Drive Analysis using Lane Semantics for Data Reduction in Naturalistic Driving Studies

Ravi Kumar Satzoda\(^1\), Pujitha Gunaratne\(^2\) and Mohan M. Trivedi\(^1\)

Abstract—Naturalistic driving studies (NDS) provide critical information about driving behaviors and characteristics that could lead to crashes and near-crashes. Such studies involve analysis of large volumes of data from multiple sensors and detection and extraction of critical events is an important step in NDS. This paper introduces techniques that analyze the visual data complemented with other sensors in the vehicle to determine critical events related to lane drifts, road departures and road delineations. To the best knowledge of the authors, this is the first work that detects and extracts events listed in visual reference dictionary of NDS studies like Strategic Highway Research Program 2 (SHRP2). Detailed evaluations with real-world NDS data is presented.

I. INTRODUCTION

Naturalistic Driving Studies (NDS) capture typical day-to-day driving sessions without artificial features that are introduced by controlled experimental studies [1]. NDS such as the 100-car study [2] and the more recent Strategic Highway Research Program (SHRP2) [1], [3] investigate the contributing factors that result in crashes or near-crashes.

In such NDS, large amounts of naturalistic driving data is collected using hundreds or thousands of instrumented vehicles. For example, the 100-car study included 100 cars with over 240 drivers and collected 2 million vehicle miles of driving data [4]. Similarly the on-going SHRP2 involves over 3000 drivers and data is being collected over a 3-year duration in six different regions in USA [5]. In such NDS, there are two main steps to analyze the naturalistic driving data as shown in Fig. 1. The first step is the data collection step where the sensors that are mounted on the vehicles collect millions of hours of data. This data is collected by sensors such as cameras, in-vehicle gyroscopes, accelerometers and magnetometers, global positioning systems (GPS) etc. The next step is called the data reduction stage (Fig. 1) in which a panel of data reductionists go through the raw data collected during the drive to detect crashes and near-crashes. Referring to a dictionary and reference manual, the reductionists manually go through raw data to determine a number of events defined in the dictionary that could lead to crashes or near-crashes.

Among the different sensor data, visual data from cameras is one of the key source of critical information about crashes and near-crashes, which is used by data-reductionists to identify events. In this paper, the visual data is considered as the primary data while other sensors are complementing the cameras with additional non-visual information.

While there are a number of events and responses that are defined in the reference dictionary, lane related information and events form a core component of NDS data reduction process [6]. Therefore, identifying critical events related to the vehicle movement and position in the lanes is one of the key steps undertaken by data reductionists. Given the scale and volume of data that is collected in such studies, manual data reduction can be a time-consuming task and is also subjective to interpretation of the manual subjects performing the data reduction. More recent NDS such as [7], [8] suggest automatic tools that can perform this data reduction step improve efficiency and accuracy.

A survey of literature shows that analyzing naturalistic driving data in order to reduce NDS data is less addressed. One of the first works in open literature in [9] which provides quantitative measures for detecting lane changes only. In this paper, techniques are presented to automatically detect a set of events related to lanes as described in the reference dictionary provided by on going NDS called SHRP2. To the best knowledge of the authors, this is the first contribution in open literature that proposes techniques for data reduction events described in the reference dictionary of visual events of NDS. Detailed evaluations will be presented using real-world NDS data from SHRP2 to show the effectiveness of the proposed techniques in automating the data reduction process.

The rest of the paper is organized as follows. In Section II, related work in the area of data reduction is presented...
briefly. The taxonomy for the events related to lanes from the SHRP2 data reduction manual is then presented in Section III followed by proposed techniques to detect the events described in Section IV. Detailed evaluations on real-world driving data including SHRP2 data are presented in Section V followed by concluding remarks in Section VII.

II. RELATED WORK

In this section, recent naturalistic driving studies (NDS) are briefly described to motivate the objectives and scope of the proposed drive analysis presented in this paper. The final objective of most NDS is to identify driver and driving behaviors and characteristics that can be correlated to crashes or near-crashes [2], [4], [11]–[13]. In addition to NDS, works such as [14]–[17] also determine behaviors such as aggressive driving, tactical driver behavior etc. using visual data complemented with other sensor data that is collected during the drive. In all these studies, the first step is to detect various events related to driver, vehicle, lanes, road, other road users etc. from the raw naturalistic drive data [6]. Given that visual data is being considered as the primary sensor data in this paper, the rest of the paper will focus on discussing events that are related to visual data as the main input.

