

Relative Performance Analyses of Independent Front Axle Suspensions for a Heavy-Duty Mining Truck

Yiting Kang and Subhash Rakheja
Concordia University Montreal

Wenming Zhang
University of Science & Technology Beijing

ABSTRACT

A range of axle suspensions, comprising hydro-pneumatic struts and diverse linkage configurations, have evolved in recent years for large size mining trucks to achieve improved ride and higher operating speeds. This paper presents a comprehensive analysis of different independent front suspension linkages that have been implemented in various off-road vehicles, including a composite linkage (CL), a candle (CA), a trailing arm (TA), and a double Wishbone (DW) suspension applied to a 190 tons mining truck. Four different suspension linkages are modeled in MapleSim platform to evaluate their kinematic properties. The relative kinematic properties of the suspensions are evaluated in terms of variations in the kingpin inclination, caster, camber, toe-in and horizontal wheel center displacements considering the motion of a hydro-pneumatic strut. The results revealed the CL and DW suspensions yield superior kinematic response characteristics compared to the CA and TA suspensions. Toe-in and horizontal wheel center displacements of the CA and TA vary significantly, which could strongly affect the vehicle handling performance and cause greater tire wear. The CL and DW suspensions may thus be considered desirable for future designs of high-speed and high-performance mining trucks.

CITATION: Kang, Y., Rakheja, S., and Zhang, W., "Relative Performance Analyses of Independent Front Axle Suspensions for a Heavy-Duty Mining Truck," *SAE Int. J. Commer. Veh.* 7(2):2014, doi:10.4271/2014-01-2320.

1. INTRODUCTION

Operators of large size mining trucks are known to be exposed to high magnitudes of whole-body vibration (WBV) arising from vehicle interactions with rough terrains [1]. Exposure to such WBV has been associated with various health risks, particularly the degeneration of the spine and reduced speeds and thereby the productivity [2, 3]. In recent years, a number of axle suspension designs have evolved for implementations in off-road vehicles for limiting the operator exposure to WBV and to attain higher operating speeds [4, 5, 6]. A number of front-axle independent suspensions have also been developed for applications in large size mining trucks [5, 6].

The axle suspensions, invariably, employ energy restoring and dissipative elements together with different types of linkages. The kinematic and dynamic properties of the suspensions strongly affect not only the ride vibration but also the handling and directional stability of the vehicle. The modern large size open-pit heavy-duty mining trucks (HDMT) are increasingly employing hydro-pneumatic struts in conjunction with different designs of linkages to realize improved ride as well handling performance on rough terrains. Owing to the known health risks of the WBV exposure, the EC has established the 'action' and 'limiting' values of the WBV exposure [5]. The reported

studies on off-road vehicle suspensions have thus generally focused on the energy restoring and dissipative properties of the suspension in order to control the WBV exposure of the operator, while neglecting the effects of suspension linkages kinematics [6, 7, 8]. Huang *et al* [9, 10] presented nonlinear mathematical models of a hydro-pneumatic suspension implemented in a HDMT considering the effects of gas mixed within the hydraulic fluid, fluid compressibility and the temperature changes. Cao *et al* [11, 12, 13, 14] proposed a generic approach for performance analyses and tuning of passive interconnected hydro-pneumatic suspensions for heavy-duty vehicles, and discussed the role of suspension in controlling the coupled roll and pitch dynamics of the vehicle.

The contributions of the suspension linkages geometry, and kinematics, which substantially influence the suspension compliance, have been mostly ignored in the afore-mentioned studies. The contributions of the suspension linkages to the overall kinematic and dynamic properties have been extensively studied for automobile suspensions [15, 16, 17]. These have clearly shown that the ride and handling properties of the vehicle are strongly dependent upon the suspension linkages designs. The handling and ride properties of the vehicle are affected by both the type and the geometric parameters of the linkages. A

comparative study on kinematic performance of Macpherson suspension and double wishbone suspension for road vehicles has been reported in [18] considering the wheel alignment and roll characteristic. Wu et al. [19] investigated kinematic performances of double Wishbone, Macpherson, four-link, and five-link type suspensions considering identical virtual lower arm position and wheel alignment parameters corresponding to the static equilibrium.

Despite the substantial works reported on the suspensions kinematics for the road vehicles, it has been suggested that a comprehensive technical review and design knowledge on different types of independent suspension systems is still lacking [20]. Even fewer similar efforts have been made for the off-road vehicle suspensions. This may in-part be attributed to relatively low speeds of the off-road vehicles, where the handling and directional stability would be of little concern.

Modern off-road vehicles, particularly those operating in open-pit mines, however, may operate at higher speeds up to 50 km/h [21]. The handling and directional performances of such vehicles are therefore of significant importance, apart from the vehicle ride quality.

