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Editors' Perspectives:

Road Vehicle Suspension Design, Dynamics, and Control

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Abstract

This paper provides an overview of the latest advances in road vehicle suspension design, dynamics, and control, together with the authors' perspectives, in the context of vehicle ride, handling and stability. The general aspects of road vehicle suspension dynamics and design are discussed, followed by descriptions of road roughness excitations with a particular emphasis on road potholes. Passive suspension system designs and their effects on road vehicle dynamics and stability are presented in terms of in-plane and full-vehicle arrangements. Controlled suspensions are also reviewed and discussed. The paper concludes with some potential research topics, in particular those associated with development of hybrid and electric vehicles.

Keywords: road vehicle suspension system, suspension design, vehicle/suspension dynamics, controlled suspensions, energy efficiency

Introduction

Suspension design has been extensively explored during the past few decades, considerably contributing to improvement of ride, handling, and safety for road vehicles. One of the primary trends for the next-generation of road vehicles is to employ alternative powertrain and propulsion systems in a hybrid or fully-electric manner, in order to offer viable solutions for reducing fossil fuel consumption and meeting the more stringent emission and safety standards. This poses significant challenges for chassis design, layout, and system integration, which thus have also a considerable impact on the vehicle/suspension dynamics and suspension design. In addition, virtual prototyping popularly used in vehicle development also requires advances and deeper insight in the fundamentals of vehicle systems, including vehicle/suspension dynamics and suspension design.

The Special Issue of the Journal of Vehicle System Dynamics on 'Advanced Suspension Systems and Dynamics for Future Road Vehicles' compiles the state-of-art progress of the suspension design, dynamics and control for addressing the challenges associated with the development of next-generation road vehicles. This paper presents the Editors' perspectives together with a concise state-of-the-art survey of the available literature on road vehicle suspension design, dynamics and control. Instead of focusing on a specific or multiple classes of vehicles, this paper is primarily concerned with different suspension design arrangements, including roll-plane, pitch-plane, and full-vehicle, and associated vehicle dynamics and stability. The popularly-used quarter-car suspension system can be treated as a special case of the roll-plane arrangement assuming identical road inputs and symmetric load distributions on the left and right vehicle wheels. Different classes of road vehicles have different requirements related to each of the in-plane suspension arrangements and thus on the full-vehicle suspension system, which will be reflected and discussed later in the article.

There are generally three fundamental elements for a typical vehicle suspension system, including springing, damping, and location of the wheel. The first two will be the main focus of this article, while the latter related to suspension geometry, kinematics and compliance (K&C) will also be briefly discussed. Compared to a large number of literatures on the suspension springing and damping, there are only very limited research publications on the suspension geometry and K&C, and associated vehicle dynamics and stability, whose analyses generally demand a complex and validated vehicle system model and supports from extensive experimental data and/or tests. These factors have hindered the technical publications in this area. As such, a comprehensive technical review and discussion on different types of independent suspension systems for road vehicles is still lacking from the literature.

This paper starts with a general discussion on vehicle/suspension dynamics and suspension design, and characterization of road excitations including random road roughness profiles and road potholes. The passive in-plane and full-wheel suspension arrangements and their associated properties and dynamics are then discussed and reviewed. Controlled suspension designs and related topics are also presented and concisely surveyed. Some potential research topics are considered.

General on Vehicle/Suspension Dynamics and Suspension Design

The literature on road vehicle suspension design, dynamics and control suggests an excellent uniformity in the terminology, although there are some differences in the axis systems employed in vehicle modeling. This diversity is also reflected by the different definitions of axis systems employed in the two Standards, SAE (Society of Automotive Engineers) J670e [1] and ISO (International Organization for Standardization) 8855 [2]. In 2008, the SAE Vehicle Dynamics Standards Committee (VDSC) updated and replaced the old version of J670e (1976), to accommodate new technologies in vehicle dynamics and suspension design and also make the definitions consistent with the current usage in the field [3]. The updated Terminology Standard (commonly referred to as the SAE J670 Standard) embraces both of the coordinate systems defined in the J670e (1976) and ISO 8855 (1991) for the vehicle/suspension design and dynamic analysis. But the co-existence of these two coordinate systems could induce certain inconvenience for effective communications for vehicle dynamics professionals and practitioners. Therefore, collaboration between SAE and ISO is highly desirable in the future to adopt only one of the two coordinate systems for future Standards.

Although the vehicle dynamics terminology defined in the SAE J670 (2008) is only limited to passenger cars and light trucks with two axles and to those vehicles pulling single-axle trailers, many of these terms could be conveniently extended to heavy vehicles. The ISO 8855 (1991) includes additional terms relating to heavy commercial vehicles with multiple axles and vehicle units. The SAE J670 (2008) does not includes the terminology related to the human perception of whole-body ride vibrations, which can be found in other documents such as the ISO Standards ISO 2631 [4]. It should be noted that the ISO 2631-1 (1997) recommends a frequency range of 0.5 to 80 Hz for assessing the potential effects of vibration on human whole-body health, comfort and perception, which is much wider than that (frequencies up to about 20 Hz) generally considered for vehicle dynamics studies. As such, the frequency-range difference should be justified, when applying ISO 2631-1 (1997) to evaluate ride qualities of road vehicles with alternative subsystem designs, based on a low-order vehicle dynamics model combined with a suspension-seat-driver model.

In the past few decades, significant efforts have been made in research, development, and design of vehicle suspensions, in particular for passenger cars. The advances include more advanced and complex passive suspensions that are able to provide a better compromise between the vehicle ride and handling, and accommodate the chassis requirements for front-wheel-drive vehicles and the lower profile, more aerodynamic vehicles. The recent advances have also included various controlled suspensions (e.g., semiactive and active suspensions, etc.), as reflected from numerous publications. Although controlled suspensions offer significant performance benefits, the current mainstream suspension systems for road vehicles are still functioning in a passive manner. Air springs can be integrated with a ride-height leveling system to maintain a nearly constant sprung mass natural frequency, irrespective of load variations. Such air suspension system is commonly considered as a passive system.

The increasing demands on overall vehicle dynamics and stability, together with the rapid development of hybrid and electric passenger cars, could boost the implementation of various controlled suspension systems and their integration within the overall vehicle control for passenger cars. Although commercial vehicle sector is conservative in adapting novel suspension technologies, there could be a few factors driving such adaptation, including the conflicting demands on operating efficiency, vehicle safety and driver comfort/health, the incentive of expanding market share, and the legislations on safety and road-friendliness. Air springs with ride-height leveling are expected to be more increasingly employed. However, such suspension system indicates a direct coupling between the sprung mass natural frequency and ride-height, and cannot realize a desirable damping tuning under different load conditions. More advanced suspension technologies, such as adaptive air/pneumatic suspensions with independent tunings of the sprung mass natural frequency, ride-height, and damping, may offer a viable solution.

An overview of the publications related to the general topics of road vehicle and suspension dynamics can be found in [5-14]. Segel [5] and Crolla [6] provide thorough review of road vehicle dynamics development and the issues associated with their practical implementation in a vehicle. Crolla nicely highlights the effect of the suspension on improving the vehicle performance and safety. In another study, Sharp [7] provides a thorough discussion on vehicle dynamic research that affects the performance and subjective feel of the vehicle. These three articles provide the fundamentals needed for better answering “What is vehicle dynamics?” Recently, Ammon [8] and Lutz et al. [9] present vehicle dynamics development with emphasizing modeling/simulation and associated pneumatic tire modeling challenges, from the automotive industry standpoint. A few SAE Standards related to tire modeling and testing are currently under development by the SAE VDSC, mainly to provide better guidelines to the automotive industry on more accurately predicting a vehicle’s dynamic performance while it is still on the drawing board, using dynamic simulation tools.

Gillespie [10] discusses the topics relating to heavy vehicle ride dynamics from the design perspective. In a more recent article, Griffin [11] reviews the human perception of vehicle vibration and its measurement, evaluation, and assessment. Cebon [12] provides an overview of the effect of heavy commercial vehicles on pavement loading, in particular the role that the suspension plays in this regard, where design guidelines and recommendations for heavy vehicle suspensions are proposed. Winkler [13] presents the fundamental aspects associated with rollover dynamics of heavy vehicles. El-Gindy [14] gives an overview on the development of a set of safety-based performance measures in North America, aiming at promoting their use in enhancing heavy vehicle dynamics and safety, from both the design and regulatory standpoints.

