Research Article

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Lane Departure Warning Estimation Using Yaw Acceleration

<https://doi.org/10.1515/eng-2021-0008>

Received Jan 03, 2020; accepted Jul 28, 2020

Abstract: Lane departure collisions have contributed to the traffic accidents that cause millions of injuries and tens of thousands of casualties per year worldwide. Due to vision-based lane departure warning limitation from environmental conditions that affecting system performance, a model-based vehicle dynamics framework is proposed for estimating the lane departure event by using vehicle dynamics responses. The model-based vehicle dynamics framework mainly consists of a mathematical representation of 9-degree of freedom system, which permitted to pitch, roll, and yaw as well as to move in lateral and longitudinal directions with each tire allowed to rotate on its axle axis. The proposed model-based vehicle dynamics framework is created with a ride model, Calspan tire model, handling model, slip angle, and longitudinal slip subsystems. The vehicle speed and steering wheel angle datasets are used as the input in vehicle dynamics simulation for predicting lane departure event. Among the simulated vehicle dynamic responses, the yaw acceleration response is observed to provide earlier insight in predicting the future lane departure event compared to other vehicle dynamics responses. The proposed model-based vehicle dynamics framework had shown the effectiveness in estimating lane departure using steering wheel angle and vehicle speed inputs.

Keywords: Lane departure warning estimation, Yaw acceleration, Model-based vehicle dynamics framework

1 Introduction

Lane departure crashes count for most highway fatalities and caused hundreds of human deaths, thousands of injuries, and billions of dollars in a loss every year. It is reported in [1] Malaysia had been ranked the country with the highest fatality risk death per 100,000 population, in the world since 1996. From a global point of view, regional distribution of 750,000 fatalities with half of all casualties is coming from Asia in the year 1999 [1]. A similar trend of road fatalities, as seen in the year 1999, where the Asia continent holds more than half of all deaths in the year 2014 [2]. Furthermore, the road fatalities statistical data found in [2] had shown an inclining trend in worldwide traffic fatalities compared to the previous years, which agrees with the predicted future development of road fatalities in different regions of the world [3]. Particularly in South Asia, the expected number of road fatalities in the year 2020 is more than 3.5 times higher of the total road fatalities recorded in the year 1990.

Based on the statistical data found in [4], it is paramount to note that the 4-wheeled vehicles are still the main contributor to the global road fatalities compared to other road user types. Many related studies found in [5] had shown that single-vehicle lane departure crashes accounted primarily in road traffic deaths that result from drifting out of the roadway into oncoming traffic, into adjacent traffic or off the pavement. Hence, automotive safety has become a concern for road users as most of the road casualties occurred due to driver's fallacious judgment of vehicle path [6]. Due to that concern, automotive safety has attracted growing attention since the last decade, with many researchers working on the goal of increasing automotive safety and comfort [7]. One of the initial efforts from the researchers working on automotive safety is the exploitation of a triggered warning signal to the driver just before the accident event by using a computed risk indicator to avoid road casualties [8], like lane departure warning system.

The current lane departure warning system mainly consists of the environment detection component, namely the vision sensor, which detects the lane edge, lane mark-

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ing, and road contour [9]. Lane departure warnings are usually applicable only on highways with distinct lane markings, and the systems may be affected due to invalid activity conditions on the road. Therefore, it is also worth mentioning that lane detection remains a difficult task to be solved by on-board detection. However, this problem has been investigated and reported in many previous works [10]. Besides, the problem encountered for vision-based lane departure warning systems is image resolution issues, poor vision conditions, and a variety of lane conditions [11]. Many vision-based lanes departure warning systems decline from performance imperfection, which caused by environmental limitations.

