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The effect of hydraulic damper characteristics on the ride and handling of ground vehicle

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***Abstract:** In this paper, ride quality and handling performance of a vehicle are quantified by the vibration transmitted to the vehicle's body. A passive suspension is designed to compromise between a good ride comfort and a good handling performance. In the development of modern passenger vehicle, subjective testing is greatly involved. In this study, a quantitative method is used to determine the range of suspension parameter for acceleration, braking, ride comfort and handling performances. The investigation involved a full car model with 7 degrees of freedom and VeDyna software was utilized to simulate the performance of the vehicle when subjected to different road profiles and different handling maneuver. The effect of 3 different nonlinear suspension characteristics towards the ride and handling was investigated. The results show that small damping ratio compromise the vehicle dynamic performance, and high damping ratio gives magnification of vibration to the vehicle. This study shows that by changing the suspension characteristics can greatly affect the comfort of the driver and the performance of the vehicle.*

***Keywords:** Ground vehicle; Ride Quality; Handling Performance; Non-linear shock absorber*

I. INTRODUCTION

Vehicle ride refers to the comfort of the passenger in the car. The ride quality refers to the effect of the vibration due to the irregularity of the road felt by the passenger in the vehicle. Road irregularities can be a road bumps or potholes. Excitation source of a vehicle can come from road roughness, tire, and wheels assembly, driveline and engine.

A damping coefficient of a shock absorber is characterized by force per unit velocity (Ns/m). During motion, shocks are generated due to road irregularities and vibrations are transmitted from the road to the tires and the body of the vehicle. The vibration from the road roughness will have a huge effect on the ride quality. As the shock absorber wear out, the damping coefficient will decrease and when the vehicle pass by a bump or pot holes, the vehicle will oscillate harshly.

Vehicle handling refers to the response of the vehicle especially when the vehicle is moving on a corner or braking. A good suspension system provides a good steering stability with a good handling. During cornering, the forces causing the turn and the force resisting it will be balanced. The job of the suspension system in handling performance of a vehicle is to ensure a good tire to road contact.

II. RIDE QUALITY OF A GROUND VEHICLE

A passenger car that travels at high speed will experience a broad spectrum of vibration. The spectrum of vibrations may be divided up according to frequency and classified as the ride (0-25 Hz) and noise (25-20,000 Hz) [1].

MATLAB/Simulink was used by [2] as a software to convert road excitation into a measured road profile. Four degrees of freedom half car model were used in this research to measure the pitching and rolling effect.

A half car model was used by [3] with passive vehicle suspension to study the wheel base delay and nonlinear parameters when subjected to different road profiles. The passive suspension systems are used to control the vertical motion of the road and the wheel. The pitch and roll are the parameters in their research.

The ride comfort was stated by [4] as the sprung mass acceleration. Passenger comfort depends on root mean square (RMS) value of acceleration and the frequency vibrations acting on the body is how the passenger comfort are viewed per ISO 2631-1.

In a study by [5] they concluded that by varying the damping coefficient alone was not an effective way of stiffening or softening the suspension system. The variable spring and damper characteristic are beneficial in refining ride comfort level. It was also confirmed by [1] that for a comprehensive treatment of shock absorber damping in ride analysis, the shock absorber should be modelled as a nonlinear model.

A study was done by [3] on the implementation of nonlinear asymmetrical shock absorber to improve comfort on a passenger vehicle. In their study, a linear and non-linear shock absorber is compared in a passenger car. They emphasized that non-linear shock absorber characteristics have more impact absorption to the passenger cars compared to the linear shock absorber.

Although many research papers would implement linear damper behaviour this has led to an unrealistic assumption since linear dampers could only handle the road vibrations for a single frequency where as it was found experimentally that the damper characteristic changes with respect to the disturbance frequencies.

III. HANDLING PERFORMANCE

To attain good handling and stable directional control performance, stiff suspension is required. A study performed

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by [5] has established relationships to objectively quantify vehicle handling. The parameters that correlated with this test is steering wheel and the lateral acceleration. The dynamic test involved “moose” test, J-turn, Fishhook and step steer. In the same study it was also affirm that the roll angle is the right parameter to study the handling performance.

