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Wheel movement during braking

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ABSTRACT

An experimental study of wheel movement arising from compliance in the front suspension and steering system of a passenger car during braking is presented. Using a Kinematic and Compliance (K&C) test rig, movement of the front wheels and the suspension sub-frame, together with corresponding changes in suspension / steering geometry under simulated braking conditions, were measured and compared with dynamic measurements of the centre points of the front wheels. The resulting knowledge of front wheel deflections has enabled the causes and effects of steering drift during braking to be better understood in the design of front suspension systems for vehicle stability.

1. INTRODUCTION

The friction brake on each wheel of a motor vehicle generates a braking torque and a resultant braking force which are reacted by the suspension components and the subframe or chassis system [(1)]. Although the suspension components may be the same side-to-side of the vehicle, the subframe and/or chassis system is generally not symmetrical from side to side. The suspension, subframe and chassis systems are compliant to a greater or lesser extent, and deflections resulting from the braking forces and torques can therefore be responsible for different wheel movements on each side of the car. The kinematic effect of this can be to create dynamic changes in wheel alignment and steering geometry during braking, and on the front wheels, where braking loads are highest, such changes can be a major contributory factor to steering "pull" or "drift" during braking.

Compliance in the suspension system is necessary to achieve a good ride characteristic, but an undesirable side-effect is compliance steer, which results from the application of lateral or longitudinal forces at the tyre contact patch, and is considered to be one of the biggest contributors to straight-line stability during braking [(2)]. Compliance steer is affected by the design of rubber components in suspensions and can be introduced into suspension systems by elastomeric (rubber) suspension bushes, and rubber mounts for cross-members and steering racks.

Steering "drift" during braking usually refers to a relatively minor deviation from straight-line braking, although even minor deviation remains unacceptable by today's standards of vehicle driveability. Previous work by the authors [(3)] used vehicle tests to investigate 4 parameters associated with steering geometry, viz. toe-steer, camber, caster, and scrub radius which affected steering drift, and found that compliance in the bushes of the lower wishbone rear bush of the front suspension of the particular vehicle studied had a significant effect on steering drift during braking. Brake "pull" associated with unequal side-to-side braking forces interacting with steering geometry was not found to occur.

The vehicle tests provided an indication of the practical significance of the identified parameters in the generation of steering drift during braking on an actual vehicle. The results of the tests showed clearly that the steered wheels did change their orientation during braking, as measured by the toe steer angle. The results also demonstrated that the most effective means of controlling any tendency towards steering drift during braking was to ensure minimum side-to-side variation in suspension deflection and body deformation both statically and dynamically.

This paper presents a further study of wheel movement and suspension deflection under forces which are representative of those generated during actual vehicle braking. Using a Kinematic and Compliance (K&C) test rig, movement of the front wheels and the suspension sub-frame, together with corresponding changes in suspension / steering geometry under simulated braking conditions, were measured at different levels of suspension movement. These measurements were then compared with dynamic measurements taken from a test car. The result is a better understanding of the causes and effects of steering drift during braking which will assist in the better design of passenger car front suspension systems for vehicle stability during braking.

2. STATIC MEASUREMENTS OF FRONT SUSPENSION DEFLECTIONS UNDER BRAKING FORCES

The test car used for the investigation presented in this paper was a front wheel drive family saloon. The front suspension was a McPherson strut design, with the lower wishbone (also known as the "A-arm") pivoted to a subframe via rubber bushes, while the subframe was mounted to the vehicle body via rubber mounts. The top of the strut was mounted directly to the vehicle body via rubber bushing at the "suspension turrets".

Static measurements were carried out under one author's instruction by IKA (Aachen University) on their Kinematic and Compliance (K&C) test rig facility. The toe-steer and camber angles, caster angle, and kingpin inclination angle were measured by a standard wheel alignment test device. A 3-D coordinate measuring device was used to measure the actual position of the wheel centre points, tyre contact patch centre, strut rotation (top), lower ball joint, and the front and rear mounting point of the sub-frame to the body. The measurement accuracy was estimated to be ± 0.05 mm.

Vertical and longitudinal forces were applied at the positions of the tyre patch centres; the wheels were not included to avoid tyre deflection effects. Full details can be found in [4]. The measurements from the K&C rig are summarized below.

Steering offset
The measured steering offset varied from –6.5 mm at the nominal condition (static load/deflection) to approximately –8.5 mm at 25 mm suspension vertical compression (jounce), as shown in figure 1. The Right side steering offset was slightly greater than the Left side by approximately 1 mm at 25 mm compression.

