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Light Vehicle Suspension System Types in the Early 21st Century

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Abstract— The variability in types of suspension systems applied to auto vehicles remains unclear and can be an impairment to vehicle manufacturers. This work aims to assess the different road vehicle suspension systems and the variations in their application within the early part of the 21st century. The suspension systems applied to 442 different car models produced within the period were identified. Inferential and descriptive statistical tools were first used to explore the data, then Principal Component Analysis (PCA) was carried out. Results showed that, although the number of each suspension system type applied annually varied significantly ($P<<0.05$), it strongly correlates with year as deduced from the Pearson Correlation analysis. Furthermore, the Multi-link, Macpherson strut and Double wishbone were the most applied types, and their application increased over the years. Whereas the application of other types either declined or were steady. PCA showed that two major principal components explains about 97% of the data variability. Whereas the first principal component accounts for the overall proportion of each type, the other depicts trends of utilization over the years. Conclusively, the different vehicle suspension systems utilized in the first few years of this century have been analyzed; the likelihood that the application of Multi-link, Macpherson strut and Double wishbone types will increase is high.

Index Terms— Automobile suspension systems, double wishbone, MacPherson strut, multi-link, Principal component analysis.

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1 Introduction

A suspension system is an assembly of different parts that work together to absorb vibrations majorly from road irregularities, thereby aiding ride comfort and vehicle stability. The major parts are springs, dampers and mechanism, and there are various types of each part. Generally, they are classified according to the manner in which different types of specific parts are designed and assembled. The different classes, based on their design configuration, are discussed in the literature [1]–[3], whereas the different types of suspension systems applied to light vehicles were highlighted in [4]. A summary of the common ones applied in road vehicles with their pros and cons is presented in Table 1. In [5], most of the patented developments on suspension systems within the early part of this century were identified while several articles on their design and related topics such as, road surfaces, modelling and control were discussed in [6]. Although researchers are currently working on diverse areas for improved performance, their application in different models of auto vehicles vary extensively.

Modelling and simulation for active and semi-active control is widely investigated, and several control approaches have been reported recently. One of such control techniques is the predictive scheme that involves certain predictive algorithm such as Fuzzy logic [7]–[9] and Neural network [10]–[12]. Other popular approaches are the Clipped approach also known as H infinity or H_∞ [13], [14] and Proportional Integral Controller [15]–[17]. Some less popular techniques recently reported are Adaptive sliding control [18] and Linear Quadratic regulator [19], [20]. In addition, there are recent reports of the hybrid control systems in which two methods are combined for better performance. For such systems, certain optimization algorithms are combined with other methods to achieve continuous control. Some examples include combination of Genetic-algorithm and fuzzy logic in [21], Particle swam optimization and neural network in [10], and Cuckoo Search Optimization and Proportional Integral Controller in [22]. Furtherance to the control of suspension systems, some researchers are looking into developing fault tolerant systems in which their control capabilities can be adjusted to cater for any failure that may occur during operation. This may involve faults detection, estimation and monitoring which is followed by control adjustment to cater for the consequence of a failing part [14], [23], [24].

Another area of interest for researchers these days is energy harvesting in suspension systems for improved fuel economy. Mostly, regenerative shock absorbers are applied to recover vibration energy in vehicle suspension systems, and a number of these systems with applications are presented in [25]. In general there are three key techniques for doing this: Mechanical, electromechanical and hydraulic [26]. And then, finally, specific components of the suspension system using have been analyzed using certain CAD software. Usually, the focus is to either get optimum dimension for uncommon applications or attempt to address existing issues. The watt linkage, a component that prevents motion of the wheel in the vertical direction, was modeled and analyzed using Finite Element Analysis (FEA) to determine the maximum total deformation for different materials [27]. Additionally, FEA and multi-body dynamics were combined to address an associated problem of side load with MacPherson strut suspension system [28]. Other recent works also reported the combination of Solidworks and MATLAB to simulate the toe characteristics of

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the double wishbone suspension systems [16], [17].

