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Full Length Article

Optimization of suspension system and sensitivity analysis for improvement of stability in a midsize heavy vehicle

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ABSTRACT

This paper presents a method for systematic investigations on static and dynamic roll behavior and improvement to the stability dynamics based on increasing roll stiffness of the suspension. One of the major differences of this study from previous work is that it includes parametric sensitivity analysis in order to increase the safety margin from the roll angle threshold using the static and dynamic tests and it compares the results within themselves. As the physical tilt table test cannot be continued until vehicle rollover actually occurs, this test was performed in a simulation with verified vehicle model using Adams/Car. Three different front anti-roll bars and two different front leaf springs were used during the tests in order to perform parametric sensitivity analysis and examine the effect of components on the stability performance.

In summary, within the scope of this work, unlike the previous studies, experiments involving physical tests (i.e. tilt table, fishhook and cornering) and numerical calculations are included. In addition, verification of the virtual model, parametric sensitivity analysis and the comparison of the virtual test and the physical test is performed. Because of the vigorous verification, sensitivity analysis and validation process, the results can be more reliable compared to previous studies.

1. Introduction

Heavy commercial vehicles may have stability problems when the driver must perform a quick maneuver to avoid an unexpected obstacle in the road.

Studies have shown that most of the severe roll-over accidents have been caused by poor dynamics which may be characterized by non-optimized roll stiffness and roll steer coefficient. The main group of vehicles which are more prone to rollover-accidents are buses and heavy-vehicles. Therefore, in this study, a virtual model of the midi bus (e.g. a heavy vehicle) is used to evaluate the stability based on roll stiffness and roll steer coefficient. In contrast to passenger cars, in midi-buses, the height of the centers of gravity and sprung mass are higher. Therefore, the design improvement for the stability characteristic of the midi bus is considered as a necessity.

In previous studies, the type of suspension and its subsystems such as anti-roll bar, leaf spring and shock absorber were identified as critical in the overall stability of the vehicle [2,13,14,19]. Studies have shown that mechanical suspension containing leaf spring positively affected the stability of the vehicle because roll stiffness of the suspension is higher than the traditional suspension systems containing air bellow [13]. Air suspension was identified as negatively impacting on stability. Therefore, if the suspension allows more roll to occur (low roll stiffness), the yaw-roll dynamic mode of the vehicle become weak and tendency of vehicles to roll over increases. For this reason, the stability of the vehicle will be improved by increasing the roll stiffness of the suspension.

The stability of the vehicle is determined by torque values acting about the ground plane. To determine the stability characteristics of the vehicle, information related to the vehicle behavior during cornering, the main features of the vehicle such as center of gravity, track width and weight parameters should be considered as well as static stability factor (SSF).

Abbreviations: RCH, roll center height of the suspension; RS, roll stiffness; α, roll angle; Kø, suspension roll stiffness; h, center of gravity height; J, cost function of optimization algorithm.

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As mentioned in the previous section, the lateral force that can be generated during cornering produces an overturning torque. Therefore, it tends to force the body to roll over. Lateral force at the center of gravity (CoG) can be translated to the roll center if the appropriate forces and moments [1,20] are known. On the other hand, roll-center can be defined as a function of the load transfer characteristics of a suspension system [2]. The suspension plays an important role in handling and stability through its effects on body roll. In a similar way, suspension causes the center of gravity of the body to roll outward in a turn relative to the axle [3]. Therefore, the characteristics of the suspension including roll stiffness take an important role for the stability because the roll stiffness is the most dominant parameter affecting the sprung mass movement. Suspension determines how sprung mass moves around the axis of rotation.

Roll stiffness is the torsional stiffness determined by the stiffness of the suspension measured about the roll center. If the suspension system has very stiff springs and anti-roll bars on one side, they cause less movement on the side they are assembled. Anti-roll bars are used in vehicles in order to provide roll-stiffness to enhance vehicle handling and stability during fast cornering. In previous studies, it was possible to obtain a considerable gain in reducing rolling when using the anti-roll bar [4]. If the anti-roll bar diameter is changed, the stiffness of the anti-roll bar also changes. Using this simple relation, in this study, roll angle is reduced as much as possible by increased anti-roll bar and leaf spring stiffness via changing the diameter. Then the results are verified using static and dynamic tests. Stiffness of the anti-roll bar is calculated according to the SAE standards in each experimental analysis [5].

