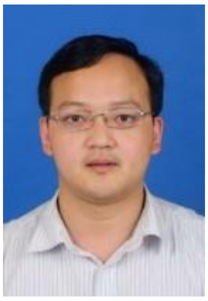
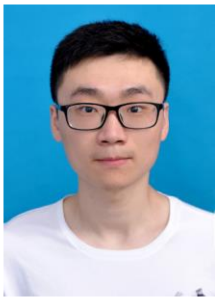
A REAL-TIME RELIABLE METHOD OF TANKER ROLLOVER WARNING BASED ON VEHICLE-ROAD COLLABORATIVE PERCEPTION







Xu Li
Full Professor
School of Instrument Science and Engineering
Southeast University

Kun Wei
Ph.D. Student
School of Instrument Science and Engineering
Southeast University

Wei Zhou
Research Fellow
Research Institute of Highway Ministry of Transport

Chunxiao Ren
Research Associate
Research Institute of Highway Ministry of Transport

Peizhou Ni
Ph.D. Student
School of Instrument Science and Engineering
Southeast University

Abstract

To improve the real-time and reliable performance of the tanker rollover warning, a novel method is proposed based on the vehicle-road collaborative perception, which includes the pre-event and in-event warning of the rollover. In the rollover pre-event warning method, it can monitor the tire state information and condition information of road ahead. When the tanker is in the potentially dangerous state, it can remind the driver to drive safely in time. In the rollover in-event warning method, three rollover probabilities are achieved based on the roll angle, lateral acceleration and yaw rate at the center of mass of the tanker. The D-S evidence theory is used to fuse the three probabilities to obtain the optimal rollover probability. According to the optimal probability, the hierarchical warning is carried out. Through the real vehicle experiment, it is proved that the proposed method can realize real-time and reliable warning of various rollover risk.

Keywords: Active Vehicle Safety Prevention and Control, Rollover Warning, Vehicle-Road Collaboration Perception, D-S Evidence Theory, Tanker

1. Introduction

In recent years, with the rapid development of the industrialized production, the demand for hazardous chemicals has continued to rise, which has led to a sharp increase in the transportation demand[1]. According to the statistics of China Federation of Logistics and Purchasing, the transportation volume of Chinese hazardous chemicals logistics industry in 2020 is about 1.739 billion tons. The road transportation volume is about 1.2 billion tons, accounting for 69%. The tanker is the tank-shaped transportation vehicle, which is used to carry various liquids, liquefied gases and powdered goods. Due to the large transportation capacity, high efficiency and low cost, the tanker has become the main vehicle for road transportation of hazardous chemicals[2]. However, the tanker body structure has the particularity and complexity, including the high center of mass, narrow track width, large vehicle weight, etc. They lead to frequent traffic accidents of the tanker on the highway.

According to the statistical analysis of 708 traffic accidents of the hazardous chemicals tanker, the main causes of tanker accidents are the rollover, rushing out of the road, rear-end collision of two vehicles, side collision of two vehicles, etc. Among them, the rollover accounts for the largest proportion that is 29.1%[3]. When the tanker carrying hazardous chemical liquids rolls over, the rupture of the tank wall causes the hazardous chemicals to leak into the densely populated areas or the natural environment, resulting in the environmental pollution, ecological damage, and other adverse effects. Due to the rapid and short duration of tanker rollover, it is difficult for the driver to detect the specific signs and take the effective measures, which makes the tanker accident difficult to avoid[4]. To reduce the frequency of tanker rollover accidents, researchers have carried out a lot of study on how to effectively carry out the tanker rollover warning.

The existing tanker rollover warning methods generally include three steps. First, the single rollover characterization parameter and the corresponding rollover threshold are defined. Then, the value of the rollover characterization parameter is obtained in real time through the sensor measurement or dynamic model estimation. Finally, the value of the rollover characteristic parameter is compared with the rollover threshold to determine whether the tanker has the rollover risk. In the above methods, the rollover characterization parameters are the key elements, which are used to quantify and evaluate the tanker rollover risk. The commonly used rollover characterization parameters include the roll angle[5], lateral acceleration[6], static stability factor[7], lateral-load transfer rate[8], time to rollover[9], tire deformation[10], etc.