Given that the ride quality and stability of a vehicle significantly depends on its suspension system which are of many types with differing characteristics, adequate studies are required to gain insights into variability of their applications in recent times. Specific information on the degree of variability, however, are yet to be characterized in the state of the art, perhaps due to the enormity of the developed vehicle models, which would require overwhelming efforts in terms of data analysis. This paper aims to assess the variability of the rear and front suspension system types applied in automobile vehicles developed within the early years of the 21st century. Specifically, statistical methods, including Principal Component Analysis (PCA), were employed to identify and characterize specific information useful for vehicle buyers and automobile researchers and manufacturers.

PCA can effectively transform large data size of calculated variables into a summarized information sets called principal components. Usually, the summarized set contains information sufficient enough to describe the data [29], [30]. The procedure of carrying out PCA, as summarized in [31], includes: data standardization, calculation of covariance matrix, determination of eigenvalues and eigenvectors of the covariance matrix, calculation of the principal components and evaluation of results via graphical representations. Further theoretical details can be found in the literature [32], [33]. The technique has extensively been applied to data compression and other areas [34], and the review of some of these is reported by [35].

Table 1 - Different suspension system types applied to motor vehicle suspension systems

S/No	Names	Dependent/ Independent	Applied to:
1	Trailing Arm / Semi-trailing arm /Trailing link/ Dual link	Independent	Mostly Rear
2	Solid axle / Dead axle / Hotchkiss / DeDion / rigid axle beam / leaf spring / Rigid axle beam	dependent	Mostly Rear
3	Torsion beam / Swing axle / Twist beam	Semi-Independent	Mostly Rear
4	Double wish-bone	Independent	Both
5	Short and long arm	Independent	Both
6	Macpherson strut / Coil over spring / strut	Independent	Mostly Front
7	Air spring	Independent	Both
8	Multi-link / 5-link / 4-link	Independent	Mostly rear
9	Others: Trapezoidal link, premium ride, touring, normal duty, HD raised, sport	Independent	Both
10	Vertical pillar strut / Coil spring	Independent	Both

2 Methodology

2.1 Data Collection

A total of 442 road vehicles were assessed for this study. The front and rear suspension system types for the different models of these vehicles developed over the last two decades were identified from popular automobile websites which include the official websites of some of the car models and few popular websites containing the specification of auto parts, namely: thecarconnection.com and Auto123.com.

2.2 Data Analysis: Descriptive and Inferential Statistics

The different vehicle types and their models assessed are shown in Table 1. Based on the collated information, the number of times each type was used per year was estimated. The resulting data were analyzed using basic descriptive statistical tools: pie charts, line graphs and boxplot (which shows their mean values, and interquartile ranges). Then the variance of the data was assessed using the two-way-ANOVA without replication, followed by computing the correlation using the Pearson Correlation Coefficient. The statistical analysis was carried out using Microsoft excel application package (version 2013).

2.3 Principal component analysis

Principal Component Analysis (PCA) can be done using different software applications that contains built-in sub-routines for the purpose. For this study, the PCA was carried out using MATLAB program (version *9.7* – R2016a). Firstly, the number of times each suspension system type was utilized for different car models in each of the 21 years considered was estimated. Then the data was imported into the MATLAB work environment for the analysis. The principal component analysis was computed by using the inverse variances of the ratings as weights in MATLAB. At first, the coefficients of the principal components were estimated, then the coefficients were transformed so that they were orthogonal. After that, the score which contains the coordinates of the original data in the new coordinate system defined by the principal components were computed. The score matrix is the same size as the input data matrix. Based on the results, the variability of each principal component was estimated and the important ones were presented using a scree plot. Then, the relevant principal component was explored interactively using scatter plots.

3 Results and Discussions

Figure 1 shows the trend of each of suspension system type used in road vehicles developed over the last two decades. As can be observed, the total number of vehicles produced increased over the years. Moreover, Multi-link and Macpherson struts which are usually applied in rear and front suspension systems, respectively, are two types which were increasingly applied over the years. The increase in their application is due to their favorable advantages. On the other hand, the application of solid axle and vertical pillar strut suspension systems declined in 2015 whereas the air spring type were never applied to vehicle models developed from 2015 till date, probably due to its design complexity and high cost. Application of torsion beam gained slight increase in its application since 2013 due to their favorable advantages over solid axle when used in rear suspension systems. The double wishbone suspension system has a high and steady application rate, despite its disadvantages over the MacPherson strut, due to its ruggedness.

