TESTING AUTOMOBILE BRAKING PARAMETERS BY VARYING THE LOAD WEIGHT

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Abstract
Modern automobiles are equipped with advanced braking systems and auxiliary safety systems, yet there is an opinion that the braking distance and time considerably increase if increasing the weight of the automobile, e.g. reaching the gross weight. The research performed tests on automobiles of three different size classes: small, medium and large, determining the key parameters – time, distance and deceleration – for braking from a speed of 50 km h^{-1}. The automobiles were road tested by loading them up with the driver or the driver and a load that increased the weights of the automobiles almost to their gross weights. The tests found that for the automobiles with a load, the braking time increased on average by 5.12% and the braking distance increased by 5.9%, while the braking deceleration, compared with no-load driving, decreased by 4.94%.

Key words: *braking time; braking distance; braking deceleration; road surface.*

INTRODUCTION

Driving safety depends on the braking parameters of the automobile. Braking is the capability of the automobile to decelerate fast and come to a complete stop within a minimum distance. When braking, the kinetic energy of the automobile transforms into thermal energy in the braking mechanisms and in the tyres' contact area with the road surface.

The key braking parameters of the automobile are braking force and deceleration, yet in practice mostly braking time and distance are used. The adhesion parameters of the automobile could be changed, e.g. by driving the automobile on diverse road surfaces and equipping it with new tyres with good tread as well as by varying the weight of the automobile, e.g. driving it loaded or unloaded. If the automobile is loaded, the distribution of load on the axes, the height of the centre of mass and the area of tyre contact with the road surface could change. In accordance with physics laws, the brake factor does not change if varying the load on the tyre.

The adhesion of the tyre to the road surface is characterised by the coefficient of adhesion, which varies, depending on the kind of road surface. Friction is important if driving on a hard surface road, yet ground resistance to shear is important if driving on a deformable surface road. If driving on a wet hard surface road, the movement of tyres cause hydrodynamic pressure on the water. At high speeds, tyres with a small tread depth could lead to aquaplaning – the tyres lose contact with the road surface *(Wong, 2008)*.

As the load on the automobile changes, the area of tyre contact with the road changes as well. At a constant weight of the automobile, the area of tyre contact with the road can change if tyre pressure changes *(Effects of, 2011)*. A change in the area of tyre contact could affect braking distance. According to research investigations done by Slovakian researchers, a 20% lower tyre pressure than that recommended by the tyre manufacturer slightly decreases braking distance. A 20% higher tyre pressure increases braking distance by 15% *(Rievaj, et al., 2013)*. Varying the load of an automobile requires for some automobile models to change the tyre pressure. As the load on the tyre increases, the area of tyre contact with the road also increases, which could change the adhesion parameters of the tyre. Other research investigations that have analysed the effect of change in tyre pressure on braking stated that lower tyre pressure increased braking distance if braking in a linear motion, making no manoeuvre or braking in a curvilinear motion *(Parczewski, 2013)*.

Increasing the load on the automobile, the following other characteristics change:

- ✓ load on springs and automobile ground clearance;
- ✓ height of the centre of mass;

- ✓ distribution of load on the axles;
- ✓ wheel radius and the area of tyre contact with the road surface *(Berjoza, 2008*; *Wong, 2008).*

Danish researchers conducted a number of braking tests involving 22 drivers. The tests involved 16 nonprofessional drivers and 6 professional ones. The braking was done from speeds of 80, 110 and 130 km h^{-1}. The braking parameters were registered electronically *(Greibe, 2007).* The braking was done on an asphalt road with the coefficient of adhesion ranging from 0.4 to 0.8 (dry and wet road surfaces).

To register braking operations, the automobiles were equipped with a fifth wheel for taking measurements, a pressure sensor was installed on the brake pedal and a computer was used for collecting and saving the data. The fifth wheel was attached to the automobiles' tow hooks and pressed to the road surface by means of a hydraulic system. The measurements were taken every 0.1 m distance *(Greibe, 2007)*. The speed and the deceleration were computed based on time measurement. The pressure force gauge installed on the brake pedal had an accuracy of 0.15 kg. Two automobiles – a Fiat Grande Punto and an Opel Vectra – were used in the braking tests *(Greibe, 2007).*

Both automobiles were equipped with an ABS and a manual transmission. The initial tread depth of tyres was 7-8 mm. The professional drivers achieved, on average, a 15-20% shorter braking distance than the nonprofessional drivers did. The dispersion of test replication data was found lower for the professional drivers than the nonprofessional ones. An analysis of the force applied to the brake pedal revealed that at the initial stage, the professional drivers applied even a two-fold larger force than the nonprofessional drivers did, which resulted in a shorter braking distance.

