HEAVY-DUTY VEHICLE ROLLOVER DETECTION AND ACTIVE ROLL CONTROL

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Abstract: The safety of road vehicles depends on the yaw-roll dynamics. A loss of roll stability results in a rollover accident. Mechanisms to warn against rollover threat and a rollover avoidance control methodology are crucial in designing a successful active safety warning/control system for heavy-duty commercial vehicles. A dynamic rollover metric, Time-To-Rollover (TTR), has become popular in rollover detection. In this paper, the TTR metric is further studied and two extended versions of TTR metrics are proposed for rollover detection. Based on the TTR rollover detection module, a prototype Active Roll Control (ARC) system is designed. Simulation results show that a heavy-duty vehicle's roll stability is considerably improved with the rollover detection and active roll control systems proposed.

Keywords: Heavy-duty vehicle, rollover detection, active roll control

1. INTRODUCTION

The rollover of heavy-duty vehicles is an important road safety problem world-wide. Although rollovers are relatively rare events, they are particularly deadly incidents when they do occur. Winkler (Winkler *et al.*, 2000) reported that, in the US between 1992 and 1996, rollover was the cause of approximately 12% of fatal truck and bus accidents and 58% of accidents in which the truck driver was dead. In 2002, 10,666 people were killed in rollover crashes, up 5% from 2001, according to the Federal National Highway Traffic Safety Administration (NHTSA). Mechanisms to warn against a potential rollover threat and a rollover avoidance control methodology are, therefore, crucial in designing a successful active safety warning/control system for heavy-duty commercial vehicles.

Considerable previous research efforts have been expended at CAR-IT of the Ohio State University on rollover prevention of Heavy-Duty vehicles, tractor semi-trailers and tanker trucks with liquid loads. Jiang (Jiang, 2002) developed a detailed tractor semi-trailer plus tanker model with consideration of liquid sloshing effects. Lateral acceleration, trailer sprung mass roll angle and the tire load ratio were proposed in (Jiang, 2002) as three suitable candidates for rollover threat detection indices. Jiang also investigated the use of each of these indices for rollover warning through simulation studies and concluded that liquid sloshing affects tanker truck rollover stability adversely, requiring more conservative rollover indices in the presence of a liquid cargo. He proposed the use of braking in the event of a rollover threat. In other related research, Acarman et al (Acarman *et al.*, 2002) proposed a rollover prevention method based on anti-rollover braking. In reference (Acarman and Ozguner, 2003), Acarman and Ozguner applied frequency shaped sliding mode control to rollover prevention of a tanker truck with liquid loads.

The determination of meaningful and accurate rollover threat indicators is an important step in developing rollover avoidance schemes. Several indicators like the Static Stability Factor (SSF), the Tilt Table Ratio (TTR), the Critical Sliding Velocity (CSV), etc. have been around for a long time. Recently, more complicated rollover sensing algorithms appeared in the references (Schubert *et al.*, 2004), (Hac, 2002) and (Aleksander Hac and Martens, 2004), which incorporate suspension properties and dynamics. All these indicators are static in nature. Essentially, rollover accidents are related to both static and dynamic factors. Rollover detection systems based only on static rollover metrics are not expected to give out satisfactory results due to neglecting the vehicle dynamics in detecting a rollover threat.

There are more recent efforts on the development of dynamic rollover threat indicators that utilize a representative model of the vehicle for online extrapolation of the vehicle motion into the future. Among all previous study, the Time-to-Rollover (TTR) metric of Chen and Peng (Chen and Peng, 1999*b*), (Chen and Peng, 1999*a*) and (Chen and Peng, 2001) is determined to be the most promising rollover threat index. The TTR metric is not only easy to understand, but also gives a dynamic perspective. The TTR value is computed at each sampling time by simulating a lower order linear yaw-roll model until a critical rollover event happens at fixed steering wheel position. TTR rollover detection is model-based open-loop prediction algorithm and is dynamic in nature (roll and yaw dynamics not neglected).