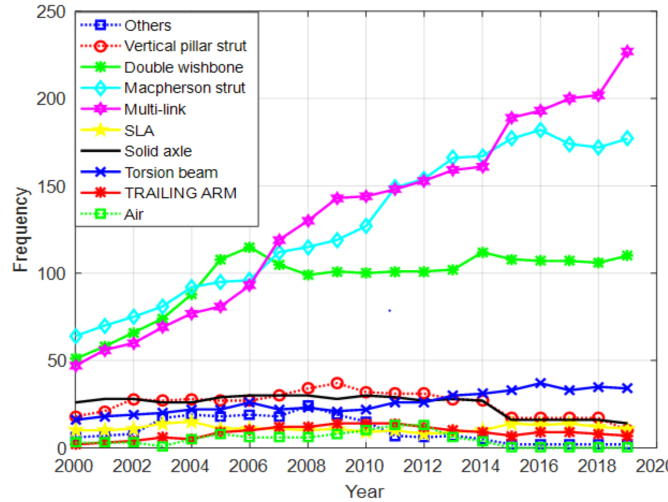

Fig. 1: Frequency of suspension system types applied in the early twenty first century

The percentage distribution of suspension system applied to front (Figures 2) and rear (Figures 3) wheels of vehicles developed in the first two decades of the 21st century. As observed, about half of the total vehicles developed within this period had MacPherson strut and multi-link in their front and rear wheels, respectively. The least applied type is air whose application seized around 2015 as earlier discussed. The double wishbone suspension system is one type that is widely applied in both rear and front suspension system types. Other types of suspension systems, as can be seen, are rarely applied, except for the solid axle and torsion beam that were proportionately applied to the rear wheels of vehicles. Some of these types which has limited application has unfavorable advantages in terms of cost, durability and efficiency when compared to the multi-link and Macpherson struts, and this may be the reason for their reduced application.

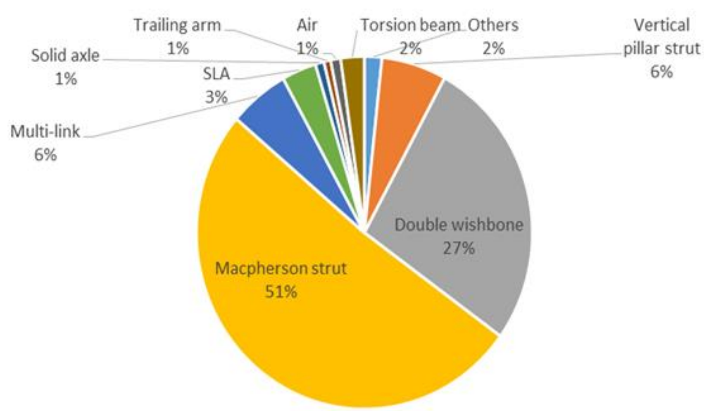

Fig. 2: Percentage distribution of front suspension system types in road vehicles developed between 2000 and 2020

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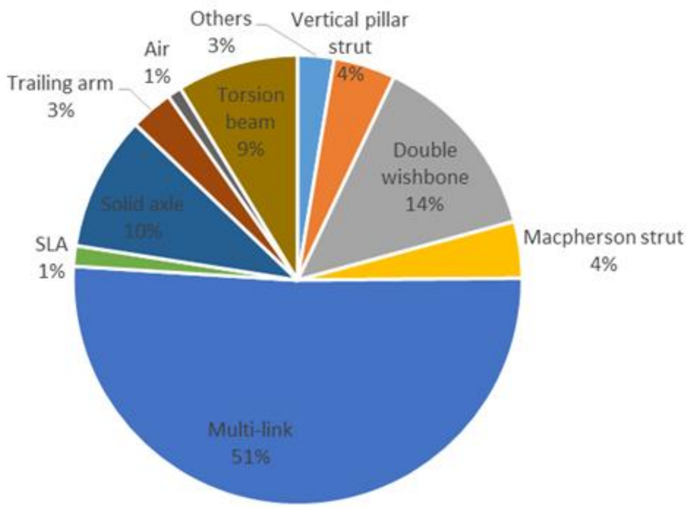

