A Novel Dynamic Rollover Threshold Model of Top-heavy Vehicle

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Abstract. This paper is aimed to propose an improved novel dynamic rollover threshold of vehicles, based on lateral load transfer ratio (LTR), which lays the foundation of rollover prediction system. The study is carried out by building a vehicle rollover model, which takes into account the characteristics of suspension and limit equilibrium of tires’ lifting-off to dynamically indicate the vehicle rolling status. Moreover, a real-time rollover warning platform is designed, on which we have compared our generalized threshold with other two commonly used thresholds. Furthermore, these thresholds in rollover are verified by a top-heavy vehicle simulation model. Results show that the novel dynamic rollover threshold can predict the impending rollover more dynamically and accurately.

Introduction

Rollovers are dangerous incidents and have a higher fatality rate than other kinds of crashes, especially for top-heavy vehicles, which have high center of gravity. Of the nearly 9.1 million-passenger car, SUV, pickup and van crashes in 2010, only 2.1% involved a rollover. However, rollovers accounted for nearly 35% of all deaths from passenger vehicle crashes [1]. Rollover has been a worldwide vehicle safety problem.

Vehicle rollover can be divided into two types: tripped and un-tripped. A tripped rollover commonly occurs when a vehicle leaves the roadway and slides sideways, digging its tires into soft soil or striking an object such as a curb or guardrail. Instead of an object serving as a tripping mechanism, un-tripped rollovers usually occur during high-speed collision avoidance maneuvers, and mostly top-heavy vehicles [2].

Researches on rollover recently are intensive and mostly focus on un-tripped rollover. C.B.Winkler et al. [3, 4] analyzed lots of rollover accidents, found that heavy vehicles were more prone to rollover accidents, because they had high center of gravity, long body, and a relatively narrow track, leading to lower static rollover threshold (SRT) than light vehicles. However, rollovers happen dynamically, Bernard J et al. [5] found that vehicles roll over at a lower threshold than static rollover threshold. Erik Dahlberg [6, 7] proposed the concept of dynamic rollover threshold (DRT), the least lateral acceleration resulting in rollover without influences of external forces, which may be different for different vehicles with the same SRT. Cooperrider et al. [8] investigated actual rollover conditions, and found that the quicker lateral acceleration increased, the shorter time the vehicle took to roll over, when its lateral acceleration exceeded SRT. The time when Preston-Thomas and Woodrooffe [9] proposed LTR as DRT, carried the rollover researches forward to practical usage in rollover prediction and prevention. Many researchers presented different LTRs as indicators in their anti-rollover systems [10-14] and verified by various axles’ vehicles [15].

We present in this paper an improved novel DRT based on LTR. We build a vehicle rollover model, considering the characteristics of vehicle suspension and limit equilibrium of tires’ lifting-off. Furthermore, we develop a much practical and generalized DRT form of LTR, under some reasonable assumptions. The model-based LTR is decided by roll angle and roll angular rate together with some
other vehicles parameters. The performances of generalized DRT comparing with two other commonly used DRTs are investigated through a bi-axial test vehicle.

**Dynamic Rollover Threshold**

**Definition of LTR as DRT**

Dynamic rollover is closely related to LTR, which could be taken as rollover indicator to evaluate vehicles’ dynamic rollover stability.

R. D. Ervin [3], in 1986, first proposed the definition of LTR and then Preston and Woodroofe [9] used it in their initial rollover-warning device, as in (1). If there is no lateral load transfer, LTR is zero; if the lateral load transfers to another side totally, LTR is ±1.

\[
LTR_{def} = \frac{(F_L - F_R)}{(F_L + F_R)}.
\]  

Many researchers began to use LTR as the normalized indicator of dynamic rollover. The following two different LTR formulas are commonly used rollover indicators, which can be compared with our novel LTR.

**Reference Rollover Thresholds**

With consideration of roll motion and roll moment, S. Selim et al. [11] proposed a dynamic rollover indicator below. From (2), we know \(k\) and \(c\) are the total torsional spring stiffness and damper coefficients, \(\phi\) is the vehicle roll angle, and \(T\) is the wheelbase.

\[
LTR_1 = -2(k\phi + c\dot{\phi}) / mgT.  
\]  

Derived from roll dynamics, the rollover estimation in (2) can detect the transient phase of rollover. However, some authors argued that this is also not sufficient to estimate the rollover since the lateral dynamics, which is a critical factor in rollover, is ignored in the formula. Furthermore, Hsun-Hsuan Huang’s rollover model [12] includes the lateral acceleration and roll dynamics simultaneously, as in (3). And \(a_{y,2}\) is a lateral acceleration of the sprung mass and \(h_R\) is the height of roll axis, measured upwards from the ground.

\[
LTR_2 = -2(k\phi + c\dot{\phi} + m_\alpha a_{y,2}h_R) / mgT.  
\]  

Cooperrider et al. [8] found that the quicker lateral acceleration increased, the shorter time the vehicle took to roll over, which means there are still additional rolling forces taking the vehicle to rollover quickly, breaking the dynamic balance of tires’ lifting-off. Therefore, in what follows, we present an improved novel dynamic rollover threshold named \(LTR_{new}\) to solve the problem.

