

6 CONCLUSIONS

In this paper, we presented a system to measure the headway using computer vision and deep learning techniques. The system is also able to estimate speeds and lane occupations, to count vehicles, etc. The system uses the faster R-CNN as a detector and classifier, which we have trained on datasets that we have built using roadside cameras. We have also proposed a method to validate speed and headway estimations. The obtained results are promising as the mean squared error (MSE) on headway estimation is shown to be around 0.002 seconds.

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