Fig. 3: Percentage distribution of rear suspension system types in road vehicles developed between 2000 and 2020

A box-plot which shows the central tendencies of each of the suspension system types applied to road vehicle between years 2000 and 2020 is shown in Figure 4. As observed, the multilink suspension system is the most applied type of suspension system with median value of about 140 as indicated by the red middle line in the box. It also has the widest range which is judged by the lines that extends from the left and right sides of the box. Macpherson strut types equally have high range of application over the years. As indicated by the line that extends from the right end of the box, suspension systems such as, air spring, trailing arms and those classed as others have their farthest observations as zero because there were some years they weren't applied at all. Finally, the air and SLA types are the least applied types of suspension systems throughout the period of consideration, but obviously, the SLA, having the slimmest box, has the least variability over the years considered.

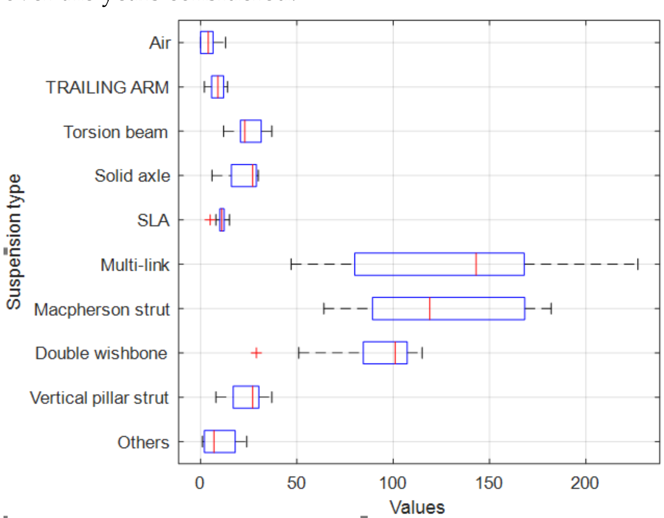

Fig. 4: Box-plot of the different suspension system types used between 2000 and 2020

The calculated correlation coefficient for each of the suspension system types is presented in Table 2. It was shown that the number of each and all the suspension system types correlate with the year of application within this period, having correlation coefficient greater than zero. However, some had negative correlation, indicating that their application decreased over the years, whereas others correlates positively. The Multi-link, MacPherson strut, torsion beam and trailing arms, have strong positive correlation because their application increased rapidly over the years. The solid axle, vertical pillar strut and other less common types showed strong negative correlation since their application dropped sharply over the years.

Table 2: Serial number tags and their correlation coefficient for the different suspension system types

S/No	Suspension system type	Correlation coefficient
1	Others	-0.6081
2	Vertical pillar strut	-0.5023
3	Double wishbone	0.3100
4	MacPherson strut	0.7628
5	Multi-link	0.8252
6	SLA	-0.1577
7	Solid axle	-0.7414
8	Trailing arm	0.2221
9	Air	-0.2835
10	Torsion beam	0.6172

The result of the two-way-ANOVA computed at 5% confidence level is shown in Table 3. The most significant values on the table are the P-values for both the rows (years) and columns (suspension system types). As shown, both P-values are far less than 0.05 which implies that the number of a particular type applied in the different years (the rows) varied significantly, and there is a significant variation in the number of each type used in a particular year.

Table 3: Result of Analysis of Variance (ANOVA)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Years	28702	20	1435.12	3.13	2.56E-05	1.63
Suspension system type	475216	10	52801.73	115.27	7.17E-70	1.93
Error	82451	180	458.06			

Total	586369	209

The scree plot (Figure 5) shows the percentage variability of the different principal components with the percentage variability of the data that they explained. As shown, only two out of the eleven principal components account for up to 98 % of the total variance. The first and the second component explains about 92% and 3%, respectively, of the variance. The dimension of the data set was thus reduced to just two main principal components with all the important information of its variance intact.

