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Modeling the effect of liquid movement on the center of gravity calculation of agricultural vehicles

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Abstract

Due to a high center of gravity (CG) location, agricultural vehicles are more vulnerable to overturns. The CG location can be calculated using the lifting axle method of ISO 16231-2:2015. But, as a vehicle is lifted, its liquid payloads are not entirely contained. The liquids will shift both in position and form, affecting the CG height calculation.

A mathematical model was developed to predict the effect of liquid movement on the CG height calculation of a tilted vehicle. The model was validated using an agricultural utility tractor and a prototype. The developed model was applied to calculate the CG location considering the effect of the liquid shift.

Results showed tilting produced a higher calculated center of gravity due to liquid movement, but by increasing the tilting angle, the calculated CG height decreased. The effect of the liquid shift on CG height measurement for the wagon with 16.0% liquid mass was 14.8% and for the tractor with 1.2% liquid mass was 0.41%. The model error was less than 1.3% for all tests. Considering the effect of the liquid shift in CG height calculation, the error in CG height calculation decreased from 11.9% to 2.6% for the wagon.

Keywords: Center of gravity; Stability; ISO 16231-2:2015; Liquid shift; Tractor; Overturn; Safety

1. Introduction

The center of gravity (CG) is the location of a theoretical point representing the total mass of a body. Dynamic and static free-body calculations routinely use CG, including studying vehicle stability (Demšar et al., 2012; Spencer, 1978), vehicle dynamics (Hyun and Langari, 2003), and vehicle continuous rolling (Fabbri and Molari, 2004). Since agricultural vehicles often possess many irregular shapes, it is practically impossible to find the CG location using analytical methods. Various techniques can physically determine the CG of vehicles. These methods are vertical hang (ISO, 1982), pendulum (Fabbri and Molari, 2004; ISO, 2011), lifting axle (ISO, 2014; Liljedahl et al., 1996; OECD, 2002; Wang et al., 2016), and tilt table. The lifting axle method (LAM) is a popular method for determining the CG height of a vehicle (ISO, 2011). In the LAM, the lateral and longitudinal CG dimensions can be measured when the vehicle is in a horizontal position. The lateral and longitudinal CG measurements are straightforward; however, the CG height measurement is a complicated procedure. When measuring the CG height of a vehicle, one axle is lifted, either the front or rear. Measured parameters in the LAM are load distribution on all tires when the vehicle is in a horizontal position, the load on the raised axle in the lifted vehicle, and some structural geometries of the

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vehicle. Several factors affect CG height measurement in the LAM, such as, scale accuracy, lifting height, liquid shift, tire deflection, loose mechanical component movement, and vehicle structure deflection.

Several authors evaluated the effect of liquid shift on CG location (Khorsandi and Ayers, 2015; Wang et al., 2016). Wang et al. (2016) used a test method to measure the effect of loose mechanical parts (e.g., springs, elastic cells) and fluids (e.g., fuel, hydraulic, and lubricant oils) on the CG height of a zero turning radius (ZTR) mower. Their test method followed ISO 16231-2. ISO 16231-2 is a standard method for stability assessment of self-propelled farm machinery (ISO, 2015). The first section of ISO 16231-2 describes measuring the CG location of non-laden, self-propelled, agricultural machinery. This standard employs the LAM. Wang et al. (2016) found that the liquid shift within a tilting vehicle affects its CG height calculation. However, ISO 16231-2 recommends to take into account the effect of moving liquids on the CG height calculation, but no method was provided to quantify the effect of liquid shift on CG height calculation.

Measurement standards call for tilting the vehicle in determining the CG height. As a vehicle tilts, any unrestrained liquids inside the vehicle shift in both their position and shape (Fig. 1). Several researchers suggest that the liquid shift affects the CG height calculation in the LAM (ISO, 2011; Wang et al., 2016) and pendulum method (Fabbri and Molari, 2004). Liquids commonly found in agricultural vehicles are fuel, coolants, hydraulic oils, lubricants, battery electrolyte, and liquid tire ballast.