Considering that the tanker on the road is susceptible to the liquid disturbance[11], the above methods have several limitations in the tanker rollover warning. First, they usually remind the driver to slow down when there is a certain degree of rollover risk in the process of tanker driving, which may lead to the problem of untimely warning. Due to the large mass and the slow deceleration process, the tanker may not be able to reduce to the safe speed in time, causing the rollover accident to still occur. Besides, they are often based on a single rollover characterization parameter to achieve rollover warning. The rollover risk identification

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method is single and the warning reliability is not high. If the value of the rollover characterization parameter obtained by the sensor or the dynamic model has a large error, it will cause the problem of false alarm when the tanker is driving safely and the problem of missing alarm when the tanker is in rollover risk.

In this paper, a real-time reliable method of tanker rollover warning based on vehicle-road collaborative perception is proposed. The novel aspects of the proposed method can be summarized as follows.

1) It simultaneously monitors the tire state information and condition information of road ahead to realize the rollover pre-event warning at a large time and space scale, thereby improving the real-time performance of the rollover warning.
2) It fuses multiple vehicle state parameters based on the D-S evidence theory and estimates the rollover risk in the form of probability to realize the rollover in-event warning under the information redundancy, thereby enhancing the reliability of the rollover warning.

2. Overview of Proposed Method

To improve the real-time and reliable performance of the tanker rollover warning, a novel method is proposed based on the vehicle-road communication[12] and D-S evidence theory. The mechanism of the proposed rollover warning method is shown in Figure 1.

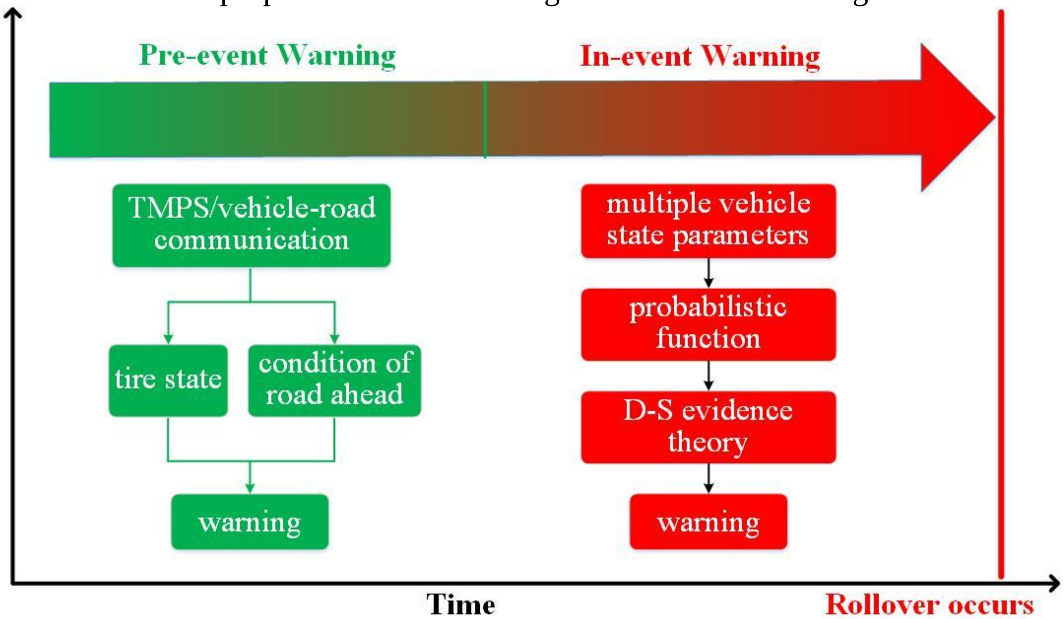

Figure 1 – Mechanism of the proposed rollover warning method

The driving state before the tanker rolls over can be divided into the potentially dangerous state and dangerous state. The potentially dangerous state is that the tanker is driving safely but it will have the rollover risk if it continues to drive. The dangerous state is that the tanker is already in the rollover risk. Aiming at two different rollover states, this paper respectively studies the warning methods of pre-event and in-event.