Some scientists have tested automobiles with and without a load *(Roos, Zimmermann, 2004).* One test driver was involved in all the braking tests. The tests were done by using three diverse automobiles, with a 400 kg load as well as without a load. The braking tests were done on dry and wet roads, with initial speeds before braking at 70, 100 and 130 km h^{-1}. Two automobiles with a load had a longer braking distance. The increase in braking distance was estimated at 4%, while the deceleration was 0.5 m s^{-2} slower. Varying the load, no difference in braking distance was found for the third automobile *(Roos & Zimmermann, 2004).*

There have been some experimental investigations into braking under various braking regimes. The deceleration of automobiles without an ABS ranged from 6.9 to 7.8 ms^2. With an ABS, the deceleration was in the range of 8.0-8.8 ms^2. A trend was observed – the deceleration of automobiles without an ABS tended to decrease if increasing the initial speed before braking, whereas that of automobiles with an ABS tended to increase if increasing it. The experimental investigations also analysed braking force increase time, which was two times shorter for automobiles with an ABS than without *(Sokolovskij, 2005).*

Road testing trucks revealed that a correctly position load on the truck deck was important in braking. In N2 category vehicles, a load could be placed in four different positions. Braking an automobile from a speed of 65 kmh^{-1}, the deceleration was in the range of 5.18-5.89 ms^2. The shortest braking distance, 29.91 m, was achieved when the load was positioned on the rear axle. In this case, the braking time was 3.36 s *(Skrucany, et al., 2017).*

USA researchers tested 10 various automobiles, varying the weights of the automobiles *(National, 2003)*. All the automobiles, including trucks, pickup trucks and a four-wheel drive automobile were manufactured in the USA. The test registered braking distances on dry and wet roads from an initial speed of 100 km h^{-1}. On a dry road, a loaded automobile had a 5-8% longer braking distance than an automobile without a load. On a wet road, the difference in braking distance was larger, in the range of 10-15% *(National, 2003).*

Automobile users are of the opinion that a heavier load – near the gross weight level – considerably increases braking time and distance. Accordingly, the research aim is to identify the effect of the weight of an automobile on the braking parameters.

MATERIALS AND METHODS

The authors carried out the experiment on three automobiles: a Renault Traffic, a Volvo V70 and a Renault Clio II. The experimental automobiles were equipped with summer tyres with a tread depth in the range of 4-7 mm. The tyre pressure was set as recommended for the weight. All the automobiles had an ABS and a ventilated disc brake in the front axle. Only the Renault Clio II had a drum brake in the rear axle. The characteristics of the experimental automobiles are presented in Tab. 1.

Tab. 1 Characteristics of the experimental automobiles

No	Characteristics	Automobile make and model		
		Renault Traffic II	Volvo V70	Renault Clio II
1	Manufacture year	2007	2001	2002
2	Kerb weight, kg	1957	1605	1035
3	Gross weight, kg	2835	2100	1515
4	Tyre size	195/65R16	195/65R15	175/65R14

During the experiment, the tyre pressure was adjusted according to the load.
The experiment employed a scientific radar Stalker ATS. The technical characteristics of the radar were as follows: speed accuracy: ± 1.609 km h^{-1}; measuring speed range: 1-480 km h^{-1}; time accuracy: 0.01 s; and maximum measuring distance: 1.80 km. A digital calliper Insize 1112 was employed to measure the depth of tyre tread. A GPS logger Holux GPS Sport 245 was used to accurately control the speed of the automobiles during the experiment. A brake and shock absorber diagnostic device VT1200 was used to weigh the automobiles; its resolution was 1 kg.
The present research aimed to identify the braking distance and time and compute the deceleration. The automobiles were not equipped with specific auxiliary equipment for measuring the driver's response time and the brake effect increase time.
The experiment was conducted on a road section with low traffic. The asphalt road was dry, with the coefficient of adhesion φ=0.75. The air temperature was in the range of +10-15ºC. During the experiment, the wind speed did not exceed 2-3 m s^{-1}. A scheme of the experiment is shown in Fig. 1.