Due to lane departure warning limitations from environmental conditions that affect the performance of identifying the correct lanes [12], a new framework development on lane departure estimation is required to enhance further the system robustness in dealing with the current challenges. For example, there is a particular sensory system that has already existed on the vehicle, which can be used with the meagre cost such as a wheel speed sensor [11] in assisting lane departure warning application. Also, vehicle dynamics motions can be utilized for sensing longitudinal velocity, yaw rate, and longitudinal acceleration. These motions are usually detected with domestic sensors like wheel speed and steering orientation communicated in the CAN bus. Previous work reported in [13] shows that any unintended lane departure is also possible to be detected by using a speedometer and yaw rate sensor from vehicle dynamics components.

In this paper, a model-based vehicle dynamics framework is proposed for estimating lane departure event using vehicle dynamics responses. This paper is organized as follows. Section 2 begins with the introduction of a model-based vehicle dynamics framework, which contains mathematical representation descriptions in subsection 2.1 for the handling model. Experimental testbed with steering wheel angle and vehicle speed datasets is described in section 3. The experimental results and discussions are presented in section 4. This paper is concluded and presented future work in section 5.

2 Model-based Vehicle Dynamics Framework

The vehicle dynamics modelling of a passenger vehicle as used in [14] is considered in this paper that consists of a single sprung mass connected to four unsprung masses and is represented as a nine degree-of-freedom system. The

sprung mass is allowed to pitch, roll, and yaw, as well as to displace in lateral and longitudinal directions [14]. Each tire is also permitted to rotate along its axle axis, and only the two front tires are free to steer. The model-based vehicle dynamics (MBVD) framework is developed using MATLAB-Simulink software. The flow chart of the MBVD framework is, as shown in Figure 1. The relationship between steering input, throttling and braking inputs, ride model subsystem, tire model subsystem, handling model subsystem, slip angle subsystem, and longitudinal slip subsystem are clearly described in Figure 1.

Figure 1: Flow chart of model-based vehicle dynamics framework in MATLAB-Simulink

In MBVD framework, three-driver inputs can be used in the vehicle dynamics analysis namely front tire steer angle, δ , throttling, and braking torques, $T_{a/b}$. It merely shows that the MBVD framework presented in this paper can perform analysis in lateral and longitudinal directions. The MBVD framework consists of the ride, tire, handling, slip angle, and longitudinal slip subsystems. The organization of this section begins with the description of the ride model subsystem in terms of the vehicle behaviours of pitching, rolling, and resulting in vertical loads, F_z , on each tire. The tire model subsystem describes the relationship between the longitudinal slip, S , vertical loads on each tire, and slip angle, α , with lateral force, F_y , and longitudinal force, F_x , on each tire. The handling model subsystem presents the three degree-of-freedom (DOF) system of yaw rate, $\dot{\gamma}$, longitudinal acceleration, a_x , and lateral acceleration, a_y , with the front tire steer angle, longitudinal forces, and lateral forces on each tire as the inputs. The slip angle subsystem illustrates the relationship of each tire's slip angle with front tire steer angle, longitudinal acceleration, lateral acceleration, and yaw rate as the inputs. The longitudinal slip subsystem illustrates the relationship of each tire's longitudinal slip with longitudinal acceleration, lateral acceleration, throttling, and braking

torques, each tire's slip angle, yaw rate, and each tire's longitudinal force as the inputs.

2.1 Theoretical Background

Intelligent vehicle system and intelligent transport system have lately appealed a growing area of research worldwide as the field of study has preferred the automotive safety that can be enhancing on comfort, safety, or efficiency of transport. In recent years, automotive manufacturers have been working on the new evolution of automotive control systems to improve automotive safety during the lane crossing manoeuvre. Due to rapid development in enhancing vehicle safety, advanced driver assistance system (ADAS) are slowly being integrated into vehicles either warning the driver in dangerous situations or automatically intervene in the driving. For example, the driver active assistance system is functioned to reduce the effect of the accident by using various sensors to help the driver controls the vehicle [15]. The passive warning signal is provided to a driver without active intervention mechanism for avoiding accidents. Hence, the vehicle's location in the centre of the roadway within the appropriate lane is an essential objective for ADAS [16]. The vital technology of ADAS applications such as lane departure warning system (LDWS) [17] has been considered in reducing the occurrence of road mishaps [18].