The pre-event warning method can remind the driver to drive safely based on the tire pressure monitoring system (TPMS) and the vehicle-road communication when the tanker is in the potentially dangerous state. It simultaneously monitors the tire state information and the condition information of road ahead to remind the driver to drive safely in time. The condition information of road ahead includes the shape turn, downward steep slope, slippery road and uneven road.

The in-event warning method can quantify the rollover risk with probability. Three rollover probabilities can be obtained from the probabilistic function with the roll angle, lateral acceleration and yaw rate output by the Inertial Measurement Unit (IMU). The optimal rollover probability can be gained by fusing the above three probabilities based on the D-S evidence theory. The hierarchical warning is carried out according to the optimal probability.

3. Rollover Pre-Event Warning

3.1 Pre-Event Warning Scenes

The tanker rollover is mainly affected by the vehicle factor and road factor. The vehicle factor is the tire burst. The road factor include the sharp turn, downward steep slope, slippery road and uneven road. Therefore, there are five scenes for the tanker rollover pre-event warning.

1) The tanker is driving safely but it will have a risk of the tire burst.

The high or low tire pressure and high tire temperature will lead to the tire burst when the tanker is driving. Once the tire burst occurs, the tanker will lose control and deviate from the original track, resulting in the side-slip, tail flick and so on. If the tanker collides with passing vehicles or road barriers on the road, it will cause the rollover.

2) The tanker is driving safely but there is a sharp turn ahead.

When the tanker makes a turn, the smaller the turn radius is, the greater the centripetal force required to safely pass the turn is. When the centripetal force provided by the lateral static friction force and the lateral force of gravity is less than the required centrifugal force, the tanker will roll over.

3) The tanker is driving safely but there is a downward steep slope ahead.

When the tanker drives down the steep slope, the speed will continue to increase due to the influence of the gravity acceleration. If the braking device fails, the tanker will not be able to maintain the safe speed and will collide with the on-road vehicles and roadside guardrails, which results in the rollover.

4) The tanker is driving safely but there is a slippery road ahead.

On the slippery road, the tire is subjected to the force of the water film and part of the tire is separated from the ground. The contact force between the tire and the road gradually tends to zero, which causes the tanker to lose control and results in the rollover accident.

5) The tanker is driving safely but there is an uneven road ahead.

When the tanker drives on the uneven road, the road has a great impact on the tanker, causing the tanker to vibrate violently. At the same time, the vertical load will laterally transfer from one tire to the other, which will cause the tanker to roll.

3.2 Rollover Pre-Event Warning in Different Scenes

1) The tanker is driving safely but it will have a risk of the tire burst.

TPMS installed on the tanker tires can output the tire pressure and temperature in real time. T_{ls} and K_{ls} indicate the pressure and temperature of the tanker left tires. T_{rs} and K_{rs} indicate the pressure and temperature of the tanker right tires. T_H is defined as the upper threshold of the tire pressure and T_L is defined as the lower threshold of the tire pressure. K_H is defined as the upper threshold of the tire temperature. When the tire pressure and temperature meet any conditions in Equation (1), the voice prompt unit plays: there is a risk of the tire burst.

$$\begin{cases} T_{ls} > T_H, T_{rs} > T_H \\ T_{ls} < T_L, T_{rs} < T_L \\ K_{ls} > K_H, K_{rs} > K_H \end{cases} \tag{1}$$

2) The tanker is driving safely but there is a sharp turn ahead.
3) The tanker is driving safely but there is a downward steep slope ahead.
4) The tanker is driving safely but there is a slippery road ahead.
5) The tanker is driving safely but there is an uneven road ahead.

The rollover pre-event warning is realized by the vehicle-road communication equipment in the above four scenes. The on-board unit (OBU) is fixed in the cab and the road-side unit (RSU) is arranged on the roadside. The rollover pre-event warning in the above four scenes is shown in Figure 2.