These articles suggest the important role of suspension design in vehicle dynamic performance, active safety, and road-friendliness. References [15-22] present general discussions on suspension design and tuning for different classes of vehicles. Williams [15, 16] discusses the theoretical and practical aspects of active suspension for road vehicles. Alexander [17, 18] presents the benefits of suspension design by providing practical examples of suspension system development. Topics related to heavy vehicle suspension design are discussed in [19-22]. Quaglia and Sorli [23] propose a generic design procedure for pneumatic suspension (including air suspension) on the basis of dimensional modeling and analysis. The role of passive suspension in controlling the coupled roll and pitch dynamics of road vehicles is discussed by Smith and Walker [24] and Cao et al. [25, 26]. The latter proposes a generic approach to designing and tuning passive interconnected hydro-pneumatic suspension systems for heavy vehicle applications, while the methodology can also be applied to other classes of road vehicles as well as off-road vehicles.

Considering the conflicting performance measures for vehicle suspension design, references [27-29] explore and propose systematic design procedures for suspension systems that are based on multi-objective optimization. They also provide an approach for the robust design of the optimization procedure [28, 29]. Other studies [30-32] use the Axiomatic Design theory [33] in suspension design so as to realize enhanced vehicle performance characteristics. Hardware-in-the-loop simulation applied to suspension development [34] and economic evaluation of alternative vehicle suspension designs [35] are also investigated.

Several survey articles on vehicle and suspension dynamics have been published during the past quarter century [36-46]. Roll dynamics and road-friendliness of road vehicles are reviewed in [36] and [37], respectively. Palkovics and Fries [38] provide a review of various advanced chassis systems for commercial vehicles and their potential benefits in enhancing vehicle traffic safety, while hardware-in-the-loop simulation for vehicle dynamics control development is surveyed by Schuette and Waeltermann [39]. A review of the suspension design, in particular the controlled suspension systems, has been conducted regularly every few years [40(1987), 41(1991), 42(1995), 43(1997), 44(2004), 45(in press)]. A review of independent suspension systems for heavy vehicles is given in [46].

The available literature suggests considerable efforts on many aspects of conventional vehicle dynamics and suspensions, for both passenger automobiles and commercial vehicles. There is, however, little evidence of efforts related to the dynamics of hybrid and electric vehicles. For the most part, to date, they have been treated to have the same fundamental characteristics as conventional road vehicles. An exception to this is the brief discussion by Beiker and Vachenauer [47] on the influence of different drivetrain architectures on the vehicle chassis design, including the suspension system and vehicle dynamics. Further efforts on fundamental vehicle dynamics of hybrid and electric vehicles should be made for the effective development of their chassis/suspension systems, various vehicle control and power management systems.

Road Excitations

Road vehicle dynamics are generally assessed under directional maneuvers and excitations arising from vehicle-road interactions, even though the effect of other excitation sources, such as aerodynamics, tire/wheel assemblies, driveline, and engine, can be evidenced for vehicle development. As such, it is well recognized that the excitations arising from road roughness primarily affect the vehicle ride comfort, while vehicle handling dynamics and roll/directional stabilities are mostly evaluated under steering and/or braking/traction maneuvers. Road excitations are also of concern in determining suspension rattle space and assessing vehicle road-holding property. Ironically, road roughness is the input over which vehicle design engineers and vehicle drivers have the least amount of control. Improved understanding of characteristics of road profiles is thus critical for chassis and vehicle development [48]. While the time histories of road profiles are popularly used as the input for analytical vehicle models, road roughness is generally characterized by its power spectral density (PSD) [49-52]. Artificial generation of time-histories of random road as well as off-road roughness profiles has also been addressed in the literature [49, 53].

The PSD of road roughness profiles is generally represented in terms of vertical displacement and/or acceleration against wavenumber. The amplitude of road elevations decreases with an increase in wavenumber, while an increase in wavenumber yields larger amplitude of the acceleration of road roughness [10, 54]. For roll-plane vehicle dynamics, the coherence of the excitations along the left and right tracks is also an important factor [20]. It has been shown that the coherence approaches zero/unity at large/small wavenumbers, respectively [20]. Cole [20] also states that sprung mass roll mode is less excited than the vertical mode at typical highway speeds, and suggests the feasibility of using a two-dimensional pitch-plane model for heavy vehicle ride dynamics analysis.

Alternatively, the roll deflection characteristics of random road roughness profiles along the left and right tracks can also be described in terms of the PSD ratio of the roll-displacement to vertical-displacement, where the roll displacement refers to the elevation difference between the left- and right-wheel tracks, and the vertical displacement represents the average of both the elevations [10, 49, 54]. The results show that at small wavenumbers, the magnitude of roll displacement is much lower than that of vertical displacement for a road vehicle. At large wavenumbers, the roll to vertical PSD ratio tends to approach unity, which suggests comparable roll-mode excitations to those of the vertical mode at large wavenumbers [10, 49, 54]. It has been stated that a typical commercial vehicle generally exhibits a softer roll mode than bounce mode, and thus bounce mode responses are dominant at large wavenumbers [10]. Gillespie [10] relates this to the absence of roll and lateral mode vibrations on heavy vehicle ride evaluations in the U.S. publications. This is consistent with Cole's suggestion on using pitch-plane model for heavy vehicle ride dynamics analysis [20]. However, roll-mode vibration may not be neglected for ride dynamic assessment of heavy vehicles employing stiffer anti-roll bars [54]. In addition, roll-mode vibration of the sprung mass considerably contributes to the lateral vibration at the driver seat, where the weighting factor is 1.4 compared to 1 for the vertical vibration, as recommended by the ISO 2631-1 [4]. These factors should be justified when choosing a vehicle model for evaluating heavy vehicle ride vibrations.

Cao et al. [54] extend the efforts on characterizing random road roughness profiles in the pitch plane considering the wheelbase filtering effect. The simulation results reveal the significant difference between the characteristics of random road profiles with and without considering wheelbase filtering effect. The vehicle wheelbase has a positive filtering effect on reducing the vertical-mode road excitations applied to vehicles, while the reduction level is strongly influenced by the load distribution, where an even load distribution tends to yield the largest reduction in the vertical-mode road excitations. More discussions on wheelbase filtering effect and pitch-plane vehicle dynamics and suspension design will be presented later in this article.

The vibration isolation properties of road vehicles are mainly evaluated for random road profiles and/or harmonic excitations, while shock isolation characteristics are generally investigated under transient road inputs, such as potholes. The random road profile is often described in terms of its PSD, and ride vibration performance of road vehicles is generally assessed in terms of the PSD responses and root-mean-square (rms) values. While the evaluation of human exposure to whole-body vibration is based on the frequency-weighted rms acceleration, such evaluation method is normally sufficient when vibration crest factor is below or equal to 9, as suggested in the ISO 2631-1 [4]. It is also noted in the ISO 2631-1 that for some types of vibrations, especially those comprising occasional shocks, such method may underestimate the discomfort severity even for a crest factor less than 9. It is thus suggested that additional evaluation methods, such as the running rms or the fourth power vibration dose value (VDV) method, also be used [4].

While various road pothole models have been used in simulation studies for road vehicle dynamics and alternative suspension design concepts, the shock isolation performance has been generally evaluated in terms of the peak acceleration response of the sprung mass. Although the influence of different shock excitation models on single degree-of-freedom (DOF) systems has been studied in terms of the shock response spectrum (SRS) [55], minimal efforts have been made to investigate the influence of a variety of pothole models on road vehicle dynamics. Additionally, it has also been stated that in spite of common familiarity with road pothole, a general method to describe its severity has not yet been developed [48].