The vehicle lateral safety that contributed to ADAS such as automatic steering system is also conducted in a variety of areas; however, most of the works on this area are targeted for achieving automated driving [19]. Other vehicles lateral safety such as lane-keeping assistance, lane departure avoidance, and lane departure warning (LDW) [20] are also notable as steering assistance system, which available on vehicles for enhancing vehicle safety in the lateral direction. For example, lane keeping assistance is a system that works concurrently with the driver for reducing driving effort in keeping the vehicle in the appropriate lane. Lane departure avoidance is a system that counters steer the car deviating from the centre of the road [7].

The rapid progress in automotive technology and appalling concerns on automotive safety have driven the advancement of intelligent transport system such as advanced safety vehicle through the sensory system. For enhancing the automotive safety system's reliability, a variety of sensory system are combined to complement the limitations of each modality. Combination of information from many sensory systems allows for a means to approximate the confidence level by estimating the outputs from different sensory system. For example, monocular cam-

era, stereo cameras, light detection and ranging (LIDAR), RADAR, vehicle dynamics data, global positioning information received using Global Positioning System (GPS), and highly accurate digital maps have been used as a sensing system for lane perception.

2.2 Handling Model

The handling model used in this study is a 3-DOF system, as shown in Figure 2. It considers lateral and longitudinal motions of the vehicle body as well as yaw motion and additional 1-DOF due to the rotational movement of each tire. The vehicle axis coordinate system, as shown in Figure 3 is used in this paper. Figure 3 illustrated the x , y , and z axes are originated from the Centre of Gravity (CoG).

The vehicle experiences motion along longitudinal x -axis, lateral y -axis, and the angular motion for yaw about the vertical z -axis. The motion in the horizontal plane can be characterized by longitudinal and lateral accelerations, denoted by a_x and a_y , respectively. Whereas, the velocities in longitudinal and lateral directions are denoted by V_x and V_y , respectively.

Figure 2: A 3-degree of freedom vehicle handling model free body diagram

Figure 3: Vehicle axis coordinate system

Acceleration in longitudinal x -axis is defined as:

$$a_x = \frac{\sum F_x}{m} \quad (1)$$

By summing all the forces in x -axis, longitudinal acceleration can be defined as:

$$a_x = \frac{F_{xrr} + F_{xrl} + (F_{xfl} + F_{xfr}) \cos \delta}{m} - \frac{(F_{yfl} + F_{yfr}) \sin \delta}{m} \quad (2)$$

Similarly, acceleration in lateral y -axis is defined as:

$$a_y = \frac{\sum F_y}{m} \quad (3)$$

By summing all the forces in y -axis, lateral acceleration can be defined as:

$$a_y = \frac{F_{xrr} + F_{xrl} + (F_{xfl} + F_{xfr}) \cos \delta}{m} - \frac{(F_{yfl} + F_{yfr}) \sin \delta}{m} \quad (4)$$

The notation F_{xij} and F_{yij} denote the tire forces in the longitudinal and lateral directions, respectively, with the index i indicating front (f) or rear (r) tire and j indicating left (l) or right (r) tire. The steering angle is denoted by δ ; yaw rate is denoted by $\dot{\gamma}$, and m denotes the vehicle mass.

The longitudinal and lateral vehicle velocities V_x and V_y can be obtained by integration of longitudinal and lateral accelerations, respectively and can be used to get the vehicle-body-side-slip angle, denoted by β , as follow:

$$\beta = \tan^{-1} \frac{V_y}{V_x} \quad (5)$$

The yaw acceleration ($\ddot{\gamma}$) is also dependent on the tire forces F_{xpq} and F_{ypq} acting on each tire:

$$\begin{aligned} \ddot{\gamma} = \frac{1}{I_z} & \left[\left(\left[F_{xrr} \cdot \frac{t_r}{2} \right] - (F_{yrr} \cdot c) - \left(F_{xrl} \cdot \frac{t_r}{2} \right) \right. \right. \\ & - (F_{yrl} \cdot c) - \left(F_{xfl} \cos \delta \cdot \frac{t_f}{2} \right) + (F_{xfl} \sin \delta \cdot b) \\ & + \left(F_{xfl} \sin \delta \cdot \frac{t_f}{2} \right) + (F_{xfl} \cos \delta \cdot b) + \left(F_{xfr} \cos \delta \cdot \frac{t_f}{2} \right) \\ & \left. \left. + (F_{xfr} \sin \delta \cdot b) - \left(F_{yfr} \sin \delta \cdot \frac{t_f}{2} \right) + (F_{yfr} \cos \delta \cdot b) \right] \right] \quad (6) \end{aligned}$$

where b and c denote the distance between the CoG and the front axle and the rear axle, respectively. Track width t_f and t_r denote the distance between the centre of the right tire to centre of left tire at the front and rear, respectively, and I_z is the moment of inertia around z -axis.

$$F_{zfl} = \left(\frac{1}{2} mg \pm m \frac{a_y h}{t_f} \right) \frac{b}{l} - \frac{1}{2} m a_x \frac{h}{l} \quad (7)$$

The longitudinal and lateral forces acting on the tire, which are required in Equations 2, 4, and 6 can be obtained from the simplified Calspan tire model. The simplified Calspan tire model [21] is used because it was widely used in published results. As with most other tire models, simplified Calspan tire model calculates the longitudinal and lateral forces based on the vertical forces, denoted by F_{zij} , the tire slip angles, denoted by α_{ij} , and the tire slip rates, denoted by S_{ij} are given by:

$$F_{zrl} = \left(\frac{1}{2} mg \pm m \frac{a_y h}{t_r} \right) \frac{c}{l} + \frac{1}{2} m a_x \frac{h}{l} \quad (8)$$

$$\alpha_{rl} = \tan^{-1} \left(\frac{V_y + b \dot{\gamma}}{V_x \pm \frac{1}{2} t_f \cdot \dot{\gamma}} \right) - \delta \quad (9)$$

$$\alpha_{rl} = \tan^{-1} \left(\frac{V_y - c \dot{\gamma}}{V_x \pm \frac{1}{2} t_r \cdot \dot{\gamma}} \right) \quad (10)$$

$$S_{rl} = \frac{\omega_{rl} R_\omega}{v_{\omega rl}} - 1 \quad (11)$$

$$S_{rl} = \frac{\omega_{rl} R_\omega}{v_{\omega rl}} - 1 \quad (12)$$

where h denotes the height of the centre of gravity, l denotes wheelbase (distance from the centre of the front axle to the centre of the rear axle), ω_{ij} denotes the tire angular speeds, $v_{\omega ij}$ denotes the longitudinal velocity of the tires, and R_ω denotes tire radius.

The component of front tires longitudinal velocity is given by:

$$v_{\omega xfl} = V_{tf} \cos \alpha_{fl} \quad (13)$$

where the speed of the front tire is,

$$v_{tf} = \sqrt{(V_y + b \dot{\gamma})^2 + V_x^2} \quad (14)$$

The rear tires longitudinal velocity component is,

$$v_{\omega xrl/r} = V_{tr} \cos \alpha_{rl/r} \quad (15)$$

where the speed of rear tire is,

$$v_{tr} = \sqrt{(V_y - c \dot{\gamma})^2 + V_x^2} \quad (16)$$

The roll and pitch motions are dependent on the longitudinal and lateral accelerations. Since the vehicle body undergoes roll and pitch, the sprung mass, denoted by m_s has to be considered in determining the effects of handling on pitch acceleration, denotes by $\ddot{\theta}$, and roll acceleration, denotes by $\ddot{\phi}$, in Equations 17 and 18, respectively [22],

$$\ddot{\phi} = \frac{-m_s h_s a_y + \phi (m_s g h_s - \kappa_\phi) + \dot{\phi} (-\beta_\phi)}{I_x} \quad (17)$$

$$\ddot{\theta} = \frac{-m_s h_s a_x + \theta (m_s g h_s - \kappa_\theta) + \dot{\theta} (-\beta_\theta)}{I_y} \quad (18)$$

where h_s denotes the height of the sprung mass centre of gravity, g the gravitational acceleration and $\kappa_\phi, \beta_\phi, \kappa_\theta, \beta_\theta$ are the damping and stiffness constant for roll and pitch. The moment of inertia of the sprung mass about the x -axis and y -axis are denoted by I_x and I_y , respectively.