One of the primary shortcomings of the method proposed by Chen and Peng ((Chen and Peng, 1999*b*) and (Chen and Peng, 2001)) is that it uses a simplified third order dynamics model with separated yaw-roll dynamics, which does not match truck dynamics very well during emergency maneuvers. Second, the decision of an impending rollover possibility is made by comparing body roll angle to a predefined fixed threshold. In practice, a vehicle does not necessarily rollover at a specific body roll angle. Furthermore, heavy-duty vehicles usually undergo large speed variation in emergence handling. TTR proposed by Chen and Peng loses its accuracy as it assumes fixed speed and steering input into the future. To overcome these shortcomings, a fifth order linear dynamic model considering tire compliance and yaw-roll dynamic coupling is proposed for TTR computation in this paper. Instead of roll angle threshold, Load Transfer Ratio (LTR) are used as indication of a critical rollover event. The use of Load Transfer Ratio has a direct interpretation of one-side tire lift-off. After tire lift-off happens, the vehicle dynamic behaviors can no longer be captured by the simplified linear model. It is, therefore, reasonable to study the vehicle dynamic behaviors only before a tire lift-off event and use LTR value near tire lift-off as a threshold for rollover detection. In this paper, two new TTR metrics are developed and their values are used as warning signal to an impending rollover accident. The two new TTR metrics are calculated with consideration of steering and acceleration patterns.

The paper is organized as follows. In section two, a fifth order linear vehicle model is developed. Its parameters are validated through parameter estimation and scheduling techniques. In section three, two levels of TTR metrics are proposed and computed based on the linear vehicle model. Level-two TTR is further used as a triggering command to a prototype active roll control system designed in the forth section. Conclusions and recommendations for further work are made in the last section.

2. LINEAR MODEL DEVELOPMENT

For simulation study, a nonlinear vehicle model is established in VDANL, a commercial software package for comprehensive vehicle simulation. The vehicle simulated in VDANL is regarded as a actual truck. To fulfill the fastness and accuracy requirements, a low order linear vehicle model characterizing the handling and roll dynamics of the heavy-duty vehicle should be established for online implementation.

The states of the fifth order linear vehicle model used for TTR computation are side slip angle (β), yaw rate (r), body roll angle (ϕ), body roll rate ($\dot{\phi}$) and axle roll angle (ϕ_u). Lateral acceleration can be calculated as a function of these variables. The only model input to this model is the steering angle.

$$\begin{aligned} I\dot{x} &= \bar{A}x + \bar{B}\delta, \quad or \\ \dot{x} &= Ax + B\delta \end{aligned} \tag{1}$$

$$x = \left[\, \beta \;\; r \;\; \phi \;\; \dot{\phi} \;\; \phi_u \,\right]^T$$

$$I = \begin{bmatrix} MU & 0 & 0 & m_s h & 0 \\ 0 & I_{zz} & 0 & -I_{xz} & 0 \\ 0 & 0 & 1 & 0 & 0 \\ m_s U h & -I_{xz} & 0 & I_{xs} & -D \\ -m_u U(h_u - h_r) & 0 & 0 & 0 & -D - D_r \end{bmatrix}$$

$$\bar{A} = \begin{bmatrix} Y_\beta & Y_r & 0 & 0 & 0 \\ N_\beta & N_r & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & -m_s U h & m_s g h - K & -D & K \\ h_r Y_{br} & h_r Y_{rr} + m_u U(h_u - hr) & -K & -D & K_u + K - m_u g(h_u - h_r) \end{bmatrix}$$