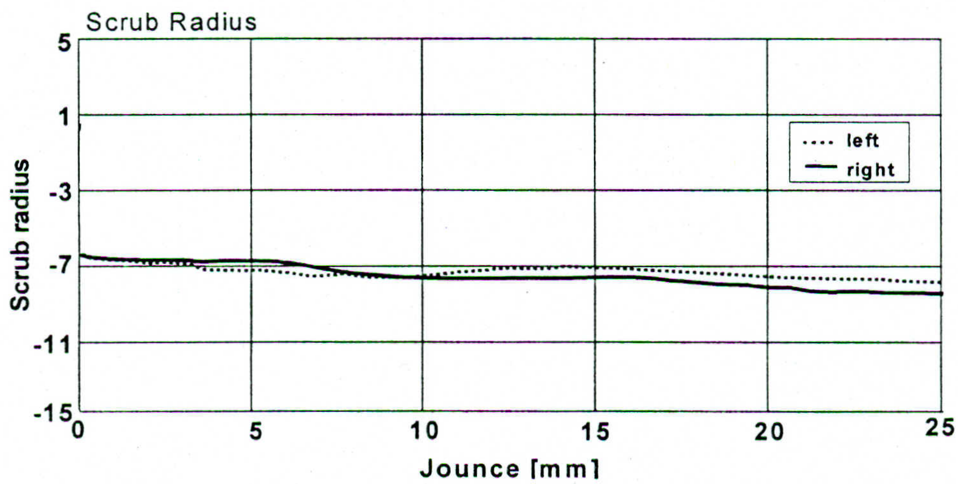

***Figure 1:** Scrub radius dependent on the jounce*

Tyre contact patch centre position
Calculations showed that at maximum measured vehicle deceleration (9.7 ms^{-2}) the brake force at each wheel was 2800 N (front) and 1500 N (rear), so longitudinal forces of these values were applied to each tyre contact patch position on the K&C rig, while the front suspension compression was increased from 0 to 25 mm in 5 mm increments. The results are summarized in figures 2 and 3.
As the suspension compressed, the track increased, but the Right wheel showed a bigger lateral deflection than the Left wheel. As expected, the longitudinal brake forces moved the contact patch backwards; both wheels were moved approximately the same amount. These results confirmed that the steering offset change was different side-to-side, but this difference was small, insufficient to change the steering offset between positive and negative values.

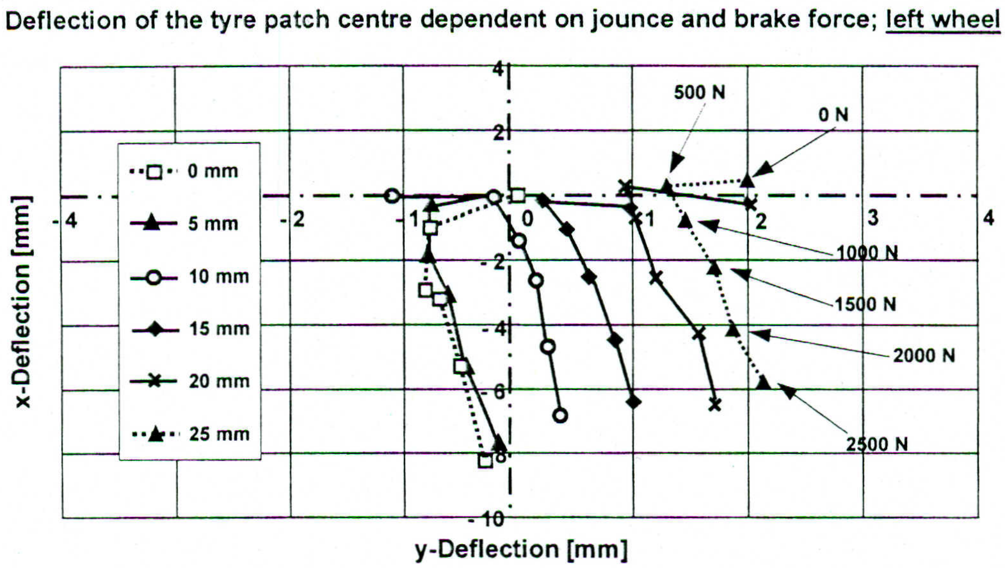

Figure 2: Horizontal deflection of the left wheel depending on compression and brake force