**Improved LTR as DRT**

**Vehicle Rollover Model**

When steering or other curvilinear motions happens, the vehicle body will roll by the action of the lateral force and the vehicle's center of gravity will tilt to the outside leading to increasing lateral movement. When the inner side of the vehicle loses support, it starts to roll. A schematic of the vehicle rollover model is shown in Figure 1. Center of gravity is a virtual point of the vehicle body, which is shown in the figure as a tilted rectangle. And some assumption should be mentioned: firstly, the frame is rigid, ignoring the body elasticity; secondly, the vehicle’s unsprung mass is ignored; finally, roll angle of each axis is the same.
Considering the forces and moments are balanced in the roll movement, vehicle mass can be approximately regarded as the sprung mass. Therefore, the roll moment balance acting on the vehicle body is as follows.

\[ k \phi + c \dot{\phi} = m_s \alpha_x + m_s h_s g \phi. \]  

(4)

\[ \Rightarrow \alpha_x = \frac{(k \phi + c \dot{\phi} - m_s h_s g \phi)}{m_s h_s}. \]  

(5)

In (4), \( h_s \) is the distance of center of sprung mass, measured from roll axis of the vehicle; contrary to \( h_u \), the height of roll axis, measured upwards from the ground.

The wheels’ lateral forces and the vehicle’s inertia forces are balanced as in (6).

\[ f_1 + f_2 = m_s \alpha_x. \]  

(6)

When in curvilinear motion, \( \Delta W_j \), load of each axis transfers to the outside, then

\[ \Delta W_j \frac{T}{2} = f_j h_{u,j} + K_{\phi,j} \dot{\phi}_j + C_{\phi,j} \phi_j (j = 1, 2). \]  

(7)

The load transfer of each axis is revealed from (5), (6) and (7). According to LTR definition in (1), we can see below.

\[ LTR_{new} = -\frac{2\left((h_s + h_u) \dot{\phi} + (h_s + h_u) k \phi - m_s g h_s h_u \phi\right)}{mg h T}. \]  

(8)

We know the novel formula LTR in (8) is also relative to roll angle and roll angle rate. After some specific assumptions and verifications, this novel LTR can be used as rollover index for vehicles.

**Real-time RWP Based on \( LTR_{new} \)**

Practical usage and experiments on the novel LTR are important, so we developed a real-time rollover warning platform (RWP) based on it. If LTR is set to ±1, it will be quite dangerous in real maneuvers. The RWP, shown in figure 2, can send out warning signals when setting the LTR thresholds to a certain percentage.
RWP is consists of four modules: acquisition module, computation module, memory module and warning module. Among the four modules, computation module is the core, based on our novel LTR formula in (8), so all our inputs should meet the requirement of $LTR_{new}$, including the intrinsic parameters of the vehicle, such as sprung mass, total torsional spring stiffness, etc. and variables of the vehicle provided by inertia devices. A computation module figures out the real-time LTR value so as to estimate the rollover danger level, and a warning module will send out rollover warnings to alarm the danger. The data will be stored in the memory for subsequent analysis to testify the rollover model as well as to make some adjustments of RWP. Dataflow is transferred through CAN (controller area network) bus, which is widely used in vehicle-mounted communication.

**Verification via Experiments**

**Test Vehicle**

Parameters of the test vehicle used in experiments are full and accurate provided by the manufacturer, so it’s convenient to compute and compare different LTRs. The matrix form of (8) is shown in (9).

$$
LTR_{new} = -\frac{2}{mghT} \left( (h_u + h_i)k - m_sgh_i h_u \right) \begin{bmatrix} \phi \\ \dot{\phi} \end{bmatrix}.
$$

(9)