3 Experimental Testbed and Datasets

The experimental testbed was configured inside Perodua Kancil 660 EX, which consists of two units of rotary encoders, one unit of Uninterrupted Power Supply (UPS), and one unit of Desktop PC. The steering wheel angle and vehicle speed datasets were acquired using two units of Encoder Model TR1 rotary encoder [23], which they are connected to National Instruments PCIe-6321 Multifunction input/output card through the pinout board. A unit of the ro-

tary encoder was mounted at the steering wheel column, while the second unit of the rotary encoder was installed at the right-hand side of the drive shaft, as shown in Figure 5. The installation of rotary encoders with the steering column and driveshaft are aligned with their respective rotating axis to ensure the rotary wheel is fully seated on the steering column and driveshaft surfaces.

The acquired steering wheel angle and vehicle speed datasets from Perodua Kancil 660 EX are presented in Figure 6. The steering wheel angle and vehicle speed responses are shown in Figure 6 represented the datasets acquired in clip #13 [24]. From Figure 6, there is a noticeable change of steering wheel angle from time frame 8th second until 13th second to reflect the right-hand side lane departure event. The corresponding road footages of clip #13 are shown in Figure 7 to highlight the lane departure event.

Figure 4: Rotary encoder configuration on steering column and drive shaft

Figure 5: Experimental testbed for acquiring steering wheel angle and vehicle speed datasets

Figure 6: Steering wheel angle and vehicle speed datasets from clip #13

Figure 7: Corresponding road footages of clip #13

4 Experimental Results and Discussions

In order to validate the MBVD framework that has been developed, validation works are performed using CarSim Education (CarSimEd) Version [25]. This provides the validation of the MBVD framework using the visual technique by merely comparing the trend of simulation results with CarSimEd output data under a similar set of input parameters, as tabulated in Table 1. Validation is defined as the comparison of the MBVD framework's responses with the CarSimEd's responses. Therefore, the validation does not

mean the fitting of simulated data exactly to the CarSimEd output data, but as gaining confidence that the vehicle handling simulation is giving insight into the behavior of the simulated vehicle references. The simulated results are also used to check whether the input parameters for the MBVD framework are reasonable. The validation can be defined as determining the acceptability of the MBVD framework using visual techniques as performed by [21].

CarSimEd is configured to validate the MBVD framework and used to perform a Double Lane Change (DLC) test. The input parameters used in the CarSimEd are similar to the MATLAB-Simulink simulation of the MBVD framework during the validation process. The steering dynam-

Table 1: Input parameters for the model-based vehicle dynamics framework and CarSim Education

Parameter	Symbol	Value
Vehicle mass	m	1700 kg
Vehicle sprung mass	m_s	1520 kg
Coefficient of friction	μ	0.85
Front track width	t_f	1.5 m
Rear track width	t_r	1.5 m
Tire rolling radius	R_ω	0.285 m
Wheelbase	l	2.7 m
Front axle to the centre of gravity distance	b	1.11 m
Rear-axle to the centre of gravity distance	c	1.59 m
Pitch stiffness constant	β_θ	4000 N/m
Roll stiffness constant	β_ϕ	4000 N/m
Centre of gravity height	h	0.55 m
Pitch moment of inertia	I_y	50 kg m ²
Roll moment of inertia	I_x	425 kg m ²
Yaw moment of inertia	I_z	3136 kg m ²
Tire moment of inertia	I_ω	1.1 kg m ²
Pitch damping constant	κ_θ	170 000 N/ms
Roll damping constant	κ_ϕ	90 000 N/ms

ics response characteristic of the MBVD framework that includes lateral acceleration and yaw rate can be validated using CarSimEd through handling test procedures, namely DLC. DLC test is used to evaluate the road holding of the vehicle during crash avoidance. In this paper, the constant speed of 80 km/h was set for the DLC test with no braking applied throughout the experiment. A DLC predefined path will be used as the input path for the CarSimEd. Then, the corresponding steering wheel angle profile of the DLC predefined path will be used as the steering input in the MBVD framework.