A survey of NDS and similar studies shows that lanes and associated events are one of the critical informations in crash-related studies [2], [4], [11]. Lane change events [11], lane type information [4], vehicle localization using lanes [18] etc. have been considered as some key measures to study crash and pre-crash events. Although there is significant amount of literature on lane estimation [19], there is limited amount of literature on analyzing the lane information in the context of NDS. This is still primarily a manual task in data reduction step of NDS. As shown in Fig. 1, the data reductionists go through the visual data to identify the different events related to lanes listed in the reference dictionary [6].

In [9], [10], drive analysis was introduced and it is one of the first works on lanes that caters to analysis and reduction of NDS data. In [9], a report is generated that shows a number of semantics that are related to both lanes and other vehicle dynamics. However, there are more events related to lanes that have not been addressed in our previous contribution in [9]. The forthcoming sections will elaborate on the different events and semantics related to lanes and techniques to detect and extract such events.

III. LANE-BASED EVENT DEFINITIONS IN NDS

Let us first define an event in the context of drive analysis for NDS. In this paper, an event is defined as anything notable that happens to one or more observable entities or variables. The observable entity that is of interest in this paper are the lanes. Therefore, an “event” refers to a notable change or modification or observation that happens to the lanes. With this definition of an event, a set of lane events are introduced that are of interest to data reductionists of NDS data. These events are collected based on the definitions given in the reference dictionary manual for data reductionists in [6], which is prepared as part of on-going SHRP2 NDS [1].

The proposed drive analysis for lane information will be limited to the following set of events. It is to be noted that extracting the entire list of lane events from [6] is out of scope of this paper.

1) Going straight with constant velocity
2) Going straight with acceleration
3) Going straight but with unintentional drifting
4) Decelerating in traffic lane
5) Starting in traffic lane
6) Stopped in traffic lane
7) Road departure: host vehicle over the left edge of road
8) Road departure: host vehicle over the right edge of road
9) Roadway delineation

Fig. 2 illustrates some of the above events related to lanes. Items (1) to (7) are related to whether the vehicle is drifting or moving straight within the lane/road boundaries. Therefore, detecting the ego-vehicle drift within the lane is necessary for these items. Items (7) to (8) involve determining the road boundary in addition to the drift of the ego-vehicle. Item (9) refers to sections of the drive where there are no lanes or road boundary. Therefore items (7) to (9) are also related to determining the type of road boundary.

IV. PROPOSED TECHNIQUES FOR EVENT DETECTION IN NDS DATA

In this section, the testbed that is used to collect NDS data is briefly described first. Thereafter, techniques to detect the different events listed in the previous section are proposed.

A. Testbed Setup

The sensor configuration and the testbed LISA-Q2 is similar to the sensor setup in on-going SHRP2, which was also discussed in detail in [9]. It has six cameras with three outward looking cameras and three inward looking cameras. Additionally, the in-vehicle sensors capture a set of twenty eight vehicle dynamics such as velocity, acceleration, braking pressure etc. These sensors’ data is collected by accessing the CAN bus. The LISA-Q2 testbed is also equipped with a global position system (GPS) which records the GPS coordinates and vehicle orientation parameters such as yaw,
pitch, roll etc. of the vehicle during the drive. There is a data capturing system implemented on this testbed which captures time-synchronized data from all these sensors.

B. Lane Estimation Algorithm

In order to detect the lane related events listed in Section III, the lane estimation algorithm described in [21], [22] called LASeR (lane analysis using selective regions) is employed. For the sake of completeness of this paper, LASeR is briefly described in this sub-section. However, more details about LASeR can be obtained from [21].

LASeR applies a set of horizontal bands on the inverse perspective mapping of the input image to detect lane features using modified steerable filters in vertical direction given by the following equation:

\[ G^H(x, y) = G_o(x, y) - \frac{\sigma^2}{\sigma^2 + (x - x_o)^2} \]

After applying the filter on each scan band, the lane features are determined in the following way using the positions \( x \) of possible lane position coordinates are obtained for every band \( B_i \) (0 \( \leq \) i \( \leq \) \( N_B \)) which are represented by:

\[ P_i = [x_i(y_1), x_i(y_2), \ldots, x_i(y_{N_B}), \ldots, x_i(y_{N_B})] \]

where \( P_i(x_i, y_i) \) represents the \( k \)-th lane feature (along horizontal x-direction) in the \( i \)-th scan band (along vertical y-direction). The lane features that are detected across the different bands are correlated to each other using the road model. Kalman tracker is further added to track the lane features temporally. Finally, if ego-lane is of interest, the LASeR algorithm gives the \( x \)-coordinates of the left and right lane markings of the ego lane in each scan band, i.e.,

\[ x_L = [x_{L1}, x_{L2}, \ldots, x_{LN_B}]^T \]

\[ x_R = [x_{R1}, x_{R2}, \ldots, x_{RN_B}]^T \]

More details about LASeR are presented in [21].