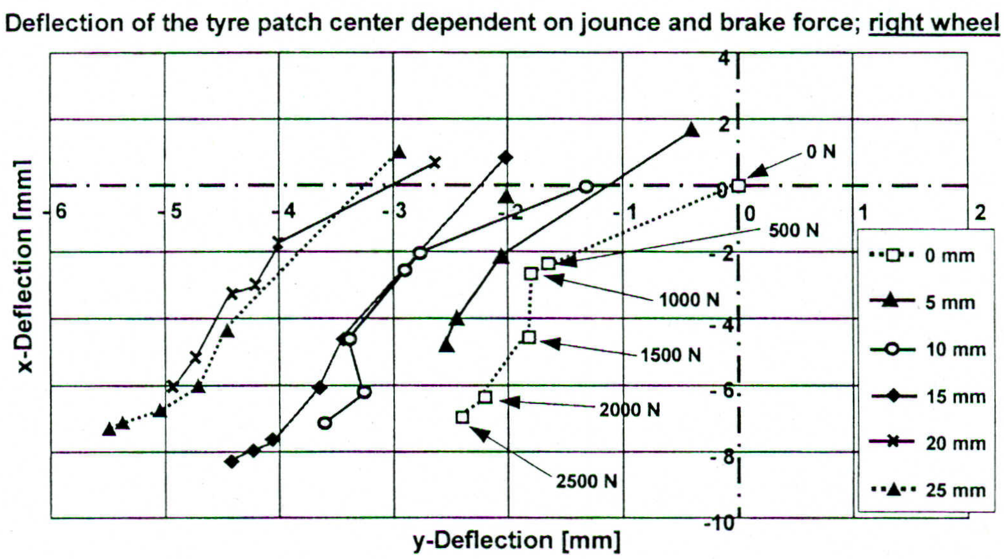

Figure 3: Horizontal deflection of the right wheel depending on compression and brake force

3. DYNAMIC MEASUREMENTS OF FRONT SUSPENSION DEFLECTIONS UNDER BRAKING FORCES

The same test vehicle was used for the dynamic tests as for the K&C tests. Deflections and movements to be measured dynamically fell into two: large movements up to 50 mm (e.g. the suspension vertical movement) and small deflections up to 5 mm (e.g. the deflection of bushes).

The instrumentation had to be tolerant of temperature, vibration and shock, and also as compact and lightweight as possible.

A "Rope Potentiometer" was selected for measuring both cases of movements and deflections. The principle of the rope potentiometer was that one end of an inextensible cord was attached to the point whose movement was to be measured, and the other end was coiled tightly around a drum attached to a rotary potentiometer. As the cord was drawn out, the potentiometer was rotated, and gave a signal proportional to the extension of the cord. This technique was accurate, robust, and convenient for use on the vehicle. Three such potentiometers were required to define precisely the movement of the point of interest in 3-D space, and as an example, the arrangement for measuring the wheel centre position is shown in figure 4. Two of the potentiometers were aligned in the X-Y plane, and the third was aligned in the Z direction. A portable computer with A/D-converter and measuring acquisition software (DIA/DAGO®) was used to log the data [16].