The vibration transmitted to the body of a vehicle are translated in the form of vehicle angle that’s usually are measured by the roll, pitch, and yaw angle. A sinusoidal wave of steering input is used in measured the lateral acceleration and yaw response. At high frequency, the steering input of a vehicle increased. A vehicle with suitable suspension system was able to driven at a higher speed during cornering and reduce the understeer gradient.

IV. COMPROMISE OF RIDE COMFORT AND HANDLING

A passive suspension can only achieve either a good ride comfort or a good handling because these two performances conflict with each other. Ride comfort requires the shock absorber to be soft while good handling performance requires the otherwise. Thus, it was the objective of this study to obtain a range of suspension parameter to attain good acceleration and braking, good ride quality and good handling performance.

The study done by [4] stated that maximizing only ride comfort has an adverse effect on road holding. From Figure 1, it can be seen that having maximum value of road comfort (RC) have the minimum value of road holding (RH) and vice versa. Thus, it is essential a correct shock absorber characteristic is chosen to achieve the desired performance.

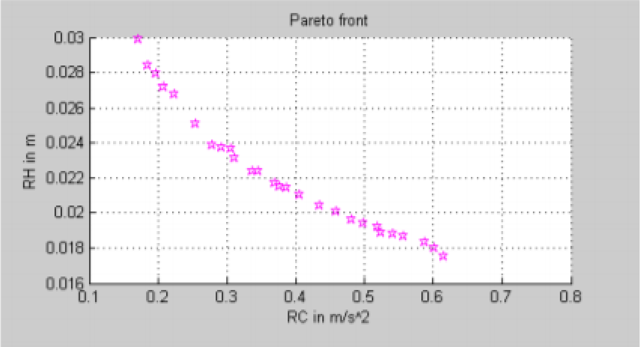

Fig. 1: Pareto front [4]

V. SUSPENSION SYSTEM

The suspension system in a vehicle urges two important matters. The first function is for the vehicle’s road holding and handling for a safe driving. The second function is to make sure the vehicle passenger have a comfortable ride and is able to isolate the road vibrations. Thus, the suspension designed for the front and the rear part of the car may be different due to the different mass distribution.

In a passive suspension design, there are always compromise between the ride comfort and vehicle handling performance. In [1] and [6], it was stated that the damping in suspension jounce and rebound are not equal. Thus, shock absorber usually has a dual rate with approximate three to one ratio between rebound and jounce damping.

Since a suspension has spring and damper stiffness, it is capable of moving in a vertical direction. The effectiveness of suspension coil spring and tire stiffness in series can be defined as the ride rate, RR:

$$RR = \frac{K_s K_t}{K_s + K_t} \qquad (1)$$

Where K_s and K_t are the suspension coil soring stiffness and tire stiffness respectively. In the absence of damping, the bounce natural frequency at each wheel of the vehicle is determined by:

$$f_n = 0.159\sqrt{\frac{RR}{W/g}} \text{ (cycles/sec) } (2)$$

Where W is the weight of the vehicle and g is the gravitational constant. When damping is present, resonance occurs at the damped natural frequency,

$$\boldsymbol{\omega_d = \omega_n}\sqrt{\mathbf{1} - \zeta^{\mathbf{2}}} \text{ (rad/sec)} \qquad (3)$$

Where ω_d is the damped natural frequency, ω_n is the natural frequency in the absence of damping and ζ is the damping ratio. It was claimed by [1] that the suspension damping ratio, ζ have to be in the range of 0.2 to 0.4 for a passenger car in order to achieve a good ride. The ride rate is influenced by the suspension spring, thus, the natural frequency of a system is in vertical mode. Road acceleration input increase in amplitude at higher frequencies. The best suspension is the suspension that can keep the natural frequency as low as possible.

The normal shock absorber characteristic was obtained by means of experiment in which a typical passenger car damper was tested on a test rig and was subjected to a sinusoidal displacement at varying frequencies. Figure 2 shows the normal characteristic of the typical damper. The sporty and the comfort damper characteristics were obtained by increasing and decreasing the damping force value of the normal damper by 30% respectively.