C. Detecting Drift in Lane

The first category of events listed in Section III are related to drift of the vehicle within the lane. In order to detect these events, the drift of the ego-vehicle in the lane is first determined in the following way using the positions \( x_L \) and \( x_R \) of the lane markings obtained from LASeR. In [9], the deviation of ego-vehicle localization is used to determine the lane change events by computing the position of the vehicle with respect to the center of the lane. This deviation in ego-vehicle position is obtained by using the lane marker positions in the nearest scan band, i.e. \( x_{L0} \) and \( x_{R0} \). If the camera is positioned at the center of the vehicle, then the vehicle position is given by \( x_V = (x_{L0} + x_{R0})/2 \). However, \( x_V \) will not be defined accurately in cases when there is no lane marking on one side of the roadway. Also, if it is required to determine the vehicle drift towards specific lanes, i.e. left or right lane drift, determining the vehicle drift towards individual lanes separately will be more appropriate.

In order to determine drifting of the ego-vehicle in lane, the drift regions are defined as shown in Fig. 3. Five regions are marked in Fig. 3 denoted by \( R_L, R_R, L_R, L_L \) and \( E_L \). The ego-vehicle is supposed to be moving in the ego-lane \( E_L \). However, when it starts drifting to the left, the lane markers will move towards the left drift regions \( L_R \) and \( L_L \), where subscripts \( R \) and \( L \) refer to the right and left markings respectively. Similarly, when the ego-vehicle drifts to the right, the lanes will start moving into right drift regions \( R_R \) and \( R_L \). In order to detect the drifts using LASeR, the positions of the lanes in \( k \) scan bands (where \( k < N_B \)) in the near field of view of the ego-vehicle are used. Mathematically, this is represented by:

\[ \text{event} = \text{left drift} \quad \text{if} \quad \left\{ \begin{array}{l} \forall x_{i,j} : L_j^L < x_{i,j} < L_j^R \smallsetminus \forall x_{i,j} : L_j^L < x_{i,j} < L_j^R \\ \forall x_{i,j} : L_j^R < x_{i,j} < L_j^R \smallsetminus \forall x_{i,j} : L_j^L < x_{i,j} < L_j^R \end{array} \right\} \]

\[ \text{event} = \text{right drift} \quad \text{if} \quad \left\{ \begin{array}{l} \forall x_{i,j} : R_j^L < x_{i,j} < R_j^R \smallsetminus \forall x_{i,j} : R_j^L < x_{i,j} < R_j^R \\ \forall x_{i,j} : R_j^R < x_{i,j} < R_j^R \smallsetminus \forall x_{i,j} : R_j^L < x_{i,j} < R_j^R \end{array} \right\} \]

\[ \text{event} = \text{in lane} \quad \text{if} \quad \left\{ \begin{array}{l} \forall x_{i,j} : L_j^L < x_{i,j} < L_j^R \smallsetminus \forall x_{i,j} : L_j^L < x_{i,j} < L_j^R \\ \forall x_{i,j} : R_j^R < x_{i,j} < R_j^R \smallsetminus \forall x_{i,j} : R_j^L < x_{i,j} < R_j^R \end{array} \right\} \]

where \( 0 < j < k \) and \( L_j^L \) and \( L_j^R \) indicate the lower and upper bounds of the \( x \)-coordinates of region \( L_L \). The other variables in the above equations denote similar bounds for the other regions \( L_R, R_L \), and \( R_R \).

D. Drift Related Event Detection

The drift information is combined with vehicle dynamics in Table I to analyze a given drive and determine the occurrence of a set of events from the reference dictionary of data reduction manual of SHRP2 NDS (listed in Section III). Table I shows a synergistic use of the sensor data to determine the variables and events for reducing NDS data by combining the drift information from visual data with the vehicle dynamics. A '*' shown for drift in the last three events indicates that the detection of lane is required for the event to be detected. In the next sub-sections, techniques will be proposed that aid in determining the presence of road boundary, which will be used to determine the items (7) to (9) listed in Section III.