Besides two variables, parameters shown below in table 1 are employed to figure out $LTR_{new}$. Definitions of those parameters can refer to the former sector.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$h_s$</td>
<td>0.449</td>
<td>[m]</td>
</tr>
<tr>
<td>2</td>
<td>$h_u$</td>
<td>0.09</td>
<td>[m]</td>
</tr>
<tr>
<td>3</td>
<td>$T$</td>
<td>1.5</td>
<td>[m]</td>
</tr>
<tr>
<td>4</td>
<td>$m_s$</td>
<td>1585</td>
<td>[kg]</td>
</tr>
<tr>
<td>5</td>
<td>$g$</td>
<td>9.8</td>
<td>[m/s^2]</td>
</tr>
<tr>
<td>6</td>
<td>$k$</td>
<td>10731</td>
<td>[Nm/rad]</td>
</tr>
<tr>
<td>7</td>
<td>$c$</td>
<td>1375</td>
<td>[Nm/(rad.s^-1)]</td>
</tr>
</tbody>
</table>

**Real-time RWP Installation**

The RWP installation on the top-heavy test vehicle is shown below.

![Real-time RWP installation on test vehicle.](image)

RT3000 inertial and GPS measurement system, a critical sensor in acquisition module of RWP, fixed in the test vehicle with a supporting pole, is used to collect demanded real-time data, and send to the computing module via CAN bus and to a laptop for offline data analysis. Required data of RT3000 in the experiment is shown below in table 2. The tests under typical working conditions were performed according to the national standard of the vehicle steering stability.
Table 2. Required CAN bus data of RT3000.

<table>
<thead>
<tr>
<th>Numble</th>
<th>CAN ID</th>
<th>Data contents</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0x604</td>
<td>Velocity (Forward/Lateral)</td>
<td>Reference</td>
</tr>
<tr>
<td>2</td>
<td>0x606</td>
<td>Accelerations (Forward, Lateral, Down)</td>
<td>Reference</td>
</tr>
<tr>
<td>3</td>
<td>0x607</td>
<td>Heading, Pitch Roll</td>
<td>Variable</td>
</tr>
<tr>
<td>4</td>
<td>0x608</td>
<td>Angular Rates (body X, Y, Z)</td>
<td>Variable</td>
</tr>
</tbody>
</table>

**Test Results**

We tried to push the tests to the limit in the premise of safety, so each high-speed test need our drivers’ full attention and passengers inside the vehicle could feel the strong rolling tendency. Step and snake tests are intense driving, and we can investigate the values of LTR in table 4 and table 5 about the testing scenes.

Table 3. Max. absolute values of LTR comparison in step conditions.

<table>
<thead>
<tr>
<th>Numble</th>
<th>$LTR_1$</th>
<th>$LTR_2$</th>
<th>$LTR_{new}$</th>
<th>Max. Lateral Acc</th>
<th>Max. Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.41</td>
<td>-0.47</td>
<td>-0.49</td>
<td>-5.4 m/s$^2$</td>
<td>35.10 km/h</td>
</tr>
<tr>
<td>2</td>
<td>-0.50</td>
<td>-0.58</td>
<td>-0.59</td>
<td>-7.6 m/s$^2$</td>
<td>41.36 km/h</td>
</tr>
<tr>
<td>3</td>
<td>-0.59</td>
<td>-0.69</td>
<td>-0.70</td>
<td>-9.7 m/s$^2$</td>
<td>47.84 km/h</td>
</tr>
</tbody>
</table>

Step tests as seen in table 3, were carried out turning left with different maximum speeds, so the values of LTR are all negative, with the lateral load transferring to the right sides of the vehicle. With the speed and lateral acceleration increasing, all the values of LTR increase, but $LTR_1$ is smaller than $LTR_2$, and $LTR_2$ closer but smaller than $LTR_{new}$.

Table 4. Max. absolute values of LTR comparison in snake conditions.

<table>
<thead>
<tr>
<th>Numble</th>
<th>$LTR_1$</th>
<th>$LTR_2$</th>
<th>$LTR_{new}$</th>
<th>Max. Lateral Acc</th>
<th>Max. Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+0.47/-0.49</td>
<td>+0.54/-0.55</td>
<td>+0.56/-0.58</td>
<td>+7.0/-7.0 m/s$^2$</td>
<td>60.95 km/h</td>
</tr>
<tr>
<td>2</td>
<td>+0.51/-0.47</td>
<td>+0.58/-0.53</td>
<td>+0.61/-0.55</td>
<td>+7.3/-6.2 m/s$^2$</td>
<td>62.06 km/h</td>
</tr>
<tr>
<td>3</td>
<td>+0.55/-0.57</td>
<td>+0.62/-0.65</td>
<td>+0.65/-0.68</td>
<td>+7.4/-8.1 m/s$^2$</td>
<td>60.44 km/h</td>
</tr>
</tbody>
</table>

Unlike step tests, snake motion moves to both sides, so results shown in table 4 indicate both positive and negative trends of the vehicle. Beside the similar disciplines as in table 3, we can also see that lateral acceleration is more relevant to LTR. However, LTR is a normalized index and is smoother, so it is better than lateral acceleration as DRT.