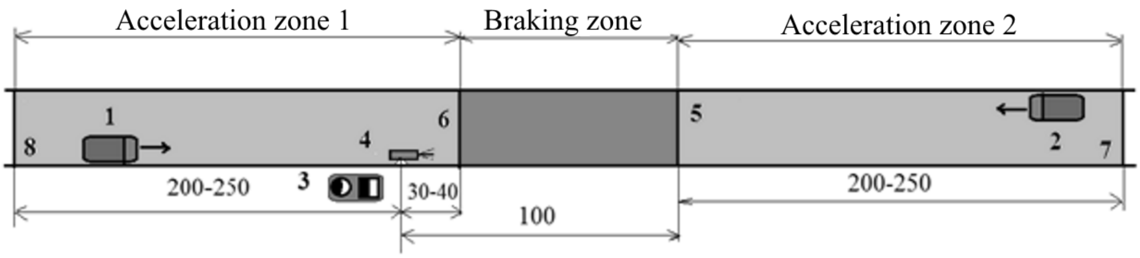

Fig. 1 Scheme of the experiment:
1 – automobile moves away from the radar; 2 – automobile moves towards the radar; 3 – operator's work zone; 4 – scientific radar Stalker; 5 and 6 – start of braking; 7 and 8 – start of acceleration

The measurements were taken in both directions. The acceleration was started either at start point 7 or at start point 8. The experiment was done in both directions to take into account the effects of wind and the road slope. Accelerating from start point 8, the radar operator turned on the radar when the automobile passed by the radar and started braking about 30-40 m behind the radar. The braking was started at a speed of 55±3 km h^{-1}. Afterwards, the automobile was turned around and the acceleration was started at start point 7. When the automobile reached a speed of more than 60 km h^{-1}, the driver signalled by headlights the moment when to activate the radar. The braking was started at a distance of approximately 80-100 m from the radar. The radar was stopped when the automobile came to a complete stop. The measurements were repeated 6-8 times, and five most accurate measurements were selected for data processing. All the measurements were taken with the engine disengaged and the gear-shift lever put in the neutral position.
The experiment was begun with the automobiles being loaded. Tractor counterweights were used as the load for the automobiles. The counterweights were fastened inside the automobiles so that they could not change their positions when braking. The counterweights were placed in the interiors in a way to simulate passengers – 80 kg per seat.

After the experiment, the radar data files were processed and readings were taken. Stalker ATS software was used to take the readings. A screenshot of the monitor for the braking zone is presented in Fig. 2. The screenshot shows two test replications carried out towards the radar (shorter distance) and two replications done away from the radar (longer distance).

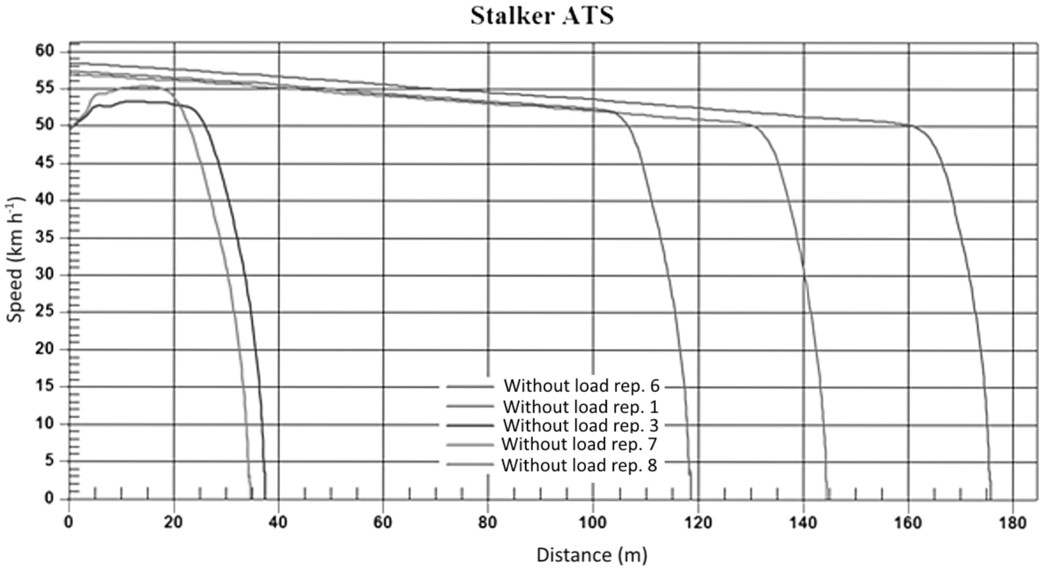

Fig. 2 Screenshot of a radar software chart v=f(s) for a loaded Renault Traffic during braking

The radar software can read the coordinates of points on the chart. Since the braking was not started exactly at a speed of 50 km h^{-1}, it was necessary to find a point being in the closest position to the initial speed. At this speed, the start time of braking was determined (since the moment the radar was activated). Afterwards, the finish time of braking was determined. The period of braking was computed by the equation (1)

$$t_\tau = t_2 - t_1 \quad (1)$$

where t_1- start time of braking (s), t_2- finish time of braking (s).

Using a chart, the data for braking distances were acquired in a similar way. The braking distances were computed by the equation (2)

$$s_\tau = s_2 - s_1 \quad (2)$$

where s_1- start of braking (m), s_2- finish of braking (m).