E. Detecting Events Related to Road Boundaries

In this paper, techniques are introduced to detect the following events related to road boundaries that are used for data reduction process in NDS:

1) Road departure
TABLE I

<table>
<thead>
<tr>
<th>Event</th>
<th>Drift Information</th>
<th>Vehicle Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll drift</td>
<td>Velocity</td>
</tr>
<tr>
<td></td>
<td>Head drift</td>
<td>Acceleration</td>
</tr>
<tr>
<td>Going straight with constant velocity</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Going straight with acceleration</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Going straight with right drift</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Drifting in traffic lane</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Staying in traffic lane</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Stopping in traffic lane</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

- * indicates lane information is required but drift is not necessary.
- - indicates does not matter.

In words, if all the scan bands do not detect any lane feature, then the lane marking or the road boundary is considered to be missing.

V. PERFORMANCE EVALUATION

In this section, the proposed techniques are evaluated for the detection of different events using real-world naturalistic driving data. The evaluation is shown in two phases. Considering that the data on which such studies are performed are large, plots showing the drifts using the entire data for illustration will not be easily readable in a single graph. Therefore, segments are selected to illustrate some key events that are discussed in Section IV. Thereafter, the final report is shown that is generated on NDS data using the proposed technique.

2) Road delineation

The scope of this paper is limited to detection of the following with regards to road boundary:

- Detect the presence of single solid road boundary marking for item 1 above.
- Detect the presence or absence of lane marking or road boundary marking for item 2 above.

LaSeR algorithm can be extended to detect the presence of solid road boundary marking in the following way. In addition to the positions of the lane markings that are captured in $x_L$ and $x_R$ in equation (3), another variable is introduced which indicates the presence or absence of left and right lane markings in the scan bands, denoted by $p_L$ and $p_R$ respectively. As discussed in Section IV-B, LaSeR has a Kalman tracker to predict the positions of lane markings in case the lane features are not detected in the scan bands. The presence or absence of a lane feature is captured in $p_L$ and $p_R$. Both these vectors are of the same length as $x_L$ and $x_R$, i.e. $N_B$ and an element in say $p_L$ is defined as follows:

$$p_L = \begin{cases} 
1 & \text{if lane feature is detected in } i-th \text{ band} \\
0 & \text{otherwise} 
\end{cases}$$

Similarly $p_R$ is defined for the right lane markers.

$p_L$ and $p_R$ are used to determine the presence of the solid road boundary in the following way. If there is a solid road boundary, all the scan bands must necessarily indicate the presence of a lane marking. Therefore,

$$p_i = 1, \forall \ i \in [0,N_B)$$

In other words, all scan bands in LaSeR must show the presence of a lane marking without tracking the lane marker. After detecting the presence of a road boundary, the drift of the vehicle in the ego-lane is analyzed using the formulations in Section IV-C. Therefore, if the left road departure is considered, the drift on the left is analyzed to check if the vehicle has crossed the threshold set for lower boundary of the left drift region, i.e. $L_L$. Similarly road departure on the right side is also defined using the upper boundary of the right drift region.

In order to determine the road delineation event, the absence of lane marking or road boundary is determined using the presence vectors in the following way:

$$p_i = 0, \forall \ i \in [0,N_B)$$

Fig. 4. Lane detection on complex and difficult road scenarios from NDS data: (a) presence of vehicles, (b) lane prediction and lane change event detection, (c) Rainy scene with wipers on, (d) poor lighting conditions, and (f) rainy and nighttime.

Fig. 5. Right lane drift detected on real-world NDS data using the proposed method.
Firstly, Fig. 4 shows the results of lane detection using LASeR on some sample complex scenarios such as rainy scene with wipers on, nighttime and raining, during lane change event etc. A more detailed evaluation of LASeR is presented in [20]. Next, Fig. 5 shows the right lane position when the ego-vehicle is drifting to the right for a segment comprising 600 frames. It can be seen that the right lane is found at about \( x_R > 215 \) pixels from Frame 6100 to 6200. It starts moving left (the position value starts reducing) hitting \( x_R < 205 \) between Frame 6300 and 6400. Thereafter, it increases again and stabilizes around \( x_R > 215 \). This trend is consistent with the detection of drifts that was discussed in Section IV-C. When the ego-vehicle is drifting to the right, the position of the right lane marker reduces (moves left). This is also illustrated using the thumbnails from the image sequence for Frames 6150, 6350 and 6600. The drift of the ego-vehicle towards the lane marker can be clearly seen in these three thumbnails, and this is also detected using the proposed drift detection method. In order to further evaluate the accuracy of the proposed method, 50 different segments of the video with lane drifts were manually annotated as having a left, right or no drift. The proposed method was able to detect the lane drifts accurately in over 98% of the cases.