The anti-roll bar and leaf spring characteristics have been determined according to the design criteria that is created in benchmarking phase. If stiffness of the front anti-roll bar was increased more, this situation caused the understeer behavior to increase eventually leading the understeering characteristics to reach a dangerous limit. Therefore, the front anti-roll bar stiffness is limited to three different diameters in the parametric sensitivity analysis. The front leaf spring is chosen based on the allowable bearing capacity of the front axle and the ride height of the vehicle. Therefore, the stiffness of the front leaf spring is limited to two different stiffness values in the parametric sensitivity analysis. Studies have shown that there is a very strong link between static stability factor (SSF) of the heavy vehicle and the actual occurrence of rollover in accidents [18,22]. SSF determines the rollover threshold of vehicle during steady speed cornering. SSF is a function of both the center of gravity height and vehicle track width and it is described by Eq. (1).

$$SSF = \frac{T_{min}}{2 \cdot H_{CG}} \qquad (1)$$

T_{min}: Minimum track width – (mm).

H_{CG}: The vertical distance between the roll center of the suspension and center of gravity of the vehicle (mm).

SSF is dependent on a number of unsprung mass properties containing shock absorber, leaf spring and air spring. Using the parameters used for SSF in the Table 1, it is calculated as 1.058 for the particular midi-bus examined in this work.

Vehicles are usually scaled based on a particular vehicle's SSF by the NHTSA. Calculating the SSF is a very compact and meaningful way of indicating rollover risk in single-vehicle crashes. As shown in Fig. 1, the lowest-rated vehicles (1 star) are at least four times more likely to roll over than the highest-rated vehicles (5 stars) when involved in a single vehicle crash [7].

The possibility of rollover is expressed by the formula as seen in Eq. (2) by NHTSA [7].

Table 1
Technical specification of the midi bus.

Vehicle parameters	Measurements
Wheelbase	3385 (mm)
Length	7305 (mm)
Width	2282 (mm)
Height	3350 (mm)
Front track width	1914 (mm)
Rear track width	1650 (mm)
Center of gravity height	1250 (mm)
H_{CG}	779.43 (mm)
Gross weight vehicle	11,500 (kg)

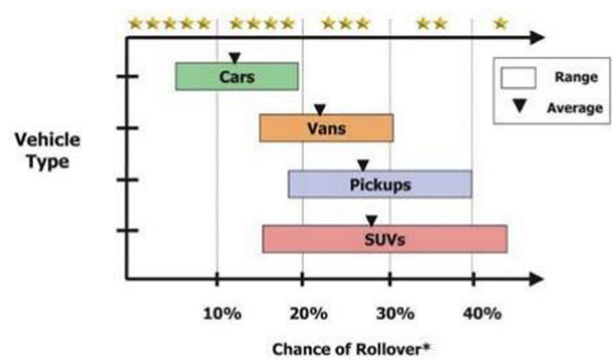

Fig. 1. SSF score of the vehicle [7].

$$\text{The possibility of rollover } (\%) = \frac{100}{1 + SSF^{6.9}} \qquad (2)$$

According to Eq. (2), the possibility of rollover of the midi bus is calculated in percentage as 40.32%. This number clearly shows that midi bus has a high probability of rollover.

One of the better known static rollover tests is the tilt table test. This test is used to measure the SSF, level of the lateral acceleration needed to roll over the vehicle and finally to estimate the static stability limit. In this study, the tilt table tests were used to compare the measured SSF with that of the simulation from the Adams/Car. This approach allowed a sound comparison between the actual tilt table tests and perform the sensitivity analyses.

Tilt table test was also performed in accordance with the SAE heavy vehicle tilt table testing recommended practice J2180. As it is recommended a minimum of three tilt tests were conducted. The tilt rate was set to be no greater than 0.25°/s and the tilt angle alignment at each axle group was not less than ±0.1° [8].

The relative rollover condition can be reached when tires on a single track of a vehicle lose the road contact. Although SSF has a strong correlation with vehicle rollover, the dynamic behavior of vehicle is not taken into account. The National Academy of Sciences recommended that dynamic maneuver tests can be used as a supplement rather than replacing Static Stability Factor [9]. Dynamic test series are very important and they represent different driving maneuvers and provide information based on real-world an operation in which rollover is inevitable.

For selecting the representative dynamic tests, previous studies and standards are examined. Amongst the standard testing maneuvers, the fishhook maneuver was the most repeatable of all rollover resistance maneuvers performed in the study [10]. Cornering represents a dangerous situation when a vehicle attempts to a turn a corner too quickly. Therefore, in this study, parametric sensitivity analysis was performed using fishhook and cornering maneuvers. This represents a worst-case scenario and sensitivity analysis reveals the limits of the fidelity of the model. There are also studies with computer simulations using mathematical models to predict

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