$$A = I^{-1}\bar{A}$$

$$\bar{B} = \begin{bmatrix} Y_d & N_d & 0 & 0 & 0 \end{bmatrix}^T$$

$$B = I^{-1}\bar{B}$$

$$Y_\beta = -(C_f + C_r)$$

$$Y_r = -MU + \frac{C_r l_r - C_f l_f}{U}$$

$$Y_d = C_f$$

$$N_\beta = C_r l_r - C_f l_f$$

$$N_r = -\frac{C_r l_r^2 + C_f l_f^2}{U}$$

$$N_d = C_f l_f$$

where l_f and l_r are longitudinal distance from front axle and rear axle to the C.G., respectively. M is total mass, m_s is sprung mass and m_u is unsprung mass. I_z denotes moment of inertia along the vertical axis and I_{xs} is the roll moment of inertia of sprung mass. H, h_r, h_u, h are height of C.G., height of axle roll center, height of unsprung mass and distance from axle roll center to C.G., respectively.

Parameter estimation is used to match the dynamics of the linear model in (1) to that of the nonlinear VDANL truck model. Parameter estimation is first carried out with typical step steer maneuvers at different speeds. These relatively simple maneuvers make it easier to capture the most important vehicle handling characteristics. The step steer candidates are chosen to spread over the scale of steering wheel angle. Speed setpoints are also chosen to cover a wide range of operation conditions from 20 t0 70 km/h. Parameter estimation results show in Figure 2 for a step steer maneuver with maximum 300 degree steering input at speed 60 km/h demonstrates a good match between the linear and nonlinear models. Simulations comparing the linear and nonlinear VDANL models are shown in Figure 3 with varying steering command and at changing speed. It is clear that the linear model is capable of capturing the main handling characteristics of the actual truck (VDANL). All these results validate the linear parameter scheduled model (1) as a good candidate to be used in model based rollover prediction/detection.

3. TIME-TO-ROLLOVER METRIC

A "Time-To-Rollover" (TTR) metric measures the time (in seconds) to an impending rollover accident. Ideally, a TTR metric will accurately "count-down" toward a pending rollover through model based prediction assuming fixed levels of current steering pattern and moving pattern, so that the danger of a rollover threat can be indicated with higher confidence. In this paper, the TTR proposed in (Chen and Peng, 1999*b*) is referred as original TTR or simply TTR.

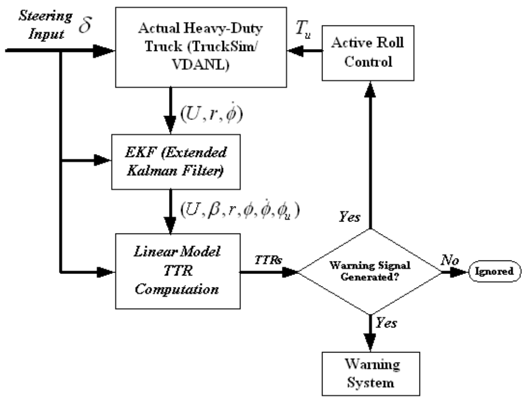

Fig. 1. Structure of TTR computation and active control/warning system

Two extended versions of TTR are proposed in this paper and are named level-one TTR and level-two TTR, respectively. The level-one TTR is defined as follows: assuming the input (steering angle $\delta(t)$) and the speed rate stay fixed at their current levels in the foreseeable future, calculate the time it takes for the vehicle load transfer ratio to reach 1 or -1. This definition presumes that the vehicle speed will continuously increase or decrease at current rate in the near future. The level-two TTR is defined as follows: assuming the input rate (steering angle rate of increase or decrease $\dot{\delta}(t)$) and the speed rate stay fixed at their current level in the foreseeable future, i.e. the steering angle will continuously increase or decrease fixed at the current rate until saturated at either maximum positive or maximum negative steering angle, calculate the time it takes for the vehicle load transfer ratio to reach 1 or -1. Level-two TTR is generated by linearly increasing or decreasing the steering angle and vehicle speed toward the future as the rates of steering and speed are held fixed in the computation. Vehicle's yaw and roll dynamics are sensitive to speed and steering input, TTR metrics extended with consideration of these factors are expected to have prompter and more accurate rollover detection quality. In practice, it is generally hard to measure the wheel load directly. The critical roll event is chosen as tire lift-off and limit values of tire load transfer ratio are used to characterize it. The load transfer ratio is calculated using the approximation equation $R_{LT} \approx K_u \phi_u$. Once the vehicle axle roll angle reaches a critical threshold value less than 1.5 sec, corresponding to total load transferred to one side, the critical roll event is detected and TTR metrics becomes the simulated time until that instant.