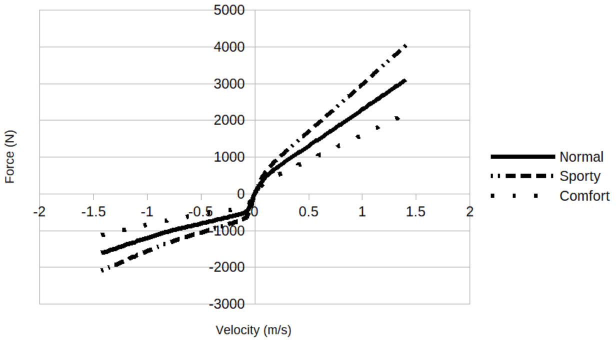

Fig. 2: 3 different damper characteristics

VI. MODELING AND SIMULATION

To study the ride and handling performance of the vehicle equipped with the 3 different shock absorbers 3 different test were conducted and the simulation was performed using the VeDyna software. The 3 different test were i) acceleration and braking, ii) ride comfort and finally iii) handling.

For acceleration test, the vehicle is subjected to two shifting gears. The vehicle accelerates in a specific time or distance in order to measure the pitch angle of the vehicle when it accelerates.

In the braking test, the pitch angle measured after the driver step on the brake pedal. For this test, the speed at which the brake pedal was fully stepped on is 100km/h.

The pitch angle of all three-different suspension parameter is measured and the result depends on the root mean square (RMS) value of the pitch angle measured. Figure 3 shows the graph when vehicle subjected to acceleration test and braking test and this test was also performed by [7] in their investigation of the vehicle's dive and squat.

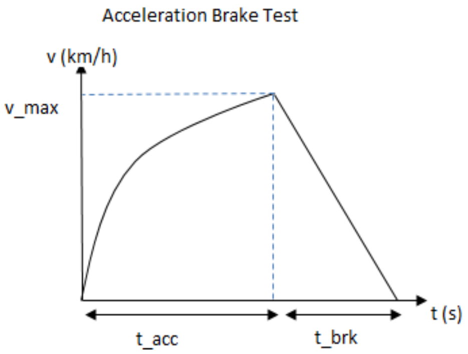

Fig. 3: Acceleration and brake test

While in the ride comfort test the ride quality is measured with the acceleration taken at the central gravity of vehicle relative to the ground. The vehicle is subjected to 3 different road profiles in order to test the vehicle comfort. Figure 4 shows the types of road profile in this study.

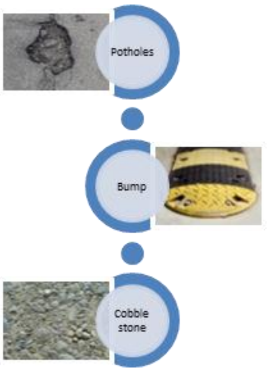

Fig. 4: Types of road profile test

Potholes and bump are first defined with respective width and thickness. Both potholes and bump are 0.1m in width. When a vehicle subjected to the potholes and bumps, the springs will absorb the energy and the shock absorber will dissipate the energy to the road.

A vehicle that has a good ride will have small amplitude and short bouncing interval. Another type of road that is introduced in this test was cobblestone road. For cobblestone road, the road is defined with power spectral density. If the road has a high power spectral density, it shows that the road is in bad quality. Even with the new highway pavement, this test can be performed.

All three ride comfort test are performed with constant speed. To achieve the best comfort ride, the suspension of the vehicle should have large suspension travel. The suspension of the vehicle should have a soft spring to absorb the vibration from the road.

Finally, for the handling test two types of vehicle maneuver profiles were used namely the fishhook maneuver and the slalom maneuver. As shown in Figure 5 the fishhook maneuver shows the ability of a vehicle handling performance. At the first point, the vehicle will drive in a straight line at the speed desired and have a rapid steering input at the second point. The third point leads overcorrection to the vehicle, thus, this leads to the fourth point where a vehicle tip usually will overturn at this point.