Figure 8 shows a comparison of the results obtained using MATLAB-Simulink simulation and CarSimEd for the DLC test. The small differences in magnitude between the MBVD framework and CarSimEd outcomes are because CarSimEd used a multi-body based for vehicle dynamics analysis as compared to the mathematical derivation of the MBVD framework. The results of the DLC test indicate that the MBVD framework and CarSimEd simulation results agree with relatively good accuracy. In terms of lateral acceleration and yaw rate, it is clear that the MBVD framework simulation results are closely followed

Figure 8: Double lane-change test at 80 km/h constant speed with no braking applied

CarSimEd results with minor differences in magnitude, as shown in Figure 8a, and Figure 8b, respectively.

Figure 9a shows the simulation result of lateral acceleration using the MBVD framework with clip #13's steering wheel angle and vehicle speed datasets under no braking condition. Based on the vehicle axis coordinate system, an increasing trend of lateral acceleration response indicates that the motion is acting in the left direction (+y-axis) of CoG. Whereas, a decreasing trend of lateral acceleration response suggests that the movement is working in the right direction (-y-axis) of CoG. Perodua Kancil 660 EX at the 8th second begins experiencing a significant reduction trend of lateral acceleration response due to the observed right-hand side lane departure event. The lateral acceleration response reached the valley at the 10th second, which corresponds to a turning point for the steering wheel to make the counter-clockwise adjustment. Thus, an increas-

Figure 9: Results of simulated vehicle dynamics responses for clip #13 using model-based vehicle dynamics framework

ing trend of lateral acceleration response is observed for the remaining right-hand side lane departure event.

Figure 9b shows the simulation result of the yaw rate using the MBVD framework with clip #13's steering wheel angle and vehicle speed datasets under no braking condition. Based on the free body diagram shown in Figure 2, an increasing trend of yaw rate response indicates that the motion in counter-clockwise rotation around the z -axis of CoG. Whereas, a decreasing trend of yaw rate response suggests that the movement in a clockwise rotation around the z -axis of CoG. A similar observation is found in Figure 9b, where there is a noticeable change of yaw rate response occurred during the right-hand side lane departure event from 8th second until 13th second. Perodua Kancil 660 EX was experiencing a clockwise rotation around the z -axis of CoG due to clockwise turning of the steering wheel to initiate the right-hand side lane departure event at the 8th second. However, in the middle of the lane departure event at the 10th second, counter-clockwise rotation of yaw rate around the z -axis of CoG is observed, which corresponds to a turning point for the steering wheel to make the counter-

clockwise adjustment. This motion is maintained until Perodua Kancil 660 EX is fully negotiated the right-hand side lane departure event at the 13th second.

Figure 9c shows the simulation result of the vehicle-body-side-slip angle using the MBVD framework with clip #13's steering wheel angle and vehicle speed datasets under no braking condition. The vehicle-body-side-slip angle is defined as the angle between the vehicle orientation and travel direction at the CoG [26]. A distinct peak is identified in Figure 9c, where the peak reflected a noticeable change of vehicle-body-side-slip angle response occurred during the right-hand side lane departure event in-between time frame of 8th second until 13th second. During the right-hand side lane departure event, Perodua Kancil 660 EX experiencing a variation of the vehicle-body-side-slip angle at CoG due to the excitation of steering wheel angle input. Consequently, the vehicle orientation is changed, and the same goes for the travel direction at the CoG of the car.