The TTR metrics are computed at each 0.1 seconds sampling intervals. Typical maneuvers like step steer, J-turn, fishhook are chosen as candidate handling patterns for simulation tests. By extracting current vehicle states from the actual truck (VDANL truck) running simultaneously and feeding them into the linear vehicle model, which is times faster than the nonlinear actual truck, the TTR metrics are calculated by simulating up to 3 seconds to the future until a tire lift-off is detected. The structure of the TTR based active roll control/warning system is shown in Figure 1.

Obviously, TTR metric values are usually quite large and can approach infinity in normal driving situations. For implementation, they are saturated at 3 seconds because it is not necessary and not dependable to extrapolate the vehicle's behaviors longer than 3 seconds. In other words, if it is found that the vehicle does not rollover in the next 3 seconds, the TTR metrics will be set at 3.0 seconds.

In a fishhook maneuver simulation, the online TTR computation records are shown in Figure 4. There are a tire lift-off happened at 6.5 seconds and a near tire lift-off happened at 5.6 seconds. It is clear from the figures that level-two TTR gives out two sets of warning signals at both instances. As a result, a rollover warning can be obtained at about 1 sec in advance of a real wheel lift-off event. Even though the truck does not experience tire lift-off at 5.6 second, it is still dangerous enough to be cautious. On the other hand, level-one TTR is conservative as it only detects the impending danger near 6.5 seconds. From the results, it is also observed that the original TTR is poor in detecting an impending rollover event with its first warning signal sent only 0.15 seconds ahead of the actually wheel lift-off event, which is not early enough for further reaction. It is not surprising to see that the original TTR gives a too conservative warning in rollover detection. It usually can not foresee an impending rollover promptly enough especially in emergency handling due to its shortcomings stated ahead. The level-one TTR gives prompter and more accurate indicating of impending rollover event in maneuvers accompanying speed variation. The level-two TTR is more aggressive in detection of an impending rollover possibility in most driving scenarios. Even though some warnings are not necessary, level-two TTR is able to gives more accurate and earlier detection of an impending rollover during sharp maneuvers. And this will save more time for roll stability control/warning systems to take effect. Thus, level-two TTR is selected as the triggering command to the active roll control system in the following study such that the system can have a larger time margin to counteract excessive roll tendency.

4. ACTIVE ROLL CONTROL SYSTEM

In this section, an Active Roll Control (ARC) system is designed based on the Linear Quadratic Regulator (LQR) method. Such an ARC system designed works in combination with the TTR module to administrate the vehicle roll dynamics, where level-two TTR signal serves as triggering command to the active control unit.

The design of an active roll control system is a problem of optimal disturbance rejection if the unforeseeable steering input is viewed as unknown disturbance, i.e. an arbitrary signal. It is desirable to optimize the active roll control system across the range of all possible steering inputs rather than in response to a constant steering value.

The steering input can be modeled as a colored noise process by filtering white noise through a band limited low pass filter. Such a filter was proposed in (Sampson *et al.*, 1999) as

$$S_\delta(\omega) = \frac{m_1}{\omega^2 + m_2} \tag{2}$$

This corresponds to white noise filtered with a first order filter with a cut-off frequency of m_2 $rand/s$ and static sensitivity m_1 :

$$\begin{aligned} \dot{x}_f &= -A_f x_f + B_f w \\ \delta &= C_f x_f \end{aligned} \tag{3}$$

LQR control law minimizes a chosen performance index according to application requirements set by the user. By selecting weighting matrices Q and R properly, a compromise can be achieved among design objectives and control efforts. The active roll control system design is thus a tradeoff between reducing lateral load transfer, constraining suspension roll angle and limiting energy consumption by active actuation components. In our study, the weighting matrices Q and R penalize the axle roll angle output $z = \phi_u$ and the control input $u = T_s$ respectively.