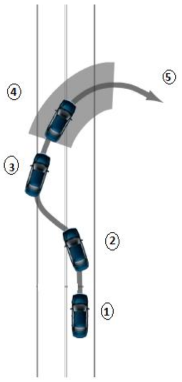

Fig. 5: Fishhook maneuver [8]

While for the slalom maneuver, obstacles are placed in a straight line with a certain distance apart. In Figure 6 the slalom maneuver uses the cones as the obstacles. Vehicles are subjected to weave left and right avoiding the cones. The slalom maneuver has successive turns which show the capability of a vehicle weight transfer when weaving left and right avoiding the obstacles. As the vehicle turn, the vehicle roll center changes. When a vehicle turns, the weight of the car shifts from side to side or from front to back. The tires that are weighted more will have better contact patch with the road while the less weighted tires have less contact. When turning, the front tires will do the turning and the rear wheels will steady the vehicle. The vehicles need to adjust the speed and the steering wheel to successfully maneuver through the slalom course. The vehicle respond can be seen with the suspension and weight distribution. When the vehicle turns, the vehicle will first lean to the other side, get the grip and then it turns to the driver desired direction.

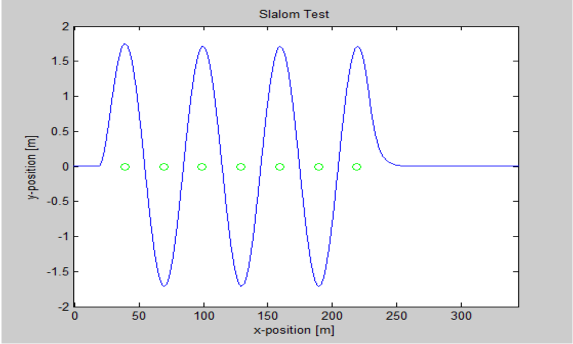

Fig. 6: Slalom maneuver test

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VII. RESULTS AND DISCUSSION

7.1. Acceleration and braking test

For acceleration and braking test, the vehicle is evaluated in terms of pitch angle. The root mean square (RMS) value of the result will indicate the best suspension design for this test.

Figure 7 shows the acceleration of the vehicle at the central gravity and since the simulation time recorded for braking test are only 1 second, thus the graph for the vehicle's speed deceleration from 100km/h to 75km/h in 1 second is shown in Figure 8.

From the result in Figure 9 and Figure 10, the sporty suspension which has stiffer dampers will provide the least magnitude of pitch angle when subjected to both tests compared to the comfort suspension design. By increasing the damping forces, the effect of dive and squat could be reduced.

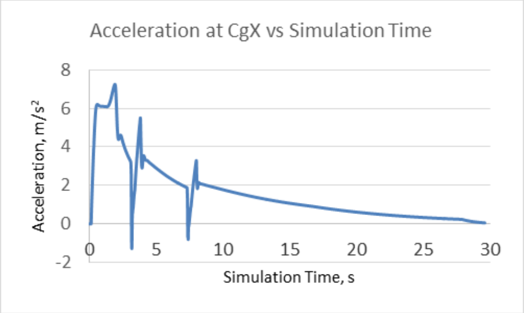

Fig. 7: Acceleration at CgX vs Simulation Time

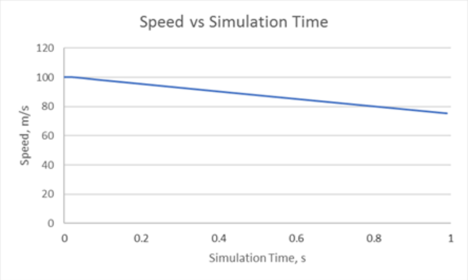

Fig. 8: Brake Speed vs Simulation Time

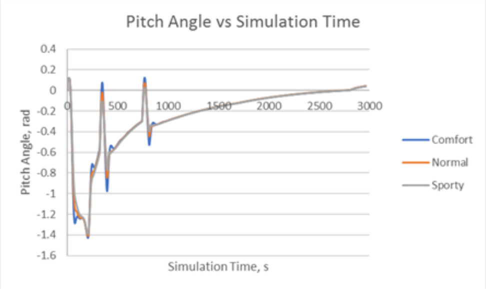

Fig. 9: Acceleration Pitch Angle vs Simulation Time

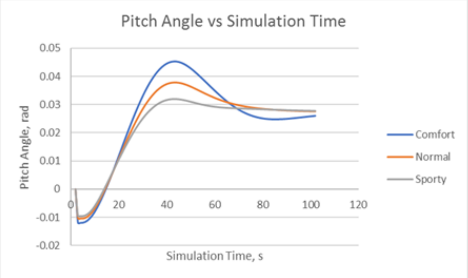

Fig. 10: Braking Pitch Angle vs Simulation Time

7.2. Ride comfort

For this investigation, the ride quality is measured with the vertical acceleration taken at the central gravity of vehicle relative to the ground. The vehicle is subjected to 3 different road profiles. The sporty suspension has stiffer damper compared to the comfort suspension at the time when the vehicle was driven over the bump. The result in Figure 11 shows the acceleration of the center of gravity along the vertical direction when the vehicle is subjected to a bump road profile. From the graph, it shows that comfort suspension shows smaller acceleration magnitude compared to sporty suspension but there are times that comfort suspension shows larger magnitude compared to sporty. In the graph, it also shows that the sporty suspension decay faster than the comfort suspension.