Furthermore, the vehicle dynamics can be used in conjunction with the lane drift information to determine the metrics listed in Table I. For example, Fig. 6 shows the acceleration profile for the same 600 frames that were analyzed for right drift using visual information. On combining the data from the two sensors, it can be inferred that the ego-vehicle was decelerating throughout the particular course of the drive. Therefore this falls under the event of unintentional drifting (to the right) and decelerating during the event.

Next, in Fig. 7, the use of the presence or absence flags that were introduced in Section IV-E is shown to detect road boundaries. Each waveform in each plot in Fig. 7 denotes the presence or absence of a lane marker in a particular scan band in LASeR. If a lane marker is detected in a scan band, a high value is detected. If LASeR does not detect a lane marker but is predicting it using a tracker such as Kalman tracker, then the presence flags will show an oscillating waveform as shown by the right lane marker in Fig. 7 (b). This is in contrast to the left lane marker which shows a constant high value for all scan bands in Fig. 7 (a). If a low value is seen on all scan bands, then it is predicted that the lane marking is missing in that frame. This is the case of road/lane delineation, which is shown in Fig. 8. In Fig. 8 (a), the waveforms for 4 scan bands of the right lane show that the right lane is initially dashed, followed by no lane marking and then solid lane marking (as shown in Fig. 8 (b)).

VI. SUMMARY REPORT OF DRIVE ANALYSIS

The proposed techniques were applied on sample videos from SHRP2 project database for NDS studies. The input video is a one-hour video with over 100000 frames, wherein the vehicle goes through a variety of road conditions including highways and urban roads. The weather conditions are sunny during most part of the drive with some places showing drizzle and moderate rain. During rainy sections, the wiper is switched on. The lighting conditions change from
daylight to nighttime as the drive progresses. The proposed techniques determine the occurrence of the different events related to lane drifts, road departure and road delineation and a summary report is generated as shown in Table II.

<table>
<thead>
<tr>
<th>Event</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Going straight with constant velocity</td>
<td>70%</td>
</tr>
<tr>
<td>Going straight with acceleration</td>
<td>10%</td>
</tr>
<tr>
<td>Going straight with left drift</td>
<td>2.5%</td>
</tr>
<tr>
<td>Going straight with right drift</td>
<td>5%</td>
</tr>
<tr>
<td>Decelerating in traffic lane</td>
<td>1%</td>
</tr>
<tr>
<td>Starting in traffic lane</td>
<td>4 occurrences</td>
</tr>
<tr>
<td>Stopping in traffic lane</td>
<td>5 occurrences</td>
</tr>
<tr>
<td>Road departures (left)</td>
<td>No</td>
</tr>
<tr>
<td>Road departures (right)</td>
<td>No</td>
</tr>
<tr>
<td>Road near departures (left)</td>
<td>Yes</td>
</tr>
<tr>
<td>Road near departures (right)</td>
<td>No</td>
</tr>
<tr>
<td>Road delineation (left)</td>
<td>Yes(4,740,10291,13641,27474)</td>
</tr>
<tr>
<td>Road delineation (right)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The different events are listed and the amount of time (in percentage) the event may have taken place in the drive is indicated. The proposed drive analysis also generates the instances (the frame numbers) where the events have occurred (this information is not shown in the table for the sake of clarity and readability). It can be seen from the report that the data reductionist will require lesser amount of time to locate the events using this report as compared to manually going through the video. It can be seen that the drive primarily consisted of constant velocity drive. In terms of drift, the drive has more right drifts as compared to left drifts. There were 4 instances of stopping and starting (possible intersections). There were no road departures but there was one instance of near road departure. Road delineation (absence of lane marking) was determined only for highways in this study because roads and lanes are expected to have road boundaries or lane markings respectively. There were a few instances where delineations were found on the right (five of those instances/frame numbers are indicated in parenthesis). Such lane delineations on the right indicate merging of incoming traffic from the right.

VII. CONCLUDING REMARKS

In this paper, techniques are proposed to detect events listed in the visual reference dictionary of NDS that are related to lanes and road boundaries. We have shown that applying the proposed techniques on NDS data helps to narrow down critical events during the drive. This paper focused on events related to lane drifts, road departures and missing road/lane markings, which are listed in SHRP2 visual reference dictionary. Applying the proposed techniques on real-world NDS data showed that they are robust to varying lighting, road and weather conditions. Future work involves investigations on robustness in weather conditions such as snow etc., followed by detecting NDS events related to obstacles in road scenes.

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