Although, a range of independent linkage suspensions have been implemented in such vehicles, the influences of the suspension linkage type and geometry could be found only in a few studies. For instance, the effects of different suspension geometry and linkage configurations such as double Wishbone, Macpherson, and pendulum configurations on the handling and ride comfort performance of an off-road vehicle have been only briefly discussed in [22, 23]. The suspension linkages employed in off-road vehicles exhibit wide geometrical differences from those used in the road vehicles. Owing to the lack of the relative analyses, particularly for the front axle suspensions for HDMT, the suspension linkage types are generally selected on the basis of the experiences of the designers and manufacturers.

This study is aimed at relative kinematics performance analyses of independent front axle suspension linkages implemented in a HDMT coupled with a hydro-pneumatic strut. Four different suspension linkages, namely a composite linkage (CL), a candle (CA), a trailing arm (TA), and a double Wishbone (DW) suspension are modeled in the MapleSim platform to evaluate their kinematic properties. The kinematic variations in the camber, caster, kingpin inclination, toe-in and horizontal wheel center displacements of the linkage suspensions are synthesized considering the strut deflection as the excitation.

2. KINEMATIC ANALYSES OF LINKAGE SUSPENSIONS

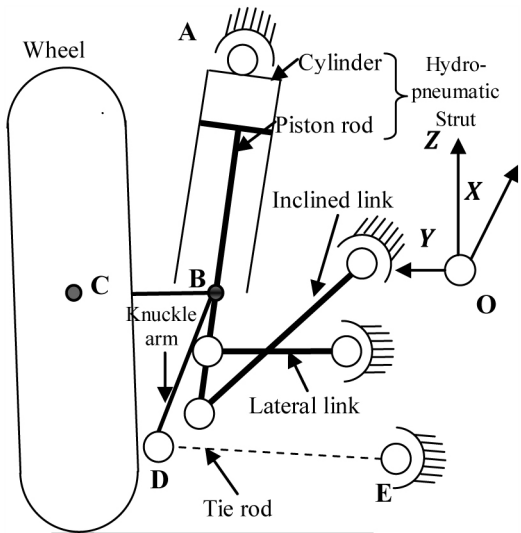
With the exception of the four-link solid beam axle employed in many large size mining trucks (e.g., MT series, Unit-Rig/Terex), independent axle suspensions are increasingly being used in

such vehicles. These employ different linkage configurations together with the hydro-pneumatic struts. Figs. 1(a), 1(b), 1(c), 1(d) schematically illustrate four different suspension mechanisms for the HDMT together with the axis system, namely the composite linkage suspension (CL), candle suspension (CA), trailing-arm suspension (TA) and double Wishbone suspension (DW). The geometric features of the four suspension mechanisms, considered, in the study are briefly described below, where the important differences between these and the road vehicle suspensions are particularly emphasized. Subsequently, the kinematic models of the four suspensions are presented to obtain their kinematic properties.

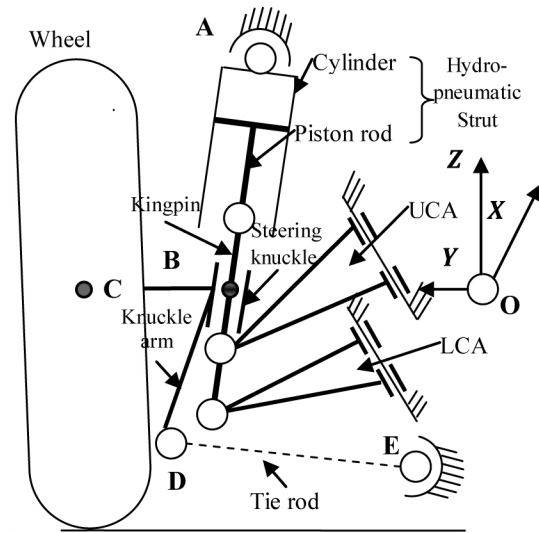
2.1. Suspension Configurations

The CL suspension, shown in Fig. 1(a), is composed of a hydro-pneumatic strut, a lateral link, and an inclined link. The hydro-pneumatic strut is connected to the chassis via a spherical plain bearing (SPB), while the piston rod also serves as the kingpin, which can undergo translational and rotational motions along the axis of the cylinder. In addition, a tie rod is connected to the knuckle arm which is fixed to the piston rod. The structure of this suspension configuration is quite simple and can be considered similar to a Macpherson suspension for the road vehicles. The CA suspension represents the simplest mechanism comprising only a hydro-pneumatic strut, as shown in Fig. 1(b). This suspension is thus most widely used in the mining trucks. The strut cylinder is fixed to the chassis, while the piston rod also acts as the kingpin, as in the case of the CL suspension. Unlike the CL mechanism, the rotational axis of the piston rod is fixed such that the alignment parameters about the kingpin (kingpin inclination and caster angle) remain constant with the wheel motion.