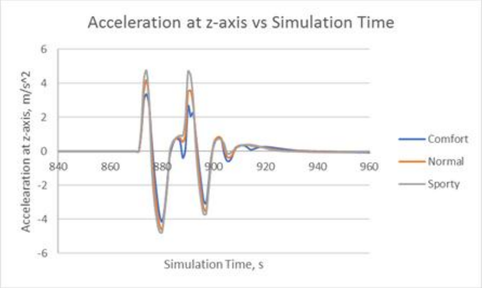

Fig. 11: Acceleration at z-axis vs Simulation Time

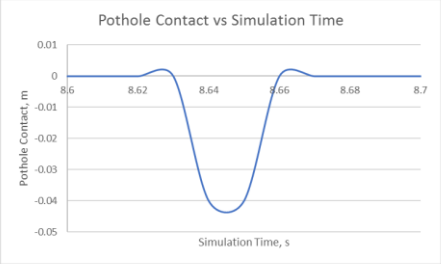

Fig. 12: Pothole Contact with Simulation Time

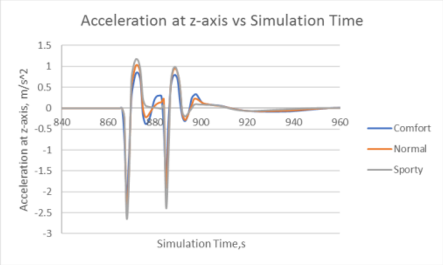

Fig. 13: Acceleration at z-axis vs Simulation Time

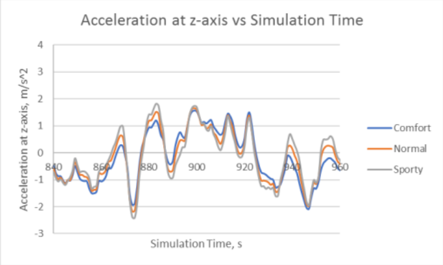

Fig. 14: Acceleration at z-axis vs Simulation Time

Figure 12 shows the characteristic for the designated pothole. The result in Figure 13 shows the acceleration along the vertical direction when driven over the pothole. Figure 14 shows that comfort suspension shows smaller magnitude compared to sporty suspension. It also shows that the sporty suspension decay rate is faster than the comfort suspension.

In this cobblestone road test, Figure 14 shows the response of the vehicle when subjected to the cobblestone road profile. The graph shows that the acceleration along the vertical direction for sporty suspension is higher compared to comfort suspension. Thus, the sporty suspension is not the best suspension when the vehicle is driven on a rough road.

7.3. Handling

When the vehicle subjected to fishhook maneuver test, the roll angle of the comfort suspension has the largest magnitude i.e. 0.129946 rad. The steering input to the vehicle can be seen as in Figure 15 where the steering wheel was turned from 0 degree to +175 deg and finally to -175 degree. It was also noted that the comfort suspension takes more time to settle compared to sporty suspension. This shows that for a good road holding, the vehicle should have a stiffer suspension and this result is illustrated as in Figure16.