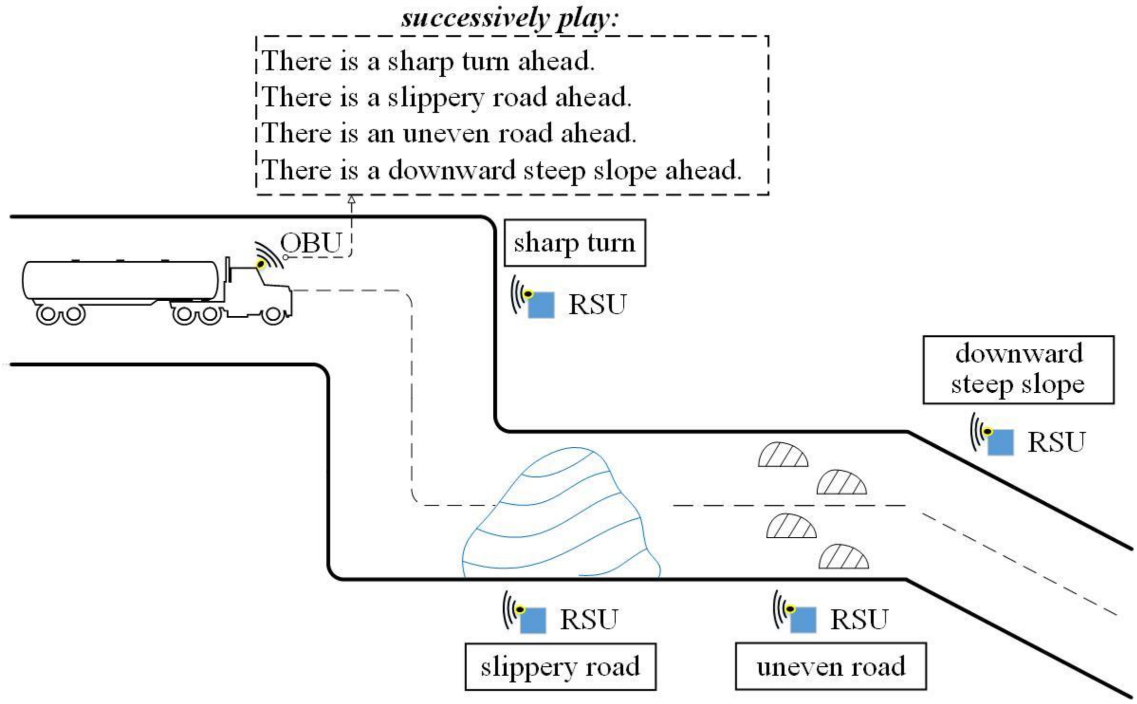

Figure 2 – Rollover pre-event warning in the above four scenes

RSU can broadcast the road condition information. OBU can receive information from multiple RSUs within the effective range of communication. When the tanker is driving, it is necessary to remind the driver of the nearest road condition information in front of the tanker. Therefore, the information received by OBU need be filtered by the distance between OBU and each RSU.

OBU and RSU can provide the longitude and latitude information. East longitude is taken as the positive value of longitude and west longitude is taken as the negative value of longitude. North latitude is taken as 90 minus the latitude value and south latitude is taken as 90 plus latitude value. (A, B) is the processed longitude and latitude information of OBU. (A_i, B_i) is the processed longitude and latitude information of each RSU. The distance d_i between OBU and each RSU can be expressed as:

$$\begin{aligned} C &= \sin(B)\sin(B_i)\cos(A - A_i) + \cos(B)\cos(B_i) \\ d_i &= R\arccos(C)\pi/180 \end{aligned} \tag{2}$$

where R is the Earth radius. The information filtering is divided into two steps:

1) If $d_i^t \geq d_i^{t-1}$, the corresponding RSU is considered to be behind the tanker. If $d_i^t < d_i^{t-1}$, the corresponding RSU is considered to be in front of the tanker. t is the current time.
2) The voice prompt unit plays the information of the RSU in front of the tanker, whose d_i^t is the smallest.

4. Rollover In-Event Warning

4.1 Probabilistic Function

When the tanker rolls, the roll angle, lateral acceleration and yaw rate at the center of mass quickly respond. Therefore, the three parameters can compensate each other and jointly reflect the change of the rollover risk. The probabilistic function is designed to obtain three rollover probabilities based on the roll angle, lateral acceleration and yaw rate.

P_α is defined to estimate the tanker rollover risk based on the roll angle, which can be expressed as:

$$P_\alpha = \begin{cases} \sin\left(\dfrac{\pi}{2\alpha_{ew}}|\alpha|\right) & |\alpha| < \alpha_{ew} \\ 1 & |\alpha| \geq \alpha_{ew} \end{cases} \tag{3}$$

where α is the roll angle output by IMU, α_{ew} is the preset roll angle threshold.