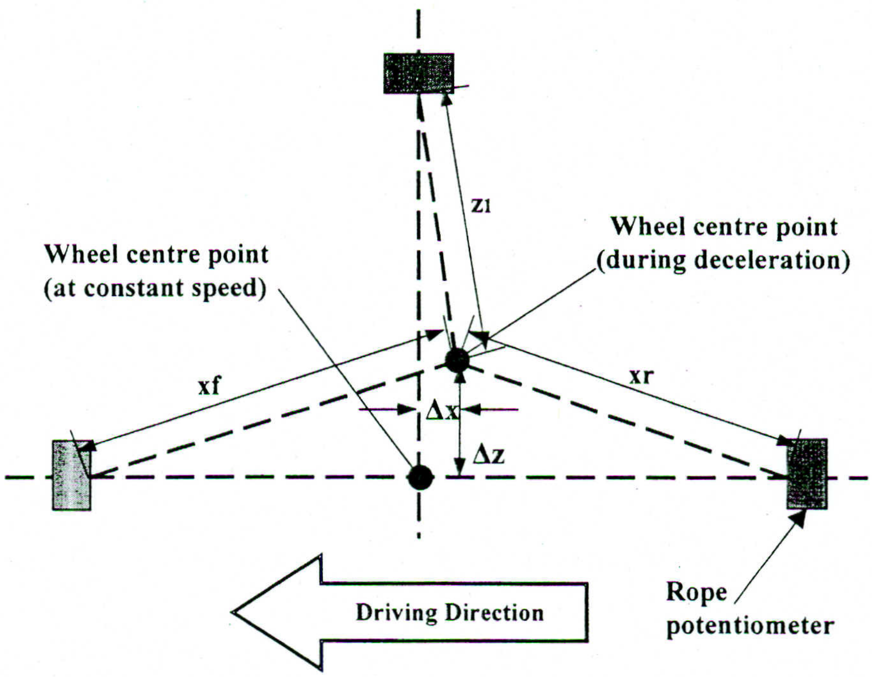

Figure 4: *Assembly at the wheel centre point of three rope potentiometers.*

Movements and deflections were measured as follows:

1. Subframe relative to vehicle body: 4 points; 2 in X and Y, 2 in X, Y, and Z (X, Y, and Z represent longitudinal, transverse, and vertical respectively),
2. Lower suspension arm deflection (Z),
3. Wheel centre (X, Y, Z),
4. Strut top (X),

The measurement positions are summarized in figure 5. Deceleration and other parameters were also recorded as previously described by the authors [3] [4].

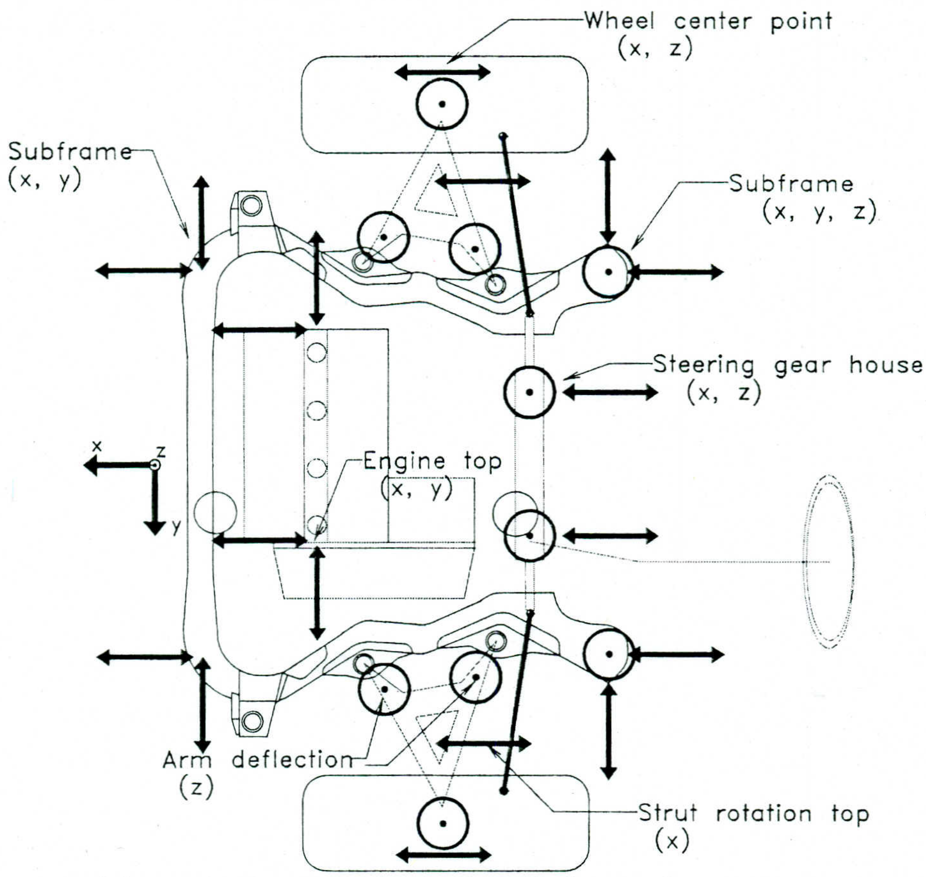

***Figure 5:** Measurement positions at the sub-frame, A-arms, strut rotation top, engine and steering gear housing*

Left and Right X deflection of the subframe is shown in figure 6; the subframe moved backwards by approximately 1.55 mm during the test. There was no noticeable difference between "fixed" and "free" control (hands on or off the steering wheel).