Different definitions of road potholes have been described in the literature, including:

(1) "A pothole may be defined as any localized loss of material or depression in the surface of a pavement" [56, 57];

(2) "Bowl-shaped holes of various sizes in the pavement surface. Minimum plan dimension is 150mm" [58];

Severity Level [58]:

- Low: <25mm deep;
- Moderate: 25mm to 50mm deep;
- High: >50mm deep;

(3) "A cavity in the road surface that is 150 mm or more in average diameter and 25 mm or more in depth" [59].

The average area of road potholes, given in [60], is about 0.05 m^2, much less than 0.5 m^2 suggested in [61]. The identified pothole distributions according to depth are described in Table 1 [62], for the measured highways (2431 Km) in the U.S. A large difference in pothole distributions is noticed between good and poor roads. The number of potholes with the same depth is significantly more in poor roads, when compared to good roads [62].

Table 1: Identified pothole distributions for the measured good-quality highways (2431 Km) in the U.S. [62].

Depth of pothole (m)	No./100 km
0.02	30
0.03	4
0.04	0.7
0.05	0.3
0.06	0.09
0.07	0.006

The shock isolation performance of road vehicles has been generally assessed under excitations arising from road potholes or bumps. A variety of different pothole models has been considered in the literature, which could be generally classified as one of the following three types:

- **Smooth:** pothole models with continuous first and second derivatives (i.e., have continuous displacement, velocity, and acceleration) in the open interval or duration of the pothole, including half sine, versed sine, cycloid, ellipse, polynomial, half round, etc.
- **Non-smooth:** pothole models with continuous displacement curve only, in the open interval of duration, including triangular, trapezoid, rectangular, etc.
- **Statistical:** pothole models described by a probability distribution, such as a rounded pulse, which can be represented by:

  $$Z_0(t) = A(\pi \frac{t}{T_c} e^{(1-\pi \frac{t}{T_c})})^2$$

  where A is a constant, T_c is the characteristic duration so that the area under the rounded pulse in the interval [0, T_c] is about 95% of the total pothole area.

Although the same model shape may be used in many studies, the selected dimensions of the pothole and vehicle forward speeds could be significantly different. Under excitations from different pothole models with different specified properties (amplitude, time duration, etc.), two alternative suspension designs or tunings could indicate different potential performance benefits. For example, one suspension design/tuning performs better than the other for a specific pothole model, but may yield worse shock isolation performance for a different pothole model. This leads to a generic question on how to effectively evaluate shock isolation performance of road vehicles with alternative suspension designs/tunings, for which a general framework or guideline should be developed. Such development should be correlated to the ride vibration evaluations under random road roughness excitations.

Another related topic is ride performance evaluation during maneuvers (e.g. steering and braking/acceleration), which has also been pointed out by Cole [20]. By comparing the ride during maneuvers to the shock responses under a pothole input, it can be observed that the vehicle body tends to experience similarly large vertical and rotational motions. A generalization or correlation of these two types of ride dynamics of road vehicles could be an interesting topic.

Roll-Plane Vehicle/Suspension Dynamics and Passive Suspension Design

Roll-plane vehicle model and dynamic analysis have been used for investigating coupled ride and roll stability characteristics of mainly heavy road vehicles and alternative suspension system designs. This is primarily due to the fact that heavy road vehicles, with their higher centers of gravity (CG), exhibit lower roll stability limits, as compared with passenger cars. Roll stability of heavy road vehicles is often assessed according to their static stability factors (SSF) and/or static rollover thresholds (SRT). Both of these measures, however, do not consider the dynamics of the suspension, tire, and other components that would affect the vehicle dynamic roll stability. The SSF, or track width ratio (TWR), is defined as the ratio of half-track width to the CG height, which is derived by assuming a very simplified rigid vehicle. The SRT of a heavy vehicle can be obtained using different methods, such as static tests including tilt-table or side-pull, a quasi-steady-state steering test, or mathematical formulations/computer simulation software [36]. Due to the fact that some heavy vehicles may exhibit yaw instability at lateral accelerations lower than their static rollover thresholds, El-Gindy [14] redefines SRT as “the maximum lateral acceleration level in g’s beyond which static rollover of a vehicle occurs.” The SRT of a fully-loaded heavy vehicle usually lies below 0.5g, which indicates that a heavy vehicle could rollover before reaching the tire-road friction limit on dry roads. For such vehicles, even a small improvement in the rollover threshold can significantly improve the vehicle roll stability and reduce the likelihood of rollover accidents [13, 20]. Increasing suspension roll stiffness and damping can improve roll stability of heavy vehicles.

Ervin [63] investigates the influence of size and weight variations on the roll stability of heavy vehicles. Roll stability is improved by increasing the width allowance for vehicles. An approximate 3% increase in the roll stability limit can be achieved with only 1% increase in both track width and transverse spring spacing. An increase in the payload CG height yields considerable reduction in the roll stability limit, of the order of -0.0024g/cm of increase in payload CG height. The weights and dimensions of commercial vehicles, however, are commonly governed by the local or Federal road regulations.

The heavy vehicle roll motion involves complex rotations of the sprung and unsprung masses. The sprung mass rolls with respect to the suspension roll center, while the unsprung masses roll about their roll centers [20, 63]. For a typical heavy vehicle, about 2/3 of the total roll angle of the vehicle involves rotation about the suspension roll center [63]. The roll moment consists of primary overturning moment, caused by the lateral acceleration induced by a directional maneuver, and lateral displacement moment, caused by roll motion of the vehicle CG. A reduction in the roll motion of the sprung mass can thus decrease the lateral displacement moment, and thereby improve the roll stability limit. In view of the ride quality implications of stiffer suspension springs, the roll stability limit is generally enhanced by introducing auxiliary roll stiffeners, such as anti-roll bars. Cole [64] provides a numerical (modeling) investigation of the roll control of heavy vehicles using five different suspension configurations. The study involves an analysis of different passive and active suspensions, and it concludes that an increase in the stiffness of an anti-roll bar can improve the vehicle roll stability at the cost of ride comfort.

The conclusions reached in [64] are supported by some other studies, which show that the use of anti-roll bars tends to add mass and potentially degrade vehicle ride quality [49]. It is also shown that the use of very stiff anti-roll bars, which makes SRT closer to SSF, may be impractical due to the reduced roll mode damping and the resulting increase in the dynamic roll responses under large amplitude and high frequency excitations [49]. Rakheja et al. investigate the roll properties of 72 different heavy vehicle configurations, involving different combinations of suspensions, tires and loading, and conclude that the SRT of a heavy vehicle is about 72% of the SSF, due to compliance of vehicle suspension and tires [65]. Goldman et al. show that treating a multiple-axle vehicle suspension system as a lumped suspension tends to overestimate the SRT and thus static vehicle roll stability [36]. Such statement can be related to the topic on stiffness tuning of front/rear anti-roll bars for handling balance of road vehicles. In general, the total roll stiffness of the front and rear anti-roll bars can be determined for roll stability, while leaving the freedom for tuning roll stiffness distributions on the front and rear axles for vehicle handling. However, different roll stiffness distributions would indicate different static roll stability limits for a vehicle, even if the total roll stiffness is maintained identical.

Winkler [13] suggests that a heavily loaded semi-trailer could exhibit a roll mode natural frequency as low as 0.5 Hz, which is in the range of excitation frequencies arising from emergency type of steering maneuvers. This suggests the importance of roll damping for controlling the roll resonant responses during such emergency maneuvers. Winkler [13] also reports that it is hard for heavy vehicle drivers to perceive their proximity to rollover while driving. The rollover threshold of a heavy vehicle varies continuously with dynamic load transfers in the roll plane, which diminishes the driver’s perception of the stability limit of the vehicle. Moreover, the flexible nature of the tractor frame tends to isolate the driver from the roll motions of the trailer, which could serve as an important cue for the impending rollover. The compliances of a vehicle’s structural frame, suspension, and tires can also contribute to the rollover process. A number of studies have established the contributions of various vehicle design factors to the vehicle roll stability limit, namely the axle loads, structure compliance, track width, CG height, etc. [13, 63]. These studies have shown that the effect of structural or articulation compliance may be small, while the combined effect of all compliances on vehicle dynamic roll stability can be significant.