P_β is defined to estimate the tanker rollover risk based on the lateral acceleration, which can be expressed as:

$$P_\beta = \begin{cases} \sin\left(\dfrac{\pi}{2\beta_{ew}}|\beta|\right) & |\beta| < \beta_{ew} \\ 1 & |\beta| \geq \beta_{ew} \end{cases} \tag{4}$$

where β is the lateral acceleration output by IMU, β_{ew} is the preset lateral acceleration threshold.

P_η is defined to estimate the tanker rollover risk based on the yaw rate, which can be expressed as:

$$P_\eta = \begin{cases} \sin\left(\dfrac{\pi}{2\eta_{ew}}|\eta|\right) & |\eta| < \eta_{ew} \\ 1 & |\eta| \geq \eta_{ew} \end{cases} \tag{5}$$

where η is the yaw rate output by IMU, η_{ew} is the preset yaw rate threshold.

4.2 D-S Evidence Theory

P_α, P_β and P_η are three rollover probabilities based on the roll angle, lateral acceleration and yaw rate. Due to the uncertainty of three estimated results caused by various interferences, these probabilities are fused by the D-S evidence theory to get the optimal rollover probability P_{best}. The D-S evidence theory uses the probability distribution function to deal with the uncertainty.

U_1 indicates the proposition that the rollover occurs. U_2 indicates the proposition that the rollover does not occur. M_α indicates the probability distribution function based on the roll angle. $M_\alpha(U_1) = P_\alpha$, $M_\alpha(U_2) = 1 - P_\alpha$. M_β indicates the probability distribution function based on the lateral acceleration. $M_\beta(U_1) = P_\beta$, $M_\beta(U_2) = 1 - P_\beta$. M_η indicates the probability distribution function based on the yaw rate. $M_\eta(U_1) = P_\eta$, $M_\eta(U_2) = 1 - P_\eta$. M is the orthogonal sum of M_α, M_β and M_η. $M(U_1) = P_{best}$, $M(U_2) = 1 - P_{best}$. The probability table of the defined proposition is shown in the Table 1.

Table 1 - Probability table of the defined proposition

	M_α	M_β	M_η	M
U_1	P_α	P_β	P_η	P_{best}
U_2	$1-P_\alpha$	$1-P_\beta$	$1-P_\eta$	$1-P_{best}$

δ indicates the normalization constant, which can be expressed as:

$$\delta = \sum_{X_\alpha \cap X_\beta \cap X_\eta \neq \varnothing} M_\alpha(X_\alpha) \cdot M_\beta(X_\beta) \cdot M_\eta(X_\eta) \tag{6}$$

Thus, $\delta = P_\alpha \cdot P_\beta \cdot P_\eta + (1-P_\alpha)\cdot(1-P_\beta)\cdot(1-P_\eta)$.

P_{best} can be expressed as:

$$P_{best} = M(U_1) = \frac{1}{\delta} \sum_{X_\alpha \cap X_\beta \cap X_\eta = U_1} M_\alpha(X_\alpha) \cdot M_\beta(X_\beta) \cdot M_\eta(X_\eta) \tag{7}$$

Thus, $P_{best} = \dfrac{P_\alpha \cdot P_\beta \cdot P_\eta}{P_\alpha \cdot P_\beta \cdot P_\eta + (1-P_\alpha)\cdot(1-P_\beta)\cdot(1-P_\eta)}$.

4.3 Hierarchical Warning

According to P_{best}, the hierarchical warning is carried out. The alarm module is the signal light, which is fixed in the cab. The warning rule can be expressed as:

$$\begin{cases} P_{best} \le 0.5 & safety \\ 0.5 < P_{best} \le 0.7 & low\ risk \\ 0.7 < P_{best} \le 1 & high\ risk \end{cases} \tag{8}$$

The rollover warning is divided into three levels, including safety, low risk and high risk. When the tanker is in safety, the signal light is green. When the tanker is in low risk, the signal light is yellow. When the tanker is in high risk, the signal light is red.

5. Experimental Results

The design of rollover warning method is described in detail above. The feasibility of the proposed method can be verified by the real vehicle experiment.