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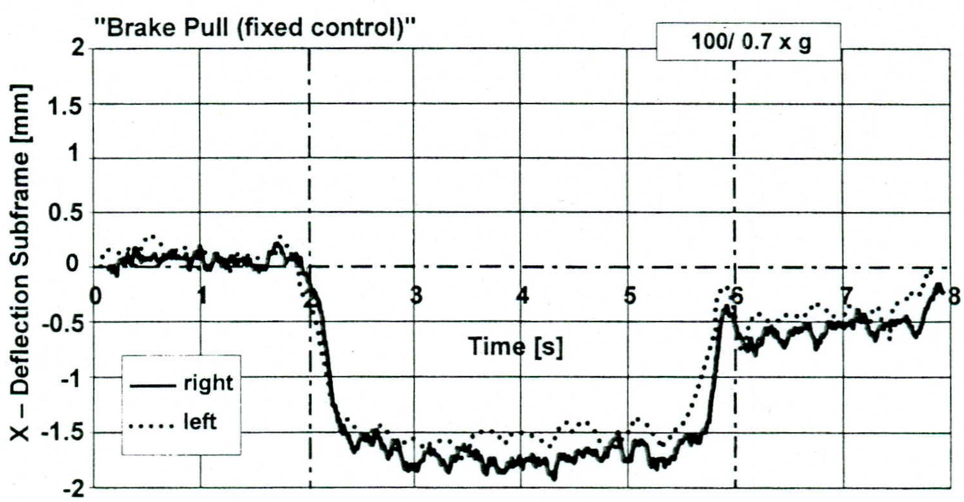

***Figure 6:** X-deflection of the sub-frame; fixed control*

At the rear subframe mounting, the measured vertical deflection (Z) was approximately 1.2 mm upwards as shown in figure 7.

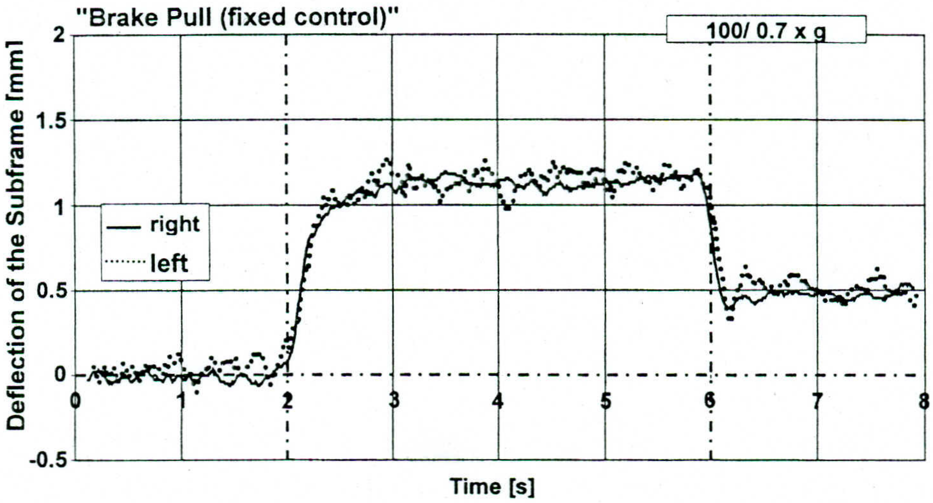

Figure 7: Z-deflection of the sub-frame, fixed control

Further analysis of the subframe deflection showed that there was some small "internal" deflection of the subframe (less than 1 mm), in that the front left corner and the rear right corner of the subframe moved closer together.
Because some suspension components are attached to the subframe, and some are attached to the body, these movements and deflections affect the steering geometry.

The vertical deflections of the front and rear bush positions of the lower suspension "A-arm" are shown in figures 8 and 9, which indicate approximately 2.5 mm upwards at the front position and approximately 4.5 mm at the rear position.