Figure 9d shows the simulation result of yaw acceleration using the MBVD framework with clip #13's steering wheel angle and vehicle speed datasets under no braking

condition. Based on the same convention for yaw rate response, an increasing trend of yaw acceleration response indicates that the motion in counter-clockwise rotation around the z -axis of CoG. Whereas, a decreasing trend of yaw acceleration response suggests that the movement in a clockwise rotation around the z -axis of CoG. An obvious valley-to-peak is identified in Figure 9d where the valley reflected a noticeable change of yaw acceleration response occurred during the right-hand side lane departure event in-between time frame of 8th second until 13th second. Perodua Kancil 660 EX was experiencing a clockwise rotation around the z -axis of CoG due to clockwise turning of the steering wheel. The right-hand side lane departure event was started ahead of the 8th second and followed by a counter-clockwise rotation around the z -axis of CoG at 9th second due to counter-clockwise turning of the steering wheel. The yaw acceleration response reaching the peak at 11th second and reduces subsequently in the following time frame. Yaw acceleration response has provided earlier insight in predicting the forthcoming right-hand side lane departure event compared to other interventions, particularly yaw rate response. Hence, yaw acceleration response can be used for forecasting the lane departure event, especially in the application of lane departure warning.

The recommendation for future work is to reduce the dependency of vehicle state information like yaw acceleration response for the application of LDWS. A vehicle state information alone is unable to overcome the limitations of environmental factors, such as rainy conditions, drastic change of illuminations conditions like night-times, non-structural road, and clutters/shadow noise on road surface [27]. Alternatively, vision data can be fused with a local sensor like the yaw rate sensor for enhancing the LDWS reliability, particularly in urban traffic situations with a variety of road signs printed on the road background. A data-fusion with a variety of sensory systems in dealing with such conditions for estimating the vehicle location and lane edges is recommended for the future direction of LDWS. The vehicle states data such as wheel speed sensor, speed sensor, steering wheel sensor, and yaw sensor are readily available in the form of CAN bus and been used for vehicle active safety algorithms. These available vehicle resources data are expected to fill the gap of vehicle dynamics state estimation in lane detection and lane warning elements of LDWS.

The goal of having this data-fusion is to let the vision data work together with the vehicle states to enhance the reliability of LDWS performance in a variety of environmental conditions. Also, it is recommended to simplify the chain of model-based vehicle dynamics framework with

the aim of real-time implementation and reduced computational effort. The future challenges for LDWS applications include the development of higher-order vehicle dynamics mathematical model for improving the accuracy of vehicle position prediction [28]. None of the previous works had shown the interest in higher-order vehicle model integration into LDWS application.

5 Conclusion

In this paper, a model-based vehicle dynamics framework is proposed for estimating the lane departure event. The proposed model-based vehicle dynamics framework is based on nine degree-of-freedom vehicle dynamics modelling, which contained a ride model, Calspan tire model, handling model, slip angle, and longitudinal slip subsystems. In experimental, clip #13's steering wheel angle and vehicle speed datasets were acquired by using the innovative test bed configured in Perodua Kancil 660 EX. Then, the trimmed datasets were used in the model-based vehicle dynamics framework simulation for predicting vehicle dynamics responses. Based on experimental results, the lateral acceleration, yaw rate, vehicle-body-side-slip angle, and yaw acceleration responses were examined and found that all vehicle dynamics responses identified the lane departure event accurately. The yaw acceleration response was observed to be able to indicate a lane departure event in an advanced manner compared to other vehicle dynamics responses. Thus, yaw acceleration response can be used as one of the vehicle dynamics response in analysing lane departure event in the future work, particularly in the application of lane departure warning. Alternatively, the validated MBVD framework has the potential to be used in conjunction with the vision-based lane departure warning system for enhancing the detection of lane departure.

Acknowledgement: The work described in this paper was supported by Multimedia University (MMU) Mini Fund (MMUI/180170) and the Malaysia Ministry of Higher Education (MOHE) for Fundamental Research Grant Scheme (MMUE/180044).

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