5.1 Pre-Event Warning Experiment

Experiment of Tire Burst

One of the tanker tires is deflated to simulate the tire burst scene, which is shown in Figure 3. The voice prompt unit plays: there is a risk of the tire burst.

Figure 3 – The tire burst scene

Experiment of Single Road Factor

OBU in the cab and RSU on the roadside are shown in Figure 4. The communication range is 800m. Taking the slippery road as the example, the warning result is shown in Figure 5. In the position a, RSU is in front of the tanker. OBU can receive information from RSU and the voice prompt unit plays: there is a slippery road ahead. In the position b, RSU is behind the tanker. OBU can receive information from RSU but the voice prompt unit does not work.

OBU RSU

Figure 4 – Vehicle-road communication equipment

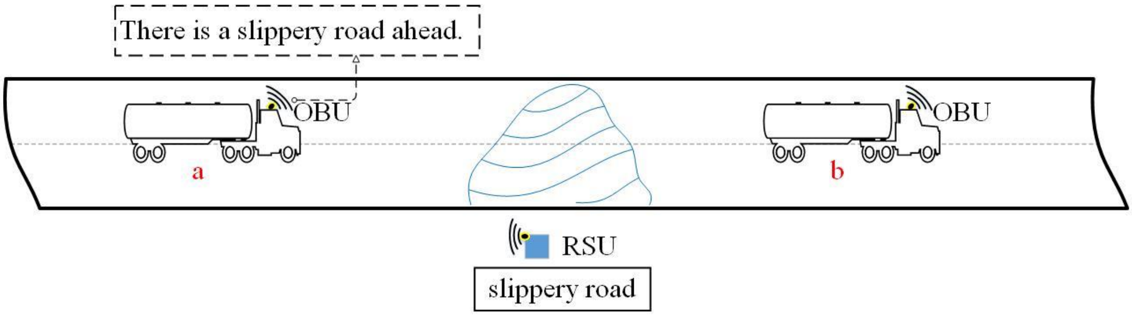

Figure 5 – Experiment of single road factor

Experiment of Multiple Road Factors

Taking the slippery road and uneven road as the example, the warning result is shown in Figure 6. In the position a, OBU can receive information from two RSUs. RSU of the slippery road is in front of the tanker and the nearest. The voice prompt unit plays: there is a slippery road ahead. In the position b, OBU can receive information from two RSUs. RSU of the uneven road is in front of the tanker and the voice prompt unit plays: there is an uneven road ahead. In the position c, two RSUs are behind the tanker. OBU can receive information from two RSUs but the voice prompt unit does not work.

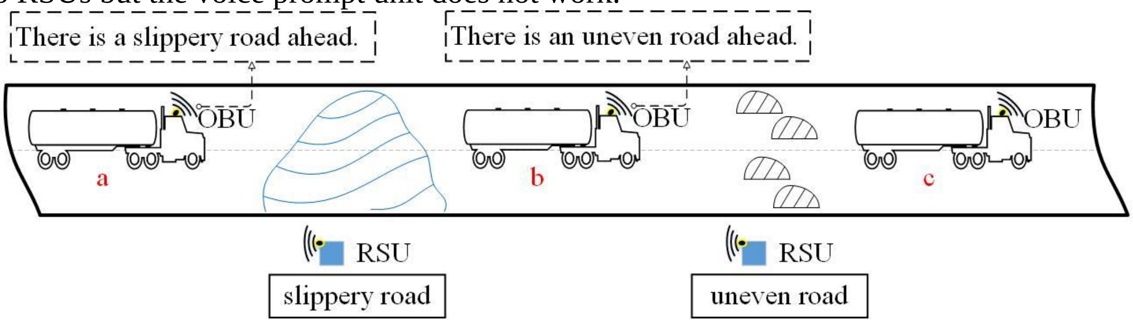

Figure 6 – Experiment of multiple road factors

5.2 In-Event Warning Experiment

Since the tanker is not equipped with the anti-rollover frame, it cannot make a turn or change lanes at the high speed. In order to ensure the experiment safety, it is necessary to choose smaller rollover thresholds to carry out the rollover warning experiment at the low speed.