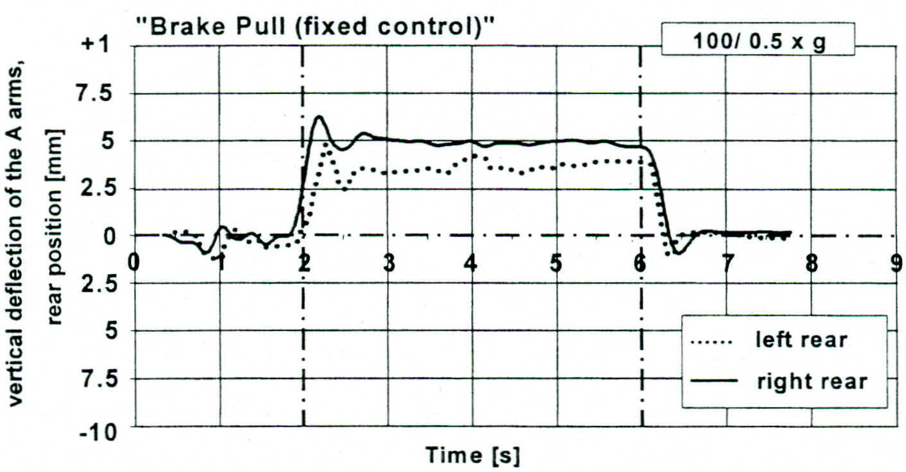

Figure 8: *Vertical deflection 'Z' of the A-arm rear position, fixed control*

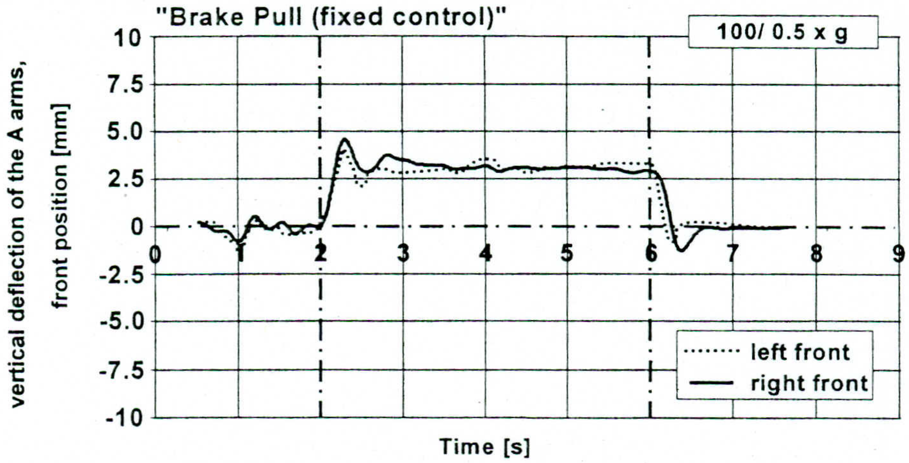

Figure 9: *Vertical deflection ‚Z' at the front position at the A-arms, fixed control*

The wheel centre movement is summarized in figures 10 and 11 in the vertical and longitudinal directions respectively. The peak vertical movement recorded was approximately 45 mm on the Right wheel and 38 mm on the Left wheel. The longitudinal measurement showed a movement of –10mm (backwards) for the Right wheel, compared with –8 mm for the Left wheel at the start of the test, while towards the end of the test the two sides converged to a value of 9 mm, with a definite indication of greater movement at the Left wheel.