The average braking acceleration was computed by the equation (3)

$$j_\tau = \frac{v_1 - v_2}{t_\tau} \quad (3)$$

where v_1- start speed of braking (m s^{-1}), v_2- finish speed of braking (m s^{-1}), t_τ- period of braking (s).

RESULTS AND DISCUSSION

The automobiles were weighed before the experiment. The data for the automobiles with no load are shown in Tab. 2.

Tab. 2 Distribution of the weights of the automobiles with no load and driver

No	Automobile	Front axle	Rear axle	Kerb weight, kg	Weight of automobile	
					no load, kg	with load kg
1	Renault Traffic	1130	774	1904	1989	2779
2	Renault Clio II	667	398	1075	1160	1515
3	Volvo V70	826	774	1600	1685	2080

Before the experiment, the force of braking was measured on a roll test bench. The measurements are presented in Tab. 3.

Tab. 3 Force of braking measured on a roll test bench for the automobiles

Automobile	Force of braking, kN			
	Front left wheel	**Front right wheel**	**Rear left wheel**	**Rear right wheel**
Renault Traffic	3.30	3.65	2.07	1.93
Volvo V70	2.47	2.14	2.26	2.82
Renault Clio II	1.58	1.72	1.00	1.13

The experimental results for all tested cars with and without a load are presented in a graph in Fig. 3., Fig. 4. and Fig. 5.
In all the cases, the Renault Traffic, Volvo V70 and Renault Clio performed better without a load than with a load, yet the differences were insignificant. The Renault Traffic braking time with a load was 0.02 s or 1.15% longer than that without a load. The Volvo V70 braking time with a load was 0.11 s or 6.83% longer than that without a load. The braking time for Renault Clio with a load was 0.12 s or 7.36% longer than that without a load.
Without a load, the Volvo V70 had the shortest braking time, 1.61 s, whereas the Renault Traffic had the longest braking time. The Renault Clio II had only a slightly longer braking time. With a load, the braking times for all the automobiles were quite similar, in the range of 1.72-1.76 s. Comparing the braking times measured with and without a load, the largest difference was found for the Renault Clio II that had a drum brake in the rear axle. The smallest differences were found for the Renault Traffic.

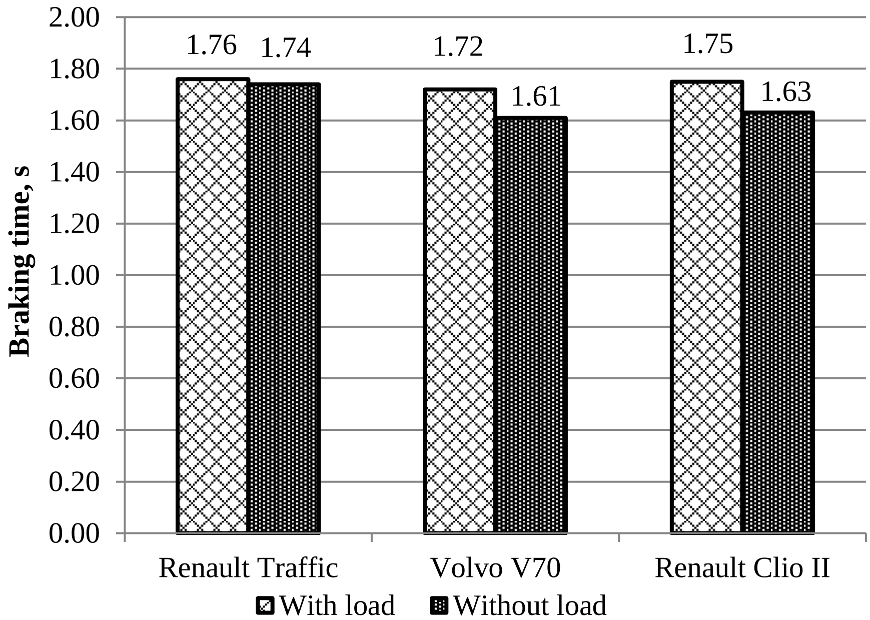

Fig. 3 Comparison of braking times for the experimental automobiles

The braking distances are presented in Fig. 4. Braking distance is one of the most important parameters pertaining to driving safety. The Renault Traffic braking distance with a load was 0.30 m or 2.46% longer than that without a load, but for Volvo V70 the braking distance with a load was 1.06 m or 9% longer than that without a load. The Renault Clio braking distance with a load was 0.73 m or 6.25% longer than that without a load Without a load, the Renault Clio II had the shortest braking distance – 11.68 m. With a load, the Renault Clio II also performed the best – 12.41 m. Performing a comparison of the braking distances with and without a load, the largest difference was found for the Volvo V70, whereas the smallest one – for the Renault Traffic.