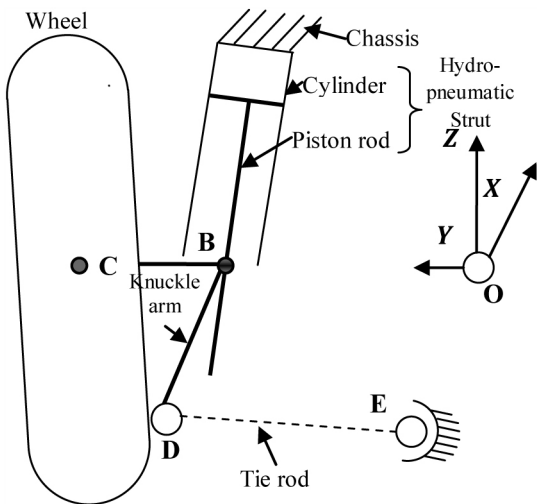
The TA suspension integrates the hydro-pneumatic strut with a kingpin and a trailing arm, as shown in Fig. 1(c). The strut cylinder and the piston rod are coupled to the chassis and the kingpin, respectively, via SPBs. Unlike the CL and CA mechanisms, the piston rod can only move along the axis of the cylinder due to the existence of an independent kingpin. The trailing arm, on the other hand, can rotate about the Y-axis of the chassis, which permits the wheel to move in a longitudinal plane parallel to the X-Z plane. The relatively large size trailing arm tends to occupy considerable longitudinal space of the front axle. The DW suspension, shown in Fig. 1(d), consists of an independent kingpin, while the hydro-pneumatic strut and the kingpin joints employ SPBs. The upper control arm (UCA) and the lower control arm (LCA) of the suspension are coupled to the chassis through revolute joints. The DW suspension represents a substantially more complex structure than the CL and CA mechanisms. The DW suspension also poses considerably greater demand for the lateral space around the front axle.



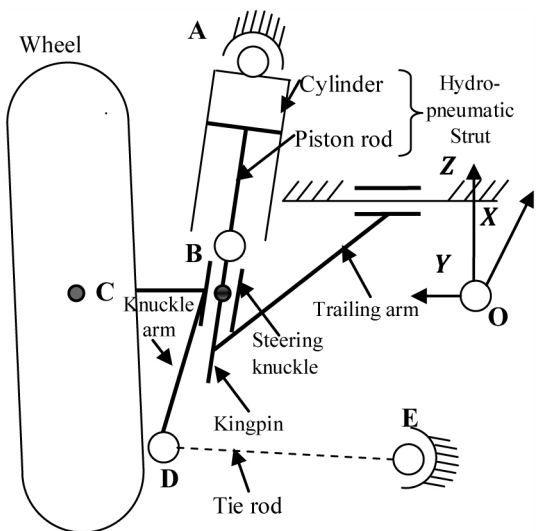
(a). Composite linkage suspension (CL)



(d). Double Wishbone suspension (DW)



(b). Candle suspension (CA)



(c). Trailing-arm suspension (TA)

Figure 1. (cont.) Schematics of the four independent axle suspension mechanisms

Although the structures of HDMT front axle suspensions are generally similar to those employed in the road vehicles, some important differences are also evident. The primary difference lies in the layout of the hydro-pneumatic strut, which plays an important role in guiding the suspension motions, especially when the strut piston rod also acts as a kingpin, as in the case of the CL and CA suspensions. Moreover, the HDMT axle suspensions employ SPBs within most of the joints, while road vehicle suspensions generally use the bushings. Furthermore, unlike the road vehicle suspensions, the HDMT suspension systems do not employ auxiliary roll stiffeners such as an anti-roll bar.

The origin O of each suspension system is considered to be located at the center of the front axle, while the X-, Y- and Z- axis are oriented along the forward, leftward and upward directions of the vehicle, respectively. The geometric parameters of the four suspension systems considered in the study are based on those developed for a 190 tons mining truck. Furthermore, the coordinates of joints A, B, C, D and E (Fig. 1) of all the suspensions corresponding to the respective static equilibrium are considered to be identical, which are summarized in Table 1 together with the alignment parameters. Fig. 2 illustrates the definitions of the alignment parameters of the suspensions, where the value is positive along the directions shown. The point A represents the cylinder and chassis joint in all the suspensions with the exception of the CA suspension, where the strut cylinder is fixed to the chassis, as illustrated in Fig. 1(b). The joint B is the kingpin center, and point C is located at the wheel center. Points D and E, respectively, represent the joints coupling the tie rod to the piston rod and the chassis. Alignment parameters including kingpin inclination, caster, camber, and toe-in and horizontal wheel center displacements are defined in Fig. 2.

Figure 1.