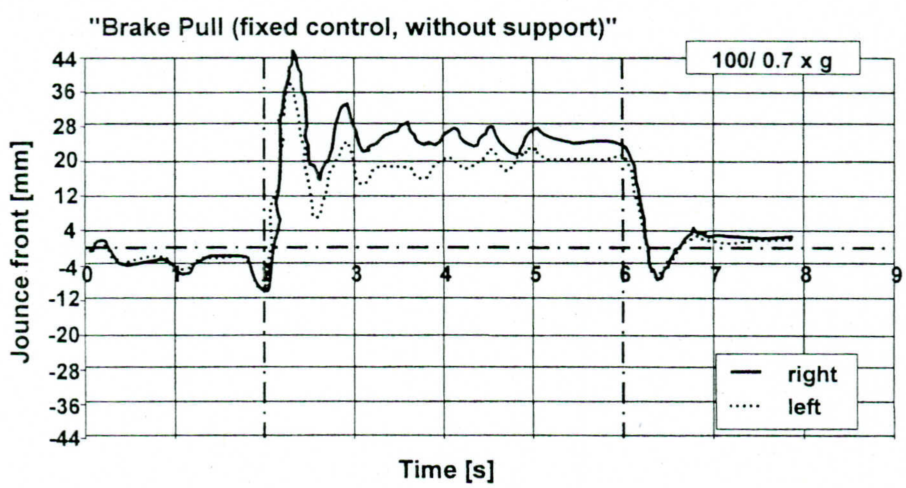

Figure 10: *Jounce at the front axle*

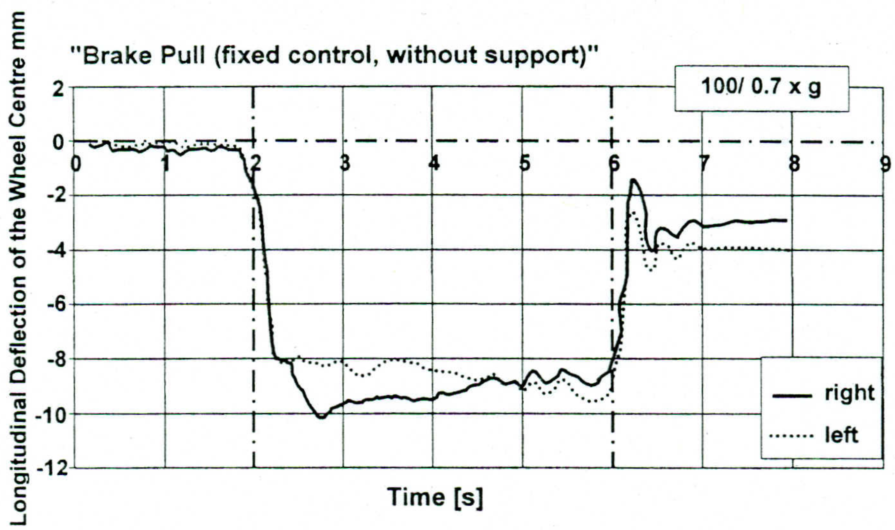

Figure 11: Longitudinal deflection of the wheel centre points, fixed control

The strut top position moved forward by up to 0.75 mm during the test (figure 12).

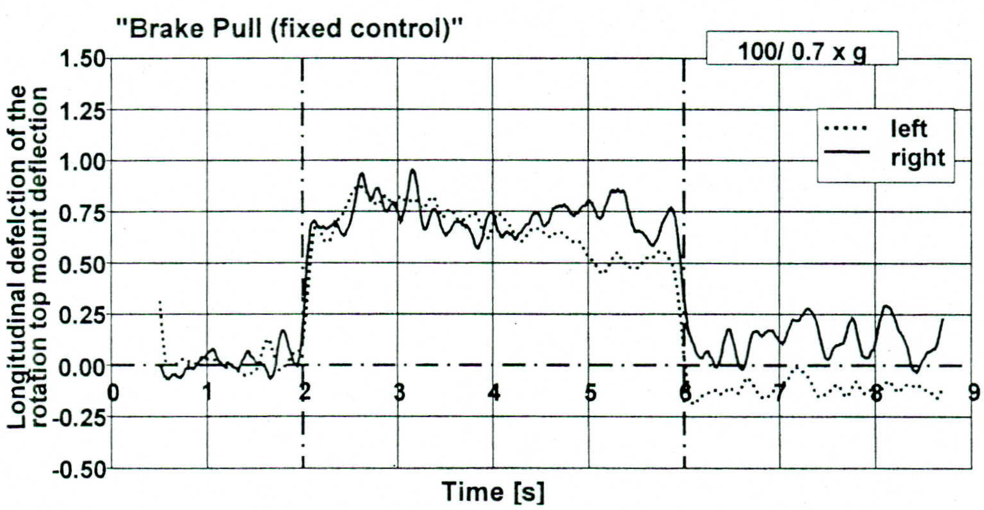

Figure 12: Longitudinal deflection of the strut rotation top, fixed control

4. DISCUSSION OF RESULTS

Both the static tests (K&C) and the dynamic measurements have shown how the suspension geometry can change during braking. The measurements have enabled changes in steering and suspension design parameters to be calculated and their effect analysed. Of particular interest was the change of steering offset and the wheel centre position during braking, which has been measured under static conditions of longitudinal braking force for different amounts of suspension compression. These measurements confirmed that not only was there a side-to-side difference but also this difference depended upon suspension compression (jounce).

Dynamic caster angle was calculated from the measured wheel centre deflection data and is considered in three parts: caster angle, caster trail (at the wheel centre) and caster offset (at the road surface). These are illustrated in figure 13. The reaction force at the tyre contact patch generates a steering force when the caster is non-zero, the magnitude of which depends upon the caster angle and the kingpin inclination. The caster angle is normally designed to be positive to give a self-aligning torque, but if the caster angle reaches a negative value, then the torque works in the opposite way. The results from the dynamic tests indicated that the caster angle did in fact change from positive to negative: this was a compound effect which included a difference of nearly 1½° between nominal and actual (+3° to +1.6° approximately), a non-zero caster trail at the wheel centre, a vehicle pitch angle of up to 1.5°, and longitudinal deflection of the wheel centre relative to the strut top. The net result was that the Right wheel in this case reached a negative caster angle during braking before the Left wheel early on in the brake application. Towards the end of the brake application, both wheels had switched from positive to negative camber, with a consequential loss of self-aligning torque.