The linear model with active control input T_s is:

$$\dot{x} = Ax + B\delta + B_u T_s \quad (4)$$
$$B_u = I^{-1} \left[0\ 0\ 0\ 1\ 1 \right]^T$$

Combining the filter dynamics into this model, the new version of extended model obtained is:

$$\dot{X} = \tilde{A}X + \tilde{B}T_s$$
$$Z = \tilde{C}X \quad (5)$$

$$\tilde{A} = \begin{bmatrix} A & BC_f \\ 0 & A_f \end{bmatrix}$$
$$\tilde{B} = \left[B_u\ 0 \right]$$
$$\tilde{C} = \left[0\ 0\ 0\ 0\ 1\ 0 \right]$$
$$X = \left[\beta\ r\ \phi\ \dot{\phi}\ \phi_u\ \delta/C_f \right]$$

The ARC feedback control design is carried out based on the linear model. For a nominal speed of $60km/h$, the weighting matrices are chosen to be:

$$Q = 17 \quad R = 2.8 * 10^{-14} \quad (6)$$

This produced a full-state feedback controller

$$K_{fb} = -LQRY(sys, Q, R)$$
$$= \left[-0.4423\ 0.1200\ -0.0864\ -0.0849 \right.$$
$$\left. 3.3899\ 0.2874 \right] \times 10^6 \quad (7)$$
$$T_s = K_{fb}\bar{C}X \quad (8)$$

This ARC feedback controller is created in VDANL as an active suspension controller. TTR module is running throughout the VDANL simulation simultaneously. Since the axle roll angle ϕ_u is not measurable directly, it is obtained through a Kalman filter and used both in the TTR module and the LQR output feedback controller. The active roll control module is triggered on after the first level-two TTR signal less than 1.5 is sent out. With the same fishhook maneuver simulated in last section, simulation results with ARC in VDANL are shown in Figures 5 − 7. The active roll control module is triggered on at 5.1 second where the level-two TTR value is 1.37 seconds. By forcing the sprung mass inward toward the center of turning, load transfer is greatly reduced and the roll stability is improved accordingly. In Figure 5, the TTR signal that triggers the active roll controller are plotted. In Figure 6, wheel loads are compared in cases with and without active roll control. Vehicle body roll angle and axle roll angle in simulations with and without active roll control are compared in Figure 7. It is clear that the vehicle roll stability in fishhook maneuver has been largely improved with the active roll controller designed. It should be noted that in Figure 5, the model embedded in TTR module is not capable of capturing the vehicle dynamic with active roll control. So, after the initialization of ARC, TTR computation results are no longer accurate detection of impending rollover with current setup. By attaching the ARC controller to the linear model in TTR module, the TTR module will be able to work after the ARC turns on. This is proposed to future research.

5. CONCLUSIONS

In this paper, Time-To-Rollover (TTR) metrics are proposed and studied for online rollover detection/prediction. Based on a fifth order linear vehicle model with parameter scheduling, TTR metrics computed in simulations give prompt and accurate indications of an impending rollover accident. A prototype active roll control system is designed and works in combination with the TTR rollover detection module. Using level-two TTR as triggering command, the proposed active roll control system largely improves the roll stability of heavy-duty vehicles, especially in emergency maneuvers. The results of an on-going research are presented in this paper.