Several standards provide suggestions to decrease the impact of uncontained liquid movement and tire deflection on CG measurements. Following ISO 789/6 (ISO, 1982), which is a standard for measuring CG height of an agricultural tractor, evaluators fill the radiator, hydraulic, and other reservoirs to a particular working level. The fuel tank is full, empty, or at a specified quantity that the manufacturer and the testing authority agrees upon (ISO, 1982). ISO 10392 (ISO, 2011) is a standard method for determining the CG of road vehicles. Based on ISO 10392, the fuel tank is full. Furthermore, this standard requires evaluators to note any effects of other liquids that may move.

Although many experts acknowledge that the liquid shift in a tilted vehicle affects the measurement of its CG, few studies have investigated the extent of the effect. Currently, there is no recommendation to adjust the CG height calculation due to liquid movement. Therefore, the overall goals of our research are to (1) develop a theoretical model to predict the effect of liquid repositioning on the CG location, (2) validate the model using a prototype wagon and an agricultural utility tractor, and (3) apply the developed model to calculate the CG location of vehicle considering the effect of liquid shift.

2. Materials and methods

The procedure is divided into three parts based on the specific objectives. The first part includes generating an analytical model to quantify the liquid shift and predict the effect of liquid movement on CG height calculation. The second part includes the model validation using a wagon that carries a liquid tank and a full-size agricultural tractor. The results of experimental tests were used to validate the developed model. The third part includes applying the experimentally measured data and calculate the CG location by considering the liquid shift.

2.1. Developing analytical model

An analytical model was developed to predict the effect of the liquid shift on CG height calculation in the LAM. The CG height calculation depends on the load on the rear and the front axles. By tilting the vehicle, the load distribution on the rear and the front axles changes, which is called weight movement. The weight movement means weight shifts from the raised axle to the fixed axle due to the

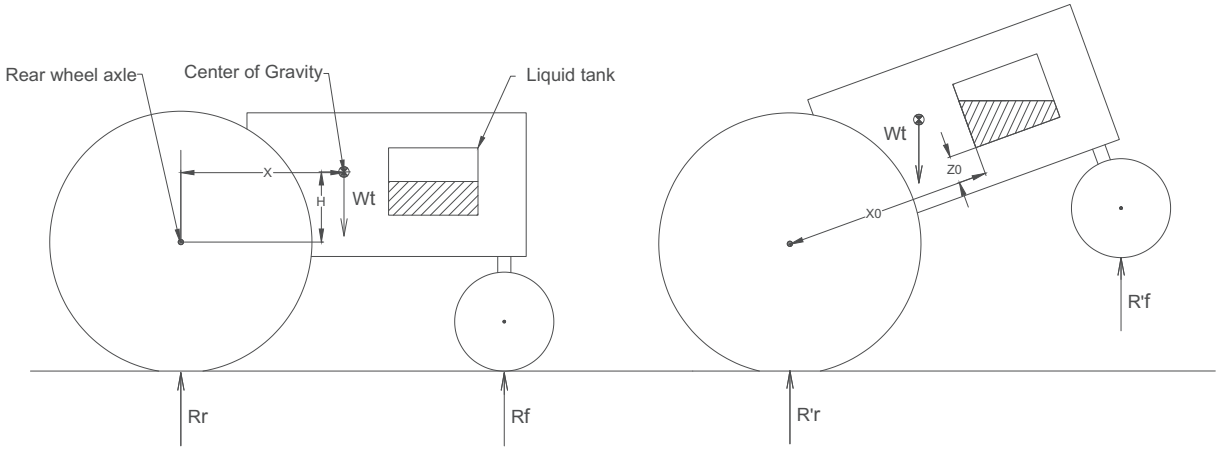

Fig. 1. Liquid fuel shifts in position and shape within a partially filled fuel tank: (a) level and (b) tilted.

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