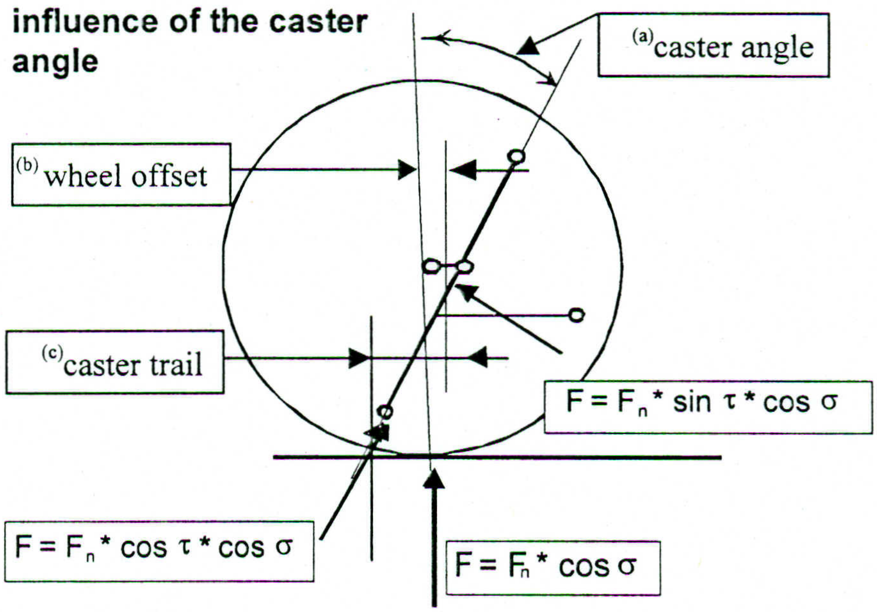

Figure 13: *Caster forces caused by the wheel load*
(kingpin inclination angle ≡ σ; caster angle ≡ τ)

The maximum values of dynamic caster angle and caster trail are shown in Table 1.

	Nominal value	Maximum dynamic value; Left	Maximum dynamic value; Right
Caster angle (°)	3.00	-0.45	-0.80
Caster trail (mm)	14.64	-1.5	-3.8

Table 1: Dynamic caster angle and caster trail

The self-aligning torque arising from the caster is only one of several sources of self-aligning torque, e.g. the pneumatic trail of the tyre, so the change from positive to negative caster angle would not destroy the vehicle stability. However, reduction in self-aligning torque is likely to allow other causes of steering drift to be more clearly felt. This was confirmed in a further test when the suspension was modified to be able to adjust the caster angle. When the settings were adjusted to give the same static caster angle each side, no effect of different caster angles was perceived (subjectively) by the driver. When the static caster angles were adjusted to be different from side to the other, the driver noticed a greater tendency to drift to one side during braking.

5. CONCLUSIONS

The major cause of steering drift during braking has previously [3] been found to be side-to-side dynamic variation in the deformation and deflection of suspension and steering components, and not side-to-side variation in brake performance. The research results presented here confirm that finding, and give more insight into this complicated phenomenon, emphasizing that steering drift during braking is an issue at the system level and not merely component level. The phenomenon cannot be addressed in terms of any single design characteristic of the vehicle suspension or brake system design. It can be concluded that a fully integrated dynamic model of the vehicle chassis will be a most valuable tool in chassis system design for stability.

The accuracy of the measurements made depended upon the transducer accuracy, and then the computational error in the derivation of parameter values. The accuracy was estimated to be no worse than 0.5 – 1%. Therefore it can be concluded that any experimental error is unlikely to affect the results so that their interpretation is invalid.

It is again concluded that control of the compliance at each side of the vehicle is critically important in minimizing steering drift during braking. In addition, though, it is concluded that it is equally important to ensure that the compliance and resulting deflections at both sides of the vehicle are as near the same as possible. Minimizing the compliance overall is helpful in achieving this aim, but this represents a compromise in terms of ride harshness and shock transmission.

Compressing the suspension increased the track width of the test vehicle, and altered the steering offset. The change in steering offset was found to be small in absolute terms (a few mm), and could be different from side-to-side. However, it is also important to note that every change in the steering offset each side will create an imbalance from side to side because of the difference in the steering arm forces. K&C tests are a useful way of measuring static deflection characteristics in a vehicle suspension, although an integrated computer model (as mentioned above) must be seen as the way forward.

ACKNOWLEDGEMENTS

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