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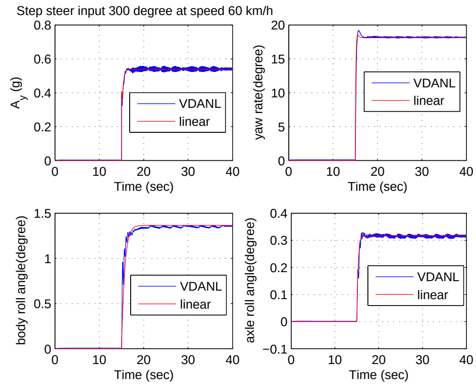

Fig. 2. Parameter estimation with 300 degree steering wheel input at 60 km/h

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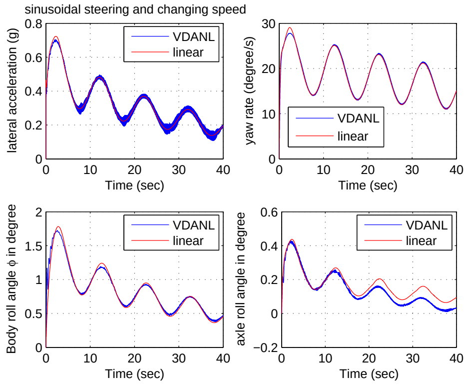

Fig. 3. Model matching simulation with continuously changing speed

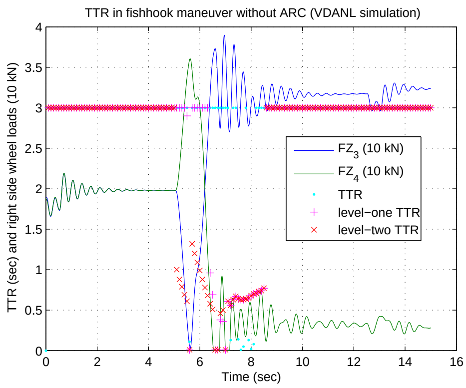

Fig. 4. TTR in VDANL simulation of fishhook maneuver

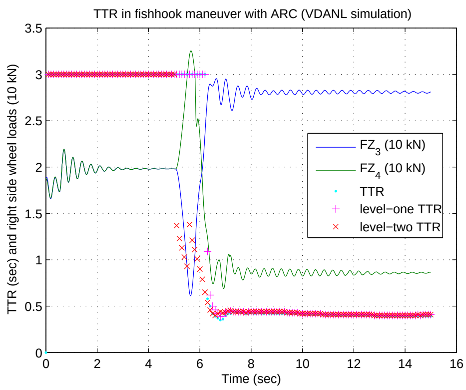

Fig. 5. TTR in VDANL simulation of fishhook maneuver with active roll control system

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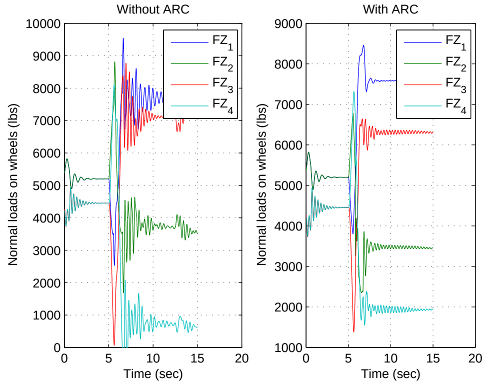

Fig. 6. Comparison of simulation results with/without Active Roll Control in fishhook maneuver

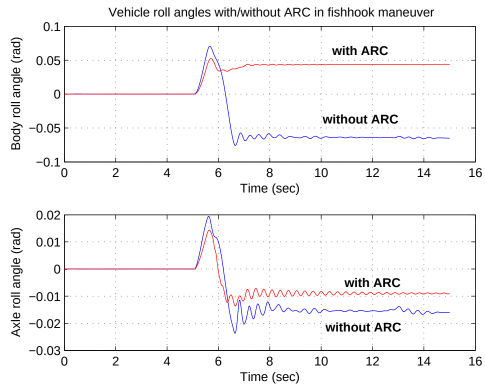

Fig. 7. Comparison of simulation results with/without Active Roll Control in fishhook maneuver

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