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A roll stability performance measure for off-road vehicles

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Abstract

The roll stability is significant for both road and off-road commercial vehicles, while the majority of reported studies focus on road vehicles neglecting the contributions of uneven off-road terrains. The limited studies on roll stability of off-road vehicles have assessed the stability limits using performance measures derived for road vehicles. This study proposes an alternative performance measure for assessing roll stability limits of off-road vehicles. The roll dynamics of an off-road mining vehicle operating on random rough terrains are investigated, where the two terrain-track profiles are synthesized considering coherency between them. It is shown that a measure based on steady-turning root-mean-square lateral acceleration corresponding to the sustained period of unity lateral-load-transfer-ratio prior to the absolute-rollover, could serve as a reliable measure of roll stability of the vehicle operating on random rough terrains. The robustness of proposed performance measure is demonstrated considering sprung mass center height variations and different terrain excitations. The simulation results revealed adverse effects of terrain elevation magnitude on the roll stability, while a relatively higher coherency resulted in lower terrain roll-excitation and thereby enhanced vehicle roll stability. Terrains with relatively higher waviness increased the magnitude of lower spatial frequency components, which resulted in reduced roll stability limits.

Keywords: Off-road vehicle; Tire–terrain interaction; Roll stability; Performance measure

1. Introduction

The roll stability is among the most significant factors for commercial road as well as off-road vehicles, while the vast majority of reported studies focus on only road vehicles assuming negligible contributions of road roughness (e.g., Goldman et al., 2001; Kamnik et al., 2003; Dahlberg and Stensson, 2006). The maneuver-induced dynamic roll stability of commercial road vehicles have been widely investigated during cornering maneuver considering smooth road surface in addition to various design factors affecting the roll stability limits (Goldman et al., 2001). These have evolved in various performance measures to assess relative roll stability limits of vehicles such as static and dynamic rollover threshold, lateral load transfer ratio (LTR), roll safety factor (RSF), rearward amplification (RA) and rollover prevention energy reserve (RPER) (Preston-Thomas and Woodrooffe, 1990; Nalecz

Abbreviations: cg, mass center; DRT, dynamic rollover threshold; ELA, effective lateral acceleration; LTR, lateral load transfer ratio; MVEE, Military Vehicles and Engineering Establishment; PI, proportional integral; PSD, power spectral density; RA, rearward amplification; RSF, roll safety factor; RCF, rollover critical factor; RMS, root mean square; RPER, rollover prevention energy reserve; SSF, Static Stability Factor

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et al., 1993; El-Gindy, 1995). Compared to road vehicles, only a few studies have reported roll stability analyses of off-road vehicles, which is partly due to relatively low speed operations of traditional off-road vehicles. High load-capacity and high-speed vehicles, however, are being increasingly employed in the resource and construction sectors to achieve enhanced productivity and operational efficiency (Bozorgebrahimi et al., 2005). The demand for high load-capacity and high-speed vehicles has been steadily growing, especially in the open-pit mining sector. A recent study has identified relatively higher frequency of fatal accidents of mining trucks, primarily attributed to vehicle rollover, apart from the structure failures and vehicle collisions (Drury et al., 2012). In order to limit the frequency of mining vehicle accidents, especially the vehicle rollover, speed limits ranging from 30 to 60 km/h have been widely reported in the mining sectors (Jois, 2011). Both the greater load capacity and high operating speeds have contributed to greater concerns related to the operational safety of such vehicles.

Owing to tires' interactions with relatively rough terrains, the off-road vehicles exhibit considerably different roll dynamics compared to the road vehicles (Crolla, 1981). In the presence of the terrain roughness, the coupled vertical and lateral tire–road interactions could adversely affect the vehicle roll dynamics and thereby the stability limits (Li et al., 2013). The changes in terrain elevations cause not only considerable variations in restoring roll moment attributed to tires' normal forces, but also affect lateral forces developed by tires and thereby the directional performance of the vehicle. Moreover, tires' interactions with rough terrains could yield greater roll and pitch motions as well as load transfer between tires of different axles, which may adversely affect roll stability of the vehicle (Pazooki et al., 2013). Considerations of tires' interactions with rough terrains would be important for assessing roll dynamic performance and stability limits of off-road vehicles.

A few studies have illustrated the adverse effects of terrain roughness on vehicle roll stability (Gonzalez et al., 2007; Li et al., 2013; Pazooki et al., 2013). Gonzalez et al. (2007) investigated roll dynamics of a vehicle where the random terrain excitation was represented by an equivalent force applied to the vehicle unsprung mass. The study concluded that in the presence of terrain roughness, the vehicle wheels may lift-off the ground before the vehicle approaches its rollover threshold limit. Li et al. (2013) and Pazooki et al. (2013) investigated terrain-induced vertical and roll responses of off-road vehicle models considering time history of the random terrain elevation and high coherency of low frequency components of the left- and right-terrain tracks. Li et al. (2013) investigated rollover risk of the vehicle negotiating a fishhook maneuver at a constant forward speed of 54 km/h on road surfaces B, C and D defined in ISO-8608 (1995). The study concluded that the roll stability limit decreases with increasing terrain roughness, which was assessed in terms of peak normalized rollover critical factor (RCF) as a function of the vehicle roll angle and instantaneous position of the mass center (cg). Pazooki et al. (2013) investigated the static and dynamic rollover thresholds of an articulated frame steered vehicle during constant-speed turning and path-change maneuvers, considering different off-road terrains, namely, pasture, MVEE (Military Vehicles and Engineering Establishment) course and plowed-field. The study employed a roll stability measure based on effective lateral acceleration (ELA) at the instant of rear axle wheel lift-off when the roll safety factor approaches a unity value (RSF = 1).

The roll stability limits of off-road vehicles in the aforementioned studies have been assessed using measures defined for heavy road vehicles. The validity of these measures, defined for road vehicles assuming negligible contributions due to tires' interactions with relatively rough terrains, may be questioned. Moreover, in off-road operations, the stability indicators based on peak ELA, RSF or RCF cannot be determined reliably due to large variations in these measures that are caused by tires' interactions with randomly distributed terrain roughness. Alternate measures thus need to be defined for assessing roll stability limits and rollover risks of off-road vehicles in the presence of terrain roughness. The above-stated studies have provided valuable insight into the effects of terrain elevation magnitude on the roll dynamics stability limits of off-road vehicles, while the effects of spectral distribution of terrain roughness have not been attempted. Moreover, these studies employed point-contact tire models neglecting the tire–terrain contact patch, which would likely yield errors in the roll stability measures due to more frequent wheel lift-off, particularly for shorter wavelength terrains (MSC software, 2010).

In this study, a roll stability performance measure is proposed for off-road vehicles considering magnitude and spectral contents of the terrain. A comprehensive mining truck model is constructed in the TruckSim platform coupled with the Matlab/Simulink to evaluate its roll dynamic responses under different terrain excitations. The vehicle model considers the variation of tire footprint using circle-line approach, while the tire force is evaluated considering a non-linear point-contact tire model. The roll dynamic responses obtained during cornering maneuver are analyzed to derive the roll stability performance measure. The robustness of proposed performance measure is subsequently assessed, and the effects of magnitude and frequency components of the terrain on roll stability limits of the off-road vehicle are studied as well.

2. Vehicle model formulation

A multi-body dynamic model of a 50 tons mining truck is constructed in the TruckSim simulation platform to study its roll dynamics behavior. The TruckSim platform permits modeling and integration of various vehicle subsystem models, such as tire, suspension and steering, in a convenient manner using either lumped-parameters or