The typical tests below in the comparison curves of LTR in figure 4 and 5 exactly indicate rolling trends of test vehicles. To be clearer about those LTRs, we set the proportion of $LTR_{new}$ to ±0.6 as rollover warning threshold. If $LTR_{new}$ is bigger than 0.6 or smaller than -0.6, warning signal is set to 1 or -1, giving out the rollover warning. Otherwise, warning signal is zero and the vehicle is safe.

![Figure 4. LTR comparison curves with lateral acceleration as reference in a step test.](image)
We have to declare that velocity presented here is just for reference, not the variable or the determinant of LTR. However, the lateral acceleration here is not just for reference but also for the figuring of $LTR_2$ in (3).

From figure 4, we can see the red warning line jumping to -1, so we know the warning signal is triggered by $LTR_{new}$. Comparing the trends and peaks of three curves of different LTRs, we also know that though $LTR_2$ and $LTR_{new}$ thought it a danger for the vehicle to rollover, $LTR_1$ thought it safe. So if it is really a danger, the rollover index $LTR_1$ will not send any warning signals.

As seen in figure 5, the snake test shows the similar trends as before, but the warning signal is not triggered by $LTR_{new}$, the most sensitive rollover index, so the red line is zero. All results on RWP show that on the test vehicle, our $LTR_{new}$ could just approach 0.70. It is already a quite high value of LTR, without anti-roll bar equipped on the vehicle.

Verification via Simulations

Simulation Platform

Experiments on test vehicle are critical but it is difficult and dangerous to get the vehicle to rollover. However, we can make the vehicle rollover truly in simulation. A Simulation platform as below is built to verify the proposed $LTR_{new}$ further. In Figure 6, a pickup model is configured together with the drive controls, and then we can get the vehicle responses, which can be used to compare $LTR_{new}$ and other thresholds.

Simulation Results

We have contrast results of rollover, as shown in figure 7 and figure 8.

Figure 7 shows two simulations of step motion with steering wheel angle (in green dash line) to be 360 degrees in 2 secs. The left one is the critical situation of safety without rollover with maximum speed 35 km/h, and the right one is the rollover situation with maximum speed of 38 km/h. Fortunately, unlike tests on RWP, we can figure out the actual load transfers under simulation, so as to acquire the $LTR_{def}$, which is the criterion for all LTRs.
From both figures, we can observe that the novel \( \text{LTR}_{\text{new}} \) much closed to \( \text{LTR}_{\text{def}} \), and both bigger than \( \text{LTR}_1 \) and \( \text{LTR}_2 \). In the right one of figure 7, when \( \text{LTR}_{\text{def}} \) is close to -1, \( \text{LTR}_1 \), \( \text{LTR}_2 \) and \( \text{LTR}_{\text{new}} \) are respectively -0.73, -0.74 and -0.84. More precisely, in the left one of figure 8, when \( \text{LTR}_{\text{def}} \) is exactly -1, \( \text{LTR}_1 \), \( \text{LTR}_2 \) and \( \text{LTR}_{\text{new}} \) are respectively -0.82, -0.83 and -0.94.

Figure 8 shows two simulations of fishhook motion with maximum steering wheel angle to be 300 degrees. The left one of figure 8 is also a limit working condition without rollover but quite close to rollover, while the right one is a rollover condition of fishhook. Not only in rollover situation, will the value of LTR in formulas run out of control, but also in a critical situation will it go too far as shown in figure 8, the fishhook with maximum speed 55 km/h, and all three LTRs exceed 1.

It is a conservative threshold of ±0.6, but we can see clearly in the right one of figure 8. When the real rollover threshold is 0.64, we send out the warning signal by \( \text{LTR}_{\text{new}} \)’s value 0.60, while the other \( \text{LTR}_1 \) and \( \text{LTR}_2 \) is 0.52 and 0.53. The novel LTR in equation (8) is much more accurate and sensitive in predicting the impending rollover than the other LTRs in (2) and (3).

Conclusions

This paper has presented an improved novel LTR threshold based on the dynamic rollover model. The proposed LTR can dynamically and accurately indicate the impending rollover status. By studying the rollover curves of different driving conditions, the characteristics of LTR in rollover can be found. In the case of no rollover, the LTRs are maintained around unity; while in the case that rollover is occurring, the LTRs increased over ±1 suddenly. To avoid rollover, it is reasonable for top-heavy vehicles to use the most accurate LTR as DRT, and set a conservative threshold of LTR.

References