Experiment of Making a Turn

The tanker makes a turn at the speed of 15km/h and the maximum value of the roll angle, lateral acceleration and yaw rate are selected as the corresponding rollover thresholds. After the rollover thresholds are determined, the tanker makes a turn at the speed of 20km/h. The rollover warning result is shown in Figure 7 and the estimated rollover probability is shown in Figure 8.

Figure 7 – Experiment of making a turn

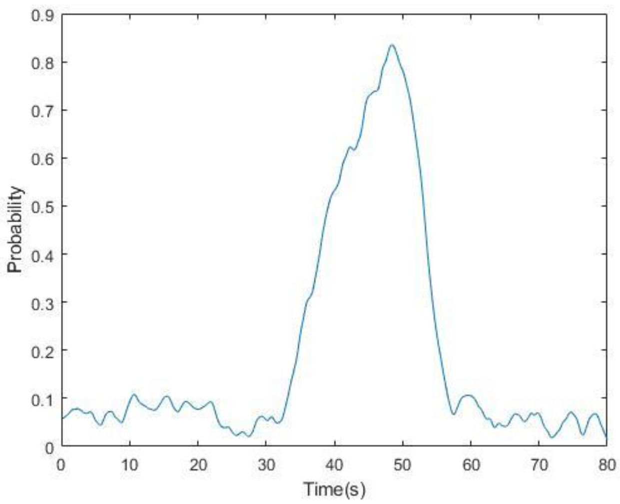

Figure 8 – Rollover probability of making a turn

When the tanker is driving in a straight line, it is in the safe state and the signal light is green. When the tanker just enters the turn, it is in the low-risk state and the signal light is yellow. When the tanker drives in the turn, it is in the high-risk state and the signal light is red.

Experiment of Changing Lanes

Like the experiment of making a turn, the tanker changes lanes at the speed of 30km/h to obtain the rollover thresholds. After the rollover thresholds are determined, the tanker changes lanes at the speed of 40km/h. The rollover warning result is shown in Figure 9 and the estimated rollover probability is shown in Figure 10.

When the tanker is driving in a straight line, it is in the safe state and the signal light is green. When the tanker starts changing lanes, it is in the low-risk state and the signal light is yellow. When the tanker returns to the positive direction, it is in the high-risk state and the signal light is red.

Figure 9 – Experiment of changing lanes

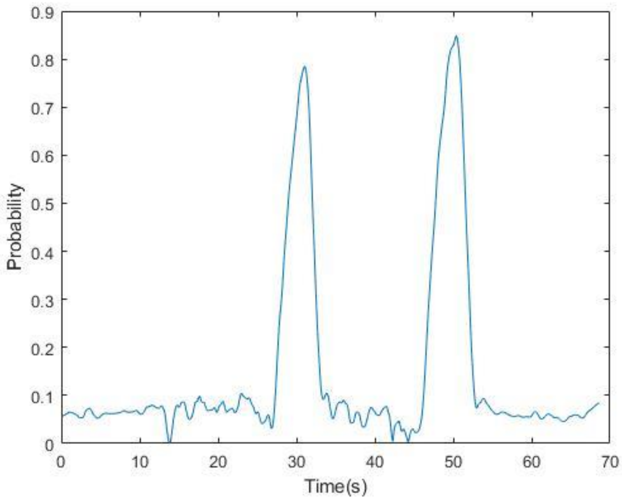

Figure 10 – Rollover probability of changing lanes

6. Conclusion

This paper has presented a novel rollover warning method for the tanker based on the vehicle-road collaborative perception. The proposed method can realize the real-time and reliable warning of various rollover risk when the tanker is on the road. The proposed method includes the pre-event and in-event warning of the rollover.

The pre-event warning method can monitor the tire state information and condition information of road ahead based on TPMS and the vehicle-road communication equipment. The experimental results indicate that the pre-event warning method can remind the driver to drive safely in time when the tanker is in the potentially dangerous state.

The in-event warning method can estimate the rollover risk with probability by fusing the roll angle, lateral acceleration and yaw rate based on the D-S evidence theory. At the same time, it can carry out the hierarchical warning. This paper carries out the rollover warning experiment of making a turn and changing lanes. The experimental results indicate that the in-event warning method can reliably estimate the rollover risk of the tanker.

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