The roll dynamic characteristics of a vehicle could differ from the static roll responses. A number of measures have evolved to assess the dynamic roll behavior of commercial vehicles. These include the lateral load transfer ratio (LTR), roll safety factor (RSF), effective lateral acceleration (ELA), normalized roll-response of semitrailer sprung mass (NRSSM), etc. [36, 66]. Cooperrider et al. [67] conclude that the lateral acceleration required to induce rollover is a function of the time duration of its application. When the lateral acceleration exceeds the static rollover limit, it needs to be sustained for only a very limited time period to cause rollover. For instance, for a typical heavy vehicle, a lateral acceleration of 110% of its static roll stability limit can lead to rollover if sustained for about 1 second, while the acceleration of 120% of the static limit needs to be sustained for only about 0.6 second to cause rollover. For articulated vehicles and tanker trucks, the dynamic roll stability is much more crucial, due to the strong coupling of yaw/roll motions and/or liquid cargos involved [13, 14]. In addition, the cross-slope of the road roughness profiles along the left and right vehicle tracks would negatively contribute to the vehicle dynamic roll stability. White [68] investigates the influence of ride-height leveling systems on roll stability of heavy vehicles with an air suspension system, and concludes that the current mechanical ride-height leveling systems do not affect the roll stability during a rapid directional maneuver. This also explains the previous statement that an air suspension integrated with a ride-height leveling system is treated as a passive system.

The above discussions are on maneuver-induced rollover, or 'untripped' rollover, which is generally applied to heavy vehicles and some types of light vehicles (e.g., sport utility vehicles) that have low roll stability limits. Rollover accidents associated with passenger cars are mostly induced by encountering a road curb or an obstacle, commonly referred to as 'tripped' rollover. Such type of rollover is generally induced with a loss of vehicle directional control or stability. Although the 'untripped' rollover would generally not occur for passenger cars, roll control of all classes of road vehicles has been an important vehicle dynamics topic. This is mostly due to the strong coupling between the vehicle roll and yaw motions, where the vehicle roll dynamics has a considerable effect on vehicle handling dynamics and directional stability. Many studies also use sprung mass roll angle response as one of the key objective handling performance measures.

Design and tuning of roll-plane suspension properties, including bounce- and roll-mode stiffness/damping, and suspension geometry and K&C, strongly affect roll dynamics and stability of road vehicles, apart from the ride quality. The number of literature on the suspension geometry and K&C is very limited. Sharp [69] suggests that analysis of the lateral suspension geometry and kinematics can be conducted at four different modeling levels, and also points out that although the analysis based on a simplified vehicle model could provide certain insights on the effect of suspension geometry design on vehicle roll motion control, such insights should be justified using a more comprehensive vehicle dynamics model. Although the locations of both suspension force center as well as kinematic center can be determined from suspension K&C measurements, Dixon [70] suggests the more important role of the suspension force center in vehicle dynamics than the kinematic center. The locations of front and rear suspension roll centers and thus the inclination angle of sprung mass roll axis with respect to road affect both the vehicle roll and directional stabilities. Apart from the suspension system itself, selection of tire properties/sizes would also influence the inclination angle of sprung mass roll axis.

Conventional passive vehicle suspension system design has to compromise between ride quality and roll stability, while the implementation of passive mechanical interconnections (e.g., anti-roll bars) indicates inherent limitations in achieving a good compromise. Goldman et al. [36] point out the little research effort conducted on anti-roll suspension designs for heavy vehicles, although such classes of vehicles indicate a considerably higher rollover risk than passenger cars. Unlike passive anti-roll bars that are heavy and do not offer additional roll damping, roll-interconnected suspension systems can offer viable options in improving anti-roll properties, while retaining soft vertical ride. The fluidic couplings can be conveniently realized in a suspension system involving hydro-pneumatic struts. Hydro-pneumatic struts can offer compact design with integrated damping control, improved ride comfort, ride height leveling control, as well as semiactive/active control. The hydro-pneumatic suspension systems have been employed in heavy military vehicles for nearly half a century, and have been regarded to hold the most significant potential for commercial vehicle applications [6, 21, 71]. Gunter et al. [71] state that the hydro-pneumatic suspension system has been selected as one of the key technologies in the development of future military vehicles.

A concept in interconnected pneumatic suspension is described by Lovins and Cramer [72]. The proposed suspension system consists of four pneumatic and electromagnetic actuators that are interconnected in the roll plane to provide improved roll stiffness. Two other recent studies [73, 74] propose two hydro-pneumatic suspension strut concepts that integrate gas chambers and damping within a single unit to realize a more compact design than the conventional air spring and damper systems used for road vehicles. Such compact strut designs not only eliminate the external gas chamber and external damping valves, but also offer a larger effective working area and, therefore, significantly lower operating pressure for a given load, as compared to those reported in [75, 76]. The struts also provide considerable flexibility for various interconnection configurations among the hydraulic and pneumatic chambers, for considerably improving roll stiffness without affecting the vertical suspension rate [73, 74, 77]. The hydraulic fluid couplings can further increase suspension roll damping. The vertical and roll dynamic responses of a heavy vehicle employing different unconnected and roll-interconnected suspension configurations were conducted using a nonlinear roll-plane vehicle model [74]. The results demonstrate the performance benefits of roll-interconnected suspensions, particularly hydraulic interconnections, in enhancing overall roll-plane vehicle dynamics and stability.

Conventional hydro-pneumatic struts and air springs exhibit asymmetric hardening and softening properties in compression and rebound motions, respectively [78]. Such properties could help inhibit the motions in compression, but tend to yield larger motions in rebound, which pose challenges concerning control of suspension topping and wheel hop. In addition, the asymmetric force-deflection properties yield a softening effect on the effective suspension roll stiffness with increasing roll deflection [73, 74], which is highly undesirable considering that rollovers are generally associated with large suspension roll deflections. The analytical and simulation results in [78] demonstrate that the proposed novel twin-gas-chamber strut suspension concept offers soft vertical ride around the static ride height and progressively hardening properties in both compression and rebound, which further yield a hardening effect in effective roll stiffness with increasing roll deflection. Such properties can help reduce ride height drift, and improve suspension topping, tire deflection, and roll response characteristics, with negligible influence on the vertical and roll ride qualities [78]. In addition, unlike conventional air suspensions, the proposed twin-gas-chamber hydro-pneumatic suspension could realize independent tunings of sprung mass natural frequency and ride-height.

It should be noted that the main compromise for passive roll-plane suspension design/tuning is the roll stiffness, for which a stiffer roll mode is desirable for roll stability, but a softer roll mode is preferred in view of roll and lateral ride vibrations. The current practice in road vehicle suspension designs converges to a stiffer roll mode, particularly for heavy vehicles, concerning the roll safety. Semi-active anti-roll bars have been widely explored to address such conflicting demands on the roll stiffness.

A proper roll-plane vehicle model should be able to capture the suspension roll centers or the lateral load transfers due to the sprung mass roll displacement about the roll axis. Since road vehicles are generally assumed to yield an even load distribution on the left and right sides, a roll-plane vehicle model can be simplified to be a quarter-car model by using identical road excitations at both the left and right tire-road contacts. A quarter-car vehicle model provides the means for a simple evaluation of alternative suspension designs and concepts, in terms of the sprung mass acceleration (vertical ride), suspension travel (rattle space) and dynamic tire force. The latter provides an estimate of the vehicle road-holding and also partially handling quality and road-friendliness. In addition, the sprung mass displacement response can partly serve as a measure for vehicle attitude variation.

Pitch-Plane Vehicle/Suspension Dynamics and Passive Suspension Design

While the roll dynamics of road vehicles have been extensively reported in the literature, fewer studies have explored the vehicle pitch dynamics. Most studies in this area relate to the analysis of controllable suspensions, and their roles in enhancing overall vehicle pitch-plane dynamics, especially ride and pitch attitude control, where the classic 4 DOF pitch-plane vehicle ride model is commonly used. The coupled vehicle pitch and bounce motions can be induced by the vehicle-road interactions, braking, or acceleration. From the ride comfort perspective, pitching motion is considered ‘objectionable’ and annoying [10, 20]. This is attributed to higher human sensitivity to vibrations in the vicinity of the pitch frequency, which occurs at approximately 1-1.5 Hz. This falls within the frequency range of 0.5-2 Hz in which the human body is most sensitive to transverse vibrations [4]. In addition, pitching motions encourage longitudinal oscillations of the seat backrest and thus ‘head nods’. Sharp describes the importance of vehicle attitude (roll and pitch motions) control [7]. The driver’s perception of the path preview is significantly deteriorated in the presence of excessive pitch motions. In order to improve the driver perception of the vehicle path with minimum effort, the roll and pitch responses of the vehicle body to excitations arising from road and crosswind inputs should be minimized.