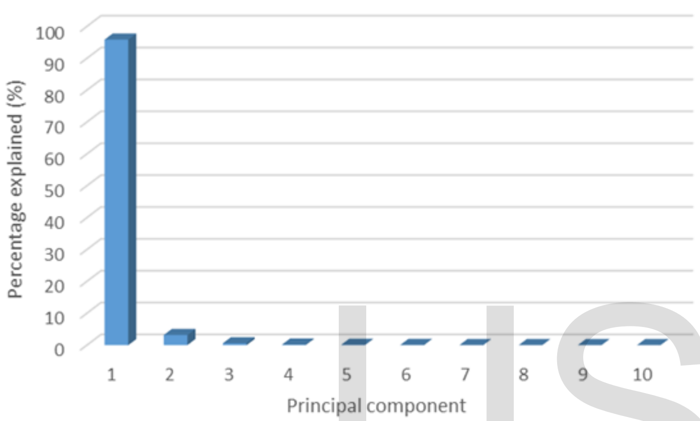

Fig. 5: Scree plot of the principal components that explained the total variance

The first two principal components were projected on a two dimensional scale shown in Figure 6, and the suspension system types for the different numbers are shown in Table 1. Clearly, for the first principal component, double wishbone MacPherson strut and Multi-link which are of numbers 3, 4 and 5, respectively, had positive values on the 1st principal component while the other types had negative values. This indicates that the first principal component contains information on the degree to which they are being applied or their proportion of application in automobiles developed over the years. Thus, it can be deduced that the proportion of a type of suspension system applied within this period varies from negative values to positive, where positive values inform that the likelihood is high.

For the second principal component axis, suspension systems types which declined in their applicability in recent times, such as, double wishbone, solid axle, and vertical pillar strut, had negative values. While those whose application rose over the years had positive values. This implies that the second principal component carries information on how application of each suspension system types dropped or increased in recent years. Negative values of suspension systems in the second principal component indicated that their applicability dropped in recent times while it is vice versa for those with positive values.

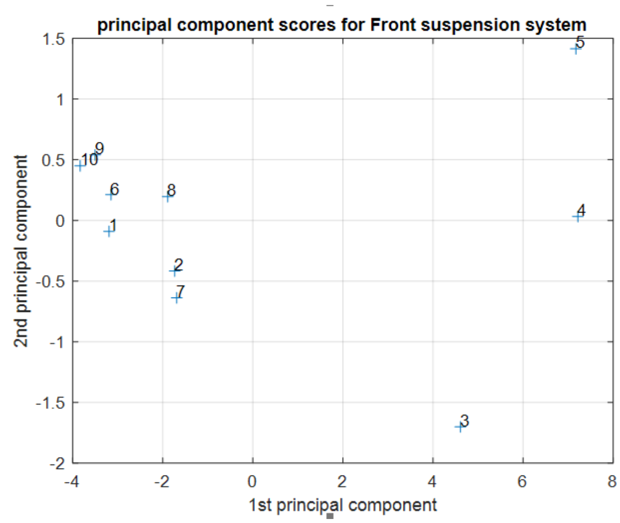

Fig. 6: Scatter plot of the 1st and 2nd principal components scores

4 Conclusion

Detailed information on the variability of different types of suspension systems applied in road vehicles within the first two decades of the 21st century have been characterized in this paper. The study showed that multilink and strut types are the most utilized front and rear suspension systems types, respectively, whereas certain suspension system types such as, air, trailing arm and SLA were rarely used in automobiles within the period. Additionally, it was deduced that application of both multi-link and MacPherson strut types are likely to increase in years to come. The PCA has shown how vehicle suspension system type utilization can be grouped into two important sets which are the proportion of their utilization and how their trends of utilization changes over time. Therefore, PCA can be effectively used to assess the important variations in various types of an automobile parts as their utilization evolves with time, an information that could be useful for automobile enthusiasts as well as researchersthough a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion.

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