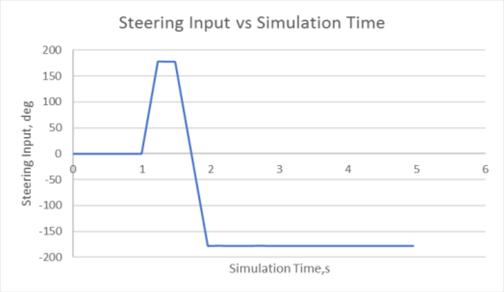

Fig. 15: Fishhook Steering Input vs Simulation Time

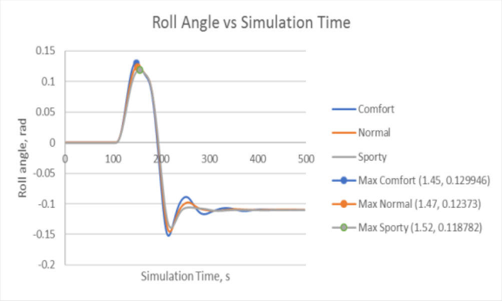

Fig. 16: Fishhook Roll Angle vs Simulation Time

As for the slalom course, the vehicle response can be seen from Figure 17. From all the three types of suspensions, the comfort suspension has the largest roll angle magnitude. This shows that when a vehicle is subjected to a slalom maneuver test, the roll angle affects the comfort suspension the most and has a small effect towards the sporty suspension.

7.4. Summary of results

From Figure 18, the three type of suspensions is compared with respect to their performances. By putting a range from 1 to 3 i.e. 1 being poor and 3 being the best a radar map corresponding to the individual suspension can be observed.

For a bump road, pothole road or cobblestone road, a comfort suspension parameter will give the best comfort ride to a passenger vehicle compared to a sporty suspension.

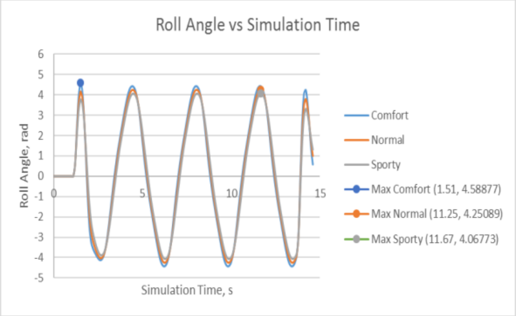

Fig. 17: Slalom Roll Angle vs Simulation Time

For performance, such as acceleration, braking, fishhook and slalom maneuver, a sporty suspension gave the best performance compared to a comfort suspension.

From here, it can be seen there is a trade off in a passive suspension. If a vehicle consists of a comfort suspension, the driver will have a comfort ride when driving through a bumpy road, pothole road or cobblestone road while when the same vehicle that has comfort suspension subjected to fishhook, slalom, acceleration and braking, the driver will experience effect of suspension whether in large magnitude of pitch angle (squat or dive effect) or large magnitude of roll angle. The comfort suspension will have less stability when driven in an extreme road condition.

Likewise, a sporty suspension gave the best handling performance when subjected to the fishhook, slalom, acceleration and braking test but the worst ride comfort when subjected to the ride comfort test.

A normal suspension conferring to the figures gave a generally good effect on all the test. If the vehicle has normal suspension parameter, the trade off with ride comfort and handling performance is the same.

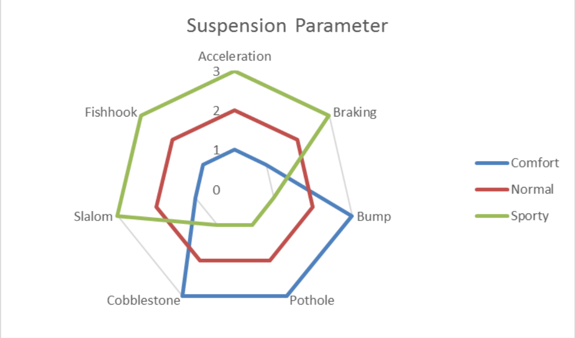

Fig. 18: Suspension Parameter

VIII. CONCLUSION

In the development of a passenger car driving behavior, subjective evaluation is used. This subjective evaluation measure the vehicle behavior at limit driving and the vehicle are driven by an expert driver. The evaluation consists of a set of procedure test, questionnaire, rating scales and driver perception. By using quantitative measures, the characteristics of the vehicle itself are telling the driver how good the vehicle are when subjected to road roughness and handling. This study focuses on the development of objective parameters for suspension system which includes the stiffness of a spring and damper that can contribute to a comfort ride and good handling.

For drivers that prefer ride comfort, the comfort suspension is the suitable suspension while for driver that prefers better road handling, sporty suspension is the best option. There are always trade off in ride comfort and ride handling in a passive suspension. Thus, the driver has to decide which parameter to be preferred more to utilize the vehicle according to their preference.

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