While the roll-plane vehicle dynamics are mostly characterized by the roll stability or rollover, a special phenomenon associated with the pitch-plane vehicle dynamics is the ‘wheelbase filtering effect’, which is partially related to the coupling between vehicle bounce and pitch vibration modes, and generally refers to the effects of the time delay between the front and rear wheels on vehicle dynamics. Rear wheels of road vehicles are generally assumed to follow the same road profiles to the front. The study [54] has shown the considerable effect of wheelbase filtering on characterization of road roughness profiles. The paper [54] also tends to correlate the pitch-plane characterization of road profiles to the pitch-plane vehicle dynamics. The simulation results of the vehicle dynamic responses demonstrate a positive effect of the wheelbase filtering on vehicle vertical ride, with a negligible influence on the averaged front and rear suspension travels as well as dynamic tire deflections. The analyses also suggest that a quarter-car vehicle model that cannot capture the wheelbase filtering effect would overestimate the bounce acceleration responses of the sprung mass, when compared to a pitch-plane vehicle model.

It has been suggested that a softer front axle suspension than the rear suspension, or ‘Olley’s tuning’, could help reduce the pitch motion of an automobile. This design approach has been argued on the basis of transient responses of a vehicle to a road bump excitation, particularly the phase lag caused by the interaction of the front and rear tires with the bump, which depends upon the forward speed, the nature of road bump, and vehicle wheelbase. This approach, however, may induce larger squat and dive during rapid acceleration and deceleration. The suspension design for pitch suppression thus involves complex challenges considering a wide range of operating speeds, road roughness, load variations, and maneuvers. Crolla [79], Sharp [80], and Cebon [81] have separately investigated the effect of pitch-plane suspension tuning on inhibiting pitch motions of passenger cars, while the effects on pitch response of heavy vehicles have been mostly limited to load equalizers for the suspension systems. These studies show that the 'Olley's tuning' is beneficial at high speeds. The conflicting requirements on the front/rear suspension stiffness tunings at low and high speeds may be alleviated using a passive pneumatic suspension system that is realized by an air spring or pneumatic cylinder connected to an accumulator. Such type of pneumatic suspension system exhibits a frequency-dependent dynamic stiffness property, which yields lower/higher stiffness at lower/higher frequencies, respectively. The study [81] concludes that the 'Olley's tuning' offers a nearly optimal solution for minimizing horizontal acceleration at the human driver chest, while the vertical chest acceleration is less optimal, for uncoupled suspensions. Cebon [81] further suggests the benefits of a pitch-coupled suspension with lower pitch stiffness in enhancing dynamic tire load and body acceleration responses of a passenger car.

The use of a fore-aft interconnection between the axle suspensions can help reduce effective pitch stiffness and thus improve pitch ride. The pitch attitude caused by acceleration or braking, however, can be reduced by higher suspension pitch stiffness. Various suspension configurations have also been explored to achieve improved anti-dive and anti-rise performances of the front and rear suspensions during rapid acceleration and deceleration. It has been suggested that anti-pitch suspension geometry tends to adversely affect vehicle handling [82]. A recent study [47] further highlights the dynamic interactions between the regenerative braking and suspension kinematic design, indicating that the hybrid and electric vehicle powertrain requirements pose additional challenges on the suspension design, besides suspension packaging.

For heavy vehicles, a number of concepts and designs in load equalizers have been proposed to equalize the axle loads in a tandem or tri-axle configuration. Such load equalizers, however, do not yield desirable dynamic performance. Dahlberg [83] investigates braking-induced pitch motion and longitudinal load transfer, and studies their effects on yaw dynamics of heavy vehicles. The study concludes that yaw dynamics and stability are strongly influenced by pitch motions and longitudinal load transfer during braking in a turn. A suspension design with improved roll and pitch performance thus offers considerable advantages for improving ride comfort, handling, and directional dynamic performance of road vehicles. Cole [20] points out that optimal suspension tunings achieved under certain driving speeds may not work well for other speeds. This is particularly important in light of the fact that most road vehicles operate in a wide range of speeds, apart from road roughness conditions. Controlling suspension travel also strongly influences both ride and handling, since minimizing suspension travel can reduce the rattle space requirements and accommodate easier packaging of the suspension, in particular for lower profile vehicles.

A recent study [84] explores the pitch dynamics and front/rear suspension stiffness tunings of two-axle heavy vehicles with unconnected suspensions, under a wide range of random road roughness excitations, driving speeds, and braking maneuvers. This study uses the two pitch-plane models [81] for two-axle heavy vehicles with uncoupled and coupled suspensions to derive and assess three dimensionless measures of suspension properties, namely pitch margin (PM), pitch stiffness ratio (PSR), and coupled pitch stiffness ratio (CPSR). The vehicle dynamic analyses are performed for different suspension tunings and load configurations, in terms of vertical and pitch ride, dynamic tire load, suspension travel, and pitch attitude control during braking. Fundamental relationships between the vehicle pitch dynamics and the proposed measures are established, and a set of basic pitch-plane suspension tuning rules is also proposed for heavy vehicles with conventional, uncoupled suspensions.

A few recent studies explore the potential benefits of pitch-interconnected suspension systems with higher pitch stiffness, using a developed nonlinear pitch-plane vehicle braking model [85, 86]. The performance benefits of the pitch-connected hydro-pneumatic suspensions are demonstrated in enhancing the pitch attitude control, suspension travel, straight-line braking performance, and vertical ride. The proposed pitch-interconnected suspension could also help slightly improve braking performance, reducing stopping distance by about 2% [86]. Using advanced controllable suspensions could yield slightly better braking performance [87], although the coordination between the controlled suspension and braking system needs to be further evaluated [88].

A wide range of pitch stiffness properties can be conveniently realized through different pitch-interconnections and tuning of suspension design parameters [77]. This indicates that desirable pitch stiffness can be achieved without greatly affecting the suspension bounce dynamics. The issue that, however, remains is that the vehicle pitch attitude control requires higher pitch stiffness than the stiffness desired for pitch ride, suggesting that a compromise between two must be reached through a passive suspension [84]. Road vehicles generally yield larger pitch angle variations during braking/acceleration than when subjected to random road inputs. This indicates that the pitch stiffness should be lower in the vicinity of the suspension design height for a better ride comfort, while it should be higher at large pitch deflections for better controlling the pitch attitude. It has been shown that the twin-gas-chamber strut suspension design could realize such desirable nonlinear pitch-mode stiffness property in a passive manner [89]. The simulation results in [89] demonstrate its considerable benefits in enhancing bounce and pitch ride, pitch attitude control, and suspension travel responses under braking inputs, without adversely affecting the vehicle ride and road holding characteristics.

Full-Vehicle Vehicle/Suspension Dynamics and Passive Suspension Design

Evaluating the effect of a suspension system design on vehicle ride, handling, roll, and directional stability necessitates a three-dimensional full-vehicle model, since these associated performance measures are strongly coupled with each other. The vehicle braking/acceleration and steering maneuvers generally can induce large pitch and roll motions of the sprung mass, and also longitudinal and lateral load transfers. The coupled rotational and translational dynamics can influence the vehicle ride vibrations, tire forces and load transfers during steering and braking/acceleration maneuvers. The variations in tire forces strongly influence the yaw and braking dynamic performance, as well as the stability limits, generally in an undesirable manner. Suspension system design also strongly affects the roll moment distribution and, therefore, the distribution of lateral load transfers among the axles, which influences the vehicle handling dynamics and directional stability. For some road vehicles, the usable region of lateral acceleration is determined by the potential yaw instability, instead of the roll instability [14, 20]. During transient maneuvers, the roll moment distribution depends on the distributions of both the effective roll stiffness and damping between the front- and rear-axle suspensions.

Vehicle roll motion is strongly coupled with yaw motion. The vehicle roll instability is associated with the lateral acceleration level, while the yaw instability is strongly influenced by both the lateral acceleration and the vehicle speed [90]. A vehicle is stable in roll when the lateral acceleration is lower than a certain threshold, irrespective of the vehicle speed. The yaw instability, however, could occur at low lateral accelerations (e.g., 0.1~0.2g) at high vehicle speeds. Roll instability could therefore be prevented by limiting the vehicle lateral acceleration, while yaw instability may still occur. It has been reported that in dynamic rollover tests, a vehicle experiences sustained body roll oscillations during a portion of the road edge recovery maneuver, while the steering angle is held constant [91]. It has been concluded that these undesirable oscillations are induced by the coupling among the vehicle roll, heave and the subsequent yaw modes that result from the jacking forces of the suspension. The jacking forces induce vehicle body bounce, which in turn causes tire normal and lateral force variations. This in turn affects the yaw response because of the coupling between the heave, roll, and yaw dynamics of the vehicle. It has been shown that sustained roll, heave, and yaw oscillations can occur even during a steady-state portion of a steering maneuver [91].

The dynamic tire load variations induced by the road roughness can also affect vehicle handling. As the surface roughness increases, the vehicle handling becomes more erratic, indicating a noticeable coupling between vehicle ride and handling, caused by the road surface irregularities [92]. On smooth roads, the overall understeer/oversteer characteristic will not change significantly, up to lateral accelerations of 0.6g [92]. Over a rough road, the understeer/oversteer behavior differs considerably in a wide range of lateral accelerations, where an understeer vehicle may exhibit oversteer behavior. This indicates an additional challenge on suspension design for rough or off-road applications, where vehicle handling dynamics and directional stability may become unpredictable during high-speed driving. It is, however, noted that the results in [92] are based on using the Magic Formula to model the tire dynamics, which may not accurately estimate the tire dynamics on rough roads or in off-road driving conditions. More accurate tire models or appropriate vehicle testing is needed to verify the conclusions obtained in this study.

Vehicle handling dynamics and directional stability can be generally assessed in three distinct ways [93], including (a) subjective rating of actual vehicles; (b) objective open-loop tests conducted using an instrumented car; and (c) analytical methods. Simulation-based studies significantly reduce the development time and cost associated with the system design and analysis, and can result in prototypes that are much closer to the final product [94]. Vehicle dynamics simulation also provides absolute control of the vehicle properties (mass, tire properties, etc.), test repeatability, ability to eliminate the risks associated with track testing, ability to conduct tests that may be physically impossible, varying individual vehicle characteristics, and the ability to discriminate among small differences in performance. The required modeling refinements, however, have been long debated in developing vehicle models for handling simulations. Industry analysts often generate very complex models to achieve greater accuracy. Experienced academic researchers, however, have put forward the view that typical industry-used vehicle models are too complex and inefficient for most design analyses [94-96]. Sharp [96] suggests that models do not possess intrinsic values; an ideal model should possess minimum complexity and be capable of solving the concerned problems with an acceptable accuracy.

A simple, linear, vehicle model could provide accurate handling analyses up to a lateral acceleration of 0.3g, while most vehicles tested for handling evaluations experience a lateral acceleration up to 0.8g [97, 98]. A linear analysis for heavy vehicles is valid only up to lateral accelerations of about 0.1g, since the high CG associated with such vehicles causes significant load transfers under lateral acceleration above 0.1g [20]. The inclusion of longitudinal and lateral load transfers is helpful for predicting handling and directional dynamic responses of road vehicles. A nonlinear 14 DOF full vehicle model, capturing the basic vibration modes of rigid-body sprung and unsprung masses, represents a quite useful tool for predicting the ride and handling dynamics of a road vehicle with alternative suspension designs without introducing the complexity of multi-body codes. It provides a good compromise between the accurate prediction of vehicle response and rapid simulation time [26, 99]. A 14 DOF vehicle model also offers the flexibility of modeling nonlinear suspension stiffness and damping components and integrating a semiactive or active suspension, or controlled anti-roll bars [26].

A variety of maneuvers has been employed to assess vehicle handling and roll characteristics, which can generally be divided into two types: open-loop and closed-loop. For open-loop maneuvers, the time history of the steering angle input is pre-defined, making it independent of the vehicle response. In closed-loop maneuvers, the steering angles are computed using paths that are based on a model that includes the vehicle and human driver dynamic characteristics. The open-loop simulation is inherently repeatable and thus yields uniform vehicle dynamics comparisons for design studies. For the open-loop simulation, two types of steering inputs are generally used: identical (or parallel) and differential steer angle input [100]. A steady-state steering analysis based on average parallel steer angle could result in as much as 5% higher lateral acceleration, when compared to an analysis based on differential left and right side values [100].

Fundamental property analysis of a full-vehicle suspension system concerns four vibration modes, namely bounce, roll, pitch and warp [24-26, 75, 101]. The vertical ride generally requires a soft bounce mode, while stiff roll and pitch modes are beneficial for inhibiting vehicle attitude during steering, braking, and acceleration. It has also been well accepted that the suspension warp mode should be as soft as possible for improved road-holding performance, although there is very limited technical literature on analytically discussing suspension warp property. These four fundamental modes are strongly coupled for a vehicle with a conventional unconnected passive suspension system. The use of passive anti-roll bars yields a stiffer suspension warp mode, which is undesirable.

The passive mechanical interconnections among the suspension units in a full vehicle model have also been developed and investigated for many years [101]. The full vehicle mechanically interconnected suspensions could decouple the different suspension modes, in order to provide a more favorable compromise between ride and handling requirements, although their implementation requires complex designs that may add considerable amount of weight to the vehicle. The complex design may also decrease the flexibility of suspension tuning to adapt various road and operating conditions. Full-vehicle fluidically-coupled suspension systems have been investigated using simulation models [24-26]. A general framework for designing and tuning a class of passive interconnected hydro-pneumatic suspension systems has been proposed in the two very recent studies [25, 26]. A generalized 14 DOF nonlinear 3-dimensional vehicle model was developed and validated to evaluate vehicle ride and handling dynamic responses, as well as the suspension anti-roll and anti-pitch characteristics under various road excitations, and steering and braking maneuvers [26]. The results [25, 26] indicate that the full-vehicle coupled hydro-pneumatic suspension systems offer considerable benefits in realizing enhanced ride and handling performance, as well as improved anti-roll and anti-pitch properties in a flexible and energy-efficient manner.

Suspension damping design/tuning plays an important role in enhancing vehicle dynamics and stability. Road vehicles commonly employ hydraulic dampers to provide sufficient and variable damping. However, the damping due to hydraulic dampers is known to be highly nonlinear and also asymmetric in the compression and rebound motions. In general, higher damping in rebound is preferred for rapid dissipation of energy stored in the suspension spring, while lower damping in compression is used to decrease the force transmitted to the vehicle body. The progressively hardening suspension stiffness properties of air springs tend to induce an upward ride height drift, while the asymmetric damping yields a downward ride height drift. They compensate each other to a certain degree.

A number of studies have also modeled the hydraulic dampers using the experimental and analytical techniques [102-104]. Allen et al. [102] concisely review different modeling approaches for hydraulic dampers, primarily including: (a) equivalent linearization; (b) restoring force maps (black box method); (c) physical models; and (d) discrete spring and dashpot models. Simms and Crolla [103] propose a set of criteria for choosing the optimal modeling strategy for damping design and tuning, including: (a) ability to capture damper nonlinearity and dynamic characteristics; (b) flexibility to model different types of dampers; (c) ease of generating the model; (d) suitability for vehicle dynamics simulations; and (e) usefulness as a predictive tool.

Based on a developed three-dimensional model of an urban bus, two very recent studies [105, 106] explore the desirable damping design for both driver ride comfort and road-friendliness through objective optimization and subjective damper tunings. The comparisons of damping properties obtained from subjective/objective tunings suggest that the subjective tuning relies greatly on the motion perception of the experiments, which tends to emphasize the vehicle roll responses, while the measures related to tire load performance would be under-represented. The designs identified through the objective optimization rely on the chosen performance measures and the effectiveness of the model in predicting the performance measures. The comparisons of the damper properties derived from the subjective and objective methods result in comparable compression mode properties but considerably different rebound properties, which are directly attributed to the roll motions of the sprung mass [106].

The effectiveness of the proposed objective and subjective optimal suspension damping designs is subsequently evaluated under a range of probable operating conditions for urban buses [106]. The results demonstrate considerable performance benefits of both the objective and subjective damping designs in terms of driver ride and road-friendliness over the range of operating conditions considered, when compared to the baseline dampers. The proposed objective and subjective methods could serve as generic guidance for passive suspension damping design/tunings for enhancing ride vibrations and road-friendliness of urban buses, and also other types of heavy road vehicles. However, the damping design/tunings should be further examined in view of vehicle handling dynamics and roll/directional stabilities, using a more comprehensive full vehicle dynamics model.

Controlled Suspension Design

The above discussions have demonstrated that suspension design involves complex challenges associated with different vehicle performance measures, for which conventional passive suspension systems are designed or tuned to achieve a compromise among various measures. Although passive fluidically-interconnected suspensions offer certain advantages in realizing a better compromise between ride and handling, additional efforts are needed to address the associated challenges, such as packaging, dynamic seal longevity, and cost. Alternatively, controllable suspension systems, the current mainstream in research related to vehicle suspension design, have also been explored for a few decades [107-110]. Much of this is attributed to the rapid advances in mechatronics as well as emerging demands from the automotive industry and consumers. Semiactive suspension systems are available on a large number of passenger vehicles, mostly high-end luxury vehicles. Their applications on large military vehicles have also been evaluated, with very promising results. The recent developments associated with semiactive and active suspensions are concisely reviewed and discussed below.

Semiactive Suspension Design

The concept of semiactive suspension system was first introduced by Karnopp and Crosby in the early-70s, based on the well-known skyhook control [107, 108]. Semiactive systems have a number of advantages over fully active systems, including low power requirements, system simplicity, ease of implementation, fail safe operation, and low cost. Another important factor is that skyhook control and various offshoots of it that have been proposed over the years, such as groundhook and hybrid control [45], are model-free control algorithms, where prior knowledge of the system parameters and excitations is not essential for their implementation. These factors have resulted in wide acceptability and implementation of semiactive systems—mostly as semiactive dampers—for vehicle suspensions during the past three decades. A survey of the semiactive suspension efforts through mid-90s can be found in [41, 42]. This section briefly discusses the significant developments with semiactive systems since then.

Skyhook Control: This refers to various variations of the original bi-state switching logic suggested by Karnopp and Crosby in their classic study, in which a two state switching policy—in case of the original skyhook control, based on the absolute velocity of the sprung mass and the relative velocity across the suspension—is used to determine the suspension force [109]. Over the years, the original skyhook control has been adapted to various forms in which other system states (e.g., displacement instead of velocity) are used in the switching policy to better adapt skyhook control to the system. For instance Koo et al. show that using displacement works best in configuring a semiactive tuned vibration absorber for controlling building floor vibrations [111-113]. Skyhook control has also been augmented to include other sensory input. Studies by Ahmadian and Simon show that using steering input is critical for increasing the effectiveness of skyhook for vehicle roll control [114, 115]. Similar to other methods, one of the challenges for successful implementation of skyhook control is tuning it, in particular when the suspension must be treated as a "gray box." Some of the approaches suggested for such systems are preview control, use of empirical data in the form of a look-up table, and adapting a FFT approach that can be implemented in real time [41, 116]. These approaches, however, either include significant computational overhead—for instance, in the case of using real time FFT—or require a trial-and-error approach, or require test data that may not be available. The studies in [117-120] explore the feasibility of skyhook control implementation. The study in [118] conducts a comparative evaluation of different skyhook dampers, such as on-off, continuously-variable, and no-jerk, and proposes a new approach that is referred to as continuous balance control.

Clipped Semiactive Control: This applies to suspension systems that can be described by a linear model with deterministic parameters. Commonly, these systems include a known control theory that can be applied to provide full control authority. Such systems, for example, include those using model-based adaptive control methods (such as Model Reference Adaptive Control (MRAC) or Least Mean Square (LMS) adaptive filter) in conjunction with optimal control, such as the Pontryagin's maximum principle, LQR, or LQG [121-125]. Other aspects of semiactive suspensions that are studied include the application of nonlinear control [126], sliding mode control [127], and robust control [128]. The full control authority has to be clipped with respect to the temporal control signal, which can degrade the system performance due to divergence from the actual semiactive control signals. Clipping the control signals can also introduce nonlinearities into the system dynamics, similar to what is observed in bi-state skyhook control.

Adaptation of Semiactive Control: The bandwidth of the semiactive damping system must be higher than the dynamics that it intends to control. Hydraulic dampers commonly have a low bandwidth that may fall below the dynamics of the system that they intend to control. For instance, it has been shown that at higher frequencies a conventional monotube hydraulic damper behaves like a spring [129, 130]. Magneto Rheological (MR) dampers commonly have a fast response time (in milliseconds for most systems), but exhibit large hysteresis at higher frequencies. Song et al. suggest an adaptive semiactive control algorithm that provides a no-clipping control approach [131]. The adaptive mechanism uses the semiactive system model to identify the distribution of excitation frequencies with respect to the resonant frequencies. A notable advantage of this model-based semiactive control approach is that it uses the same sensors that are commonly used for the conventional skyhook control, to identify the unknown system parameters in real time. Because the vibration frequencies are provided in terms of the system resonance frequencies, the bandwidth issue is automatically mitigated. This approach is successfully applied to skyhook control [132]. The results show that it can provide a systematic approach for optimizing the performance of skyhook semiactive systems.

Active Suspension Design

The early studies on active suspensions are included in a comprehensive review by Hrovat that was published in 1997 [43]. The studies include well-known approaches such as modal analysis, eigenvalue assignment, model order reduction, nonlinear programming, multi-criteria optimization, and optimal control. Classic methods have also been considered, such as root locus, Bode diagrams, and Nichols plots. A common prerequisite for these methods is access to a well-defined, linear model for the system. For nonlinear systems, it is required to linearize the system about an operating point for designing the controller. The nonlinearities inherent in suspension systems could not be effectively addressed by such approaches. More recent studies suggest using control methods such as sliding mode control [133] and constrained H_∞ control [134]. The results show that these approaches are able to deal with the negative effects such as force saturation, force nonlinearity, and model uncertainty, although the applications that have been considered are limited to quarter-car models. Linear Matrix Inequality (LMI) optimization methods have shown promising results for dealing with these challenges, when full-state feedback systems are possible [135].

The automotive industry provides customers viable options of best-in-class vehicles with all-round active suspension systems. The main obstacle for commercialization of such systems is the significant power requirement. In order to reduce the cost associated with the required power, practical active suspension designs generally function as a low-bandwidth system that require a modest 4 peak kw of power for road vehicle applications. One of the production systems is the active body control (ABC) from Mercedes-Benz. It uses a skyhook control approach that works in the primary ride mode. The ABC system, however, does not include an energy-regeneration function. Other systems that have been developed are the Bose active suspension that is based on linear electromagnetic actuators (motors). A main challenge associated with the Bose system is the significant weight that it adds to the unsprung mass, when compared to the ABC system. A heavier unsprung mass is considered undesirable in view of vehicle dynamics and stability control. Another promising system is the suspension developed by Visteon Corp, which includes compressible fluid struts and digital displacement pump motor [136, 137]. This system takes advantage of the fluid flow to achieve power regeneration for energy harvesting. It uses a frequency-domain control approach to synthesize established suspension controls to achieve the desired dynamic performance.

Nonlinear Dynamic Analysis of Controlled Suspensions

Suspension control systems usually need to deal with broadband random vibration excitations as well as unpredictable discrete event inputs such as potholes and bumps. The nonlinearity of the dampers and frictional components imposes an additional complexity in the dynamic analysis. Moreover, skyhook control itself introduces nonlinearity [138-142]. The bi-state skyhook can force a linear spring-mass system to create nonlinear dynamics such as sub- and super-harmonics, and even jerk [143].

The existence and effects of sub- and super-harmonics were first reported in [138], where the skyhook control was implemented in a seat suspension using an electromagnetic force generator. Both the simulation results and experimental data demonstrate the nonlinear dynamics of sub-harmonics below the seat resonant frequency range, and super-harmonics in the range of 2.8-3.6 Hz. These unresolved issues were left as future research topics [138]. For various skyhook or clipped semiactive controls, the inherent bi-state nonlinearity together with the damper nonlinearities makes the system dynamics complicated or even impractical for certain operating situations [118, 139]. Traditional methods such as root mean square (RMS), temporal describing functions, and spectral FFT may help to partially illuminate these.

The super harmonics phenomenon is also observed in two studies that implemented an MR suspension with skyhook control on a heavy truck seat [139, 143]. The source of the phenomenon is determined to be the control current, which introduces components of even multiples of the controlled vibration frequency. This causes the skyhook control to generate super harmonics that are odd multiples of the controllable vibration frequency, particularly in the systems whose dynamics are dominated by a single natural frequency mode such as seat suspensions. The adaptive semiactive control proposed in [131] eliminates such super harmonics.

A temporal analysis of the control inputs [139] shows that the phase lag between the estimated and actual suspension velocities results in dynamic jerks for skyhook control. Although these can be mitigated with the application of no-jerk skyhook control, the higher harmonics cannot be eliminated if using bi-state skyhook or any of its variations. The adaptive semiactive vibration control algorithms in [131, 139] avoid the higher harmonics and jerks because the adaptive control law is continuously selected as “hard”, “soft” or “in between”, in place of a bi-state current to the damper.

Energy Harvesting Suspension Systems

The stiffness and damping properties of vehicle suspension systems yield a coupled effect on suspension power consumption and utilization characteristics due to complex operating conditions, on which a number of efforts have been attempted in the past three decades [144-152]. However, no generally-accepted guidance has been developed on the suspension power characteristics, partially due to the fact that vehicles generally operate in a wide range of speeds and road roughness conditions. Karnopp [144] points out that a suspension tuning could affect the power demands depending upon the ground profile and driving speed, while Velinsky and White [145] show a possibly up to 20 percent increase in the total vehicle rolling loss due to ground roughness. The aerodynamic drag coefficient is also found to increase while driving on rough roads [145], which is mainly due to the pitch and vertical oscillations of the vehicle body, indicating an additional benefit of controlling vehicle pitch attitude and vertical motions. The findings in [146] suggest the validity of a linear dynamic analysis over smooth roads from an energy loss point of view, which may not be true for rough or off-road operations.

The analysis of power dissipation property of vehicle suspension systems is critical for not only better understanding the suspension design/tuning and dynamic performance, but also developing energy harvesting or regenerative functions for further improving vehicular energy utilization efficiency. Karnopp [147] discusses a theoretical possibility of adjusting the suspension forces such that the motions require little energy, and suggests a higher power dissipation of an active suspension (without energy regeneration) than a passive system. Suda et al. [148] proposes a DC motor based energy-regeneration suspension system. Both the simulated and experimental results show that the proposed controllable suspension system can offer satisfactory performance in vibration reduction while consuming less energy than conventional active control without energy-regeneration function. Karnopp and So [149] apply the bond graph in analyzing energy requirements of active suspensions, and emphasizes the effectiveness of the fast load leveler system in controlling low-frequency vehicle attitudes. Ballo [150] shows the compromise between the performance enhancement and power demand for an active suspension. In contrast to Karnopp's suggestion in [147], Efatpenah et al. [151] conclude that for rough or off-road operations, an electromechanical suspension system could considerably enhance vehicle ride, with more power saving than a passive suspension system. Such topic should be further examined, which also indicates the important role of ground roughness conditions in the power dissipation of a vehicle suspension system, where energy loss can be significant over rough ground. A brief literature survey on regenerative suspensions by using electro-mechanical actuators is found in a very recent study [152]. Another very recent study [110] uses a digital displacement pump-motor based suspension system to realize energy regeneration. It should be noted that whether to include an energy-regeneration function within road vehicle suspension systems should be justified considering the vehicle class and operating conditions (mainly ground roughness and driving speed). For a very light passenger car mainly operating on smooth urban roads, the benefits of using energy-regenerative suspension systems could be minimal.

Summary and Future Research

The recent advances in road vehicle suspension dynamics, design, and control have been briefly reviewed and discussed together with the authors' perspectives. Undoubtedly, the research and development in these areas have considerably contributed to the enhancements of road vehicle dynamic performance and safety, as well as road-friendliness. Due to the conflicting requirements on a road vehicle suspension system, the research on passive suspension system designs has been converging to seeking alternative solutions in realizing decoupled suspension vibration modes/performance measures, where interconnected suspensions have demonstrated the considerable potentials. Controlled suspensions offer superior vehicle performance, for which to minimize the system cost and power demand (energy consumption) is critical for their wide applications to road vehicles, where an inclusion of energy-regeneration function may provide an alternative valuable solution.

Contributing to the rapid development of next-generation road vehicles, in particularly hybrid and electric vehicles, some future research topics should be addressed:

- <u>Dimensionless vehicle and suspension system modeling and dynamics</u>: A dimensionless system representation would facilitate underlying parametric relationships that are difficult to observe in a dimensional formulation. Moreover, a dimensionless approach indicates a considerable reduction in the parametric uncertainty. Some preliminary efforts include [23, 153-155].
- <u>Road vehicle pothole dynamics</u>: Characterization of potholes and dynamic responses of road vehicles to provide a general framework for evaluating shock isolation properties of alternative suspension designs/tunings, as well as controlled suspensions.
- <u>Fundamental dynamics and stability of hybrid and electric vehicles</u>: Efforts on fundamentals of hybrid/electric vehicle dynamics and stability should be conducted for

the rapid development of hybrid and electric vehicle systems, and for facilitating various vehicle controls and power management systems.

- Suspension kinematics and their effects on vehicle dynamics and stability: As one of the three main elements of a suspension system, analysis of suspension kinematics and their effects on vehicle dynamics and stability have attracted very small concerns from academic units, as reflected from the little technical literature. Such topics should be conducted so as to provide some general guidance for Automotive R&D for more effective vehicle dynamics tuning and refinement. Some very recent efforts include [156, 157].
- Adaptive suspensions/tires: Adaptive suspensions offer a viable alternative for future vehicle applications when operating in a complex environment, such as on- and off-road conditions. The main challenge is to identify and optimize the stiffness and damping settings for different road conditions and forward speeds, to enable real-time adaptation of the suspension (stiffness, damping, ride-height) based on the operating conditions. Its integration with adaptive tire pressure management system would offer further enhancements in vehicle dynamics and stability.
- Interconnected hydro-pneumatic suspensions: Interconnected hydro-pneumatic suspensions could also easily incorporate the adaptive-suspension and energy-regeneration functions, as well as semi-active and active controls. Some very recent efforts include [158, 159].
- In-wheel suspension concept: such concept generally integrates suspension mechanism (stiffness and damping components) within an airless tire and wheel unit, which replaces the traditional tire, wheel, valve and tire-pressure monitoring system for conventional vehicle applications. Such a mechanism can also provide a decoupled ride and handling tuning while offering a compact and lightweight design, improved traction, better road-holding and road-friendliness, and superior driving safety and fuel efficiency. Some preliminary efforts include [160]. An example of this type of systems is the Michelin Active Wheel, which integrates suspension, motor, and braking within one unit.
- Suspension power dissipation and energy harvesting: an improved understanding of power dissipation characteristics of vehicle suspension systems is needed, based on which energy harvesting should be further investigated. Such development is consistent with the development with next-generation hybrid and electric vehicles. An example of this type of systems is the regenerative suspension cited in [161].
- Electrification and integration of controlled suspensions: such development, e.g. [110], is consistent with the development of next-generation hybrid and electric vehicles. Specifically, this includes the integration of controllable suspensions with other vehicle control systems, in order to maximize the overall vehicle performance and safety in an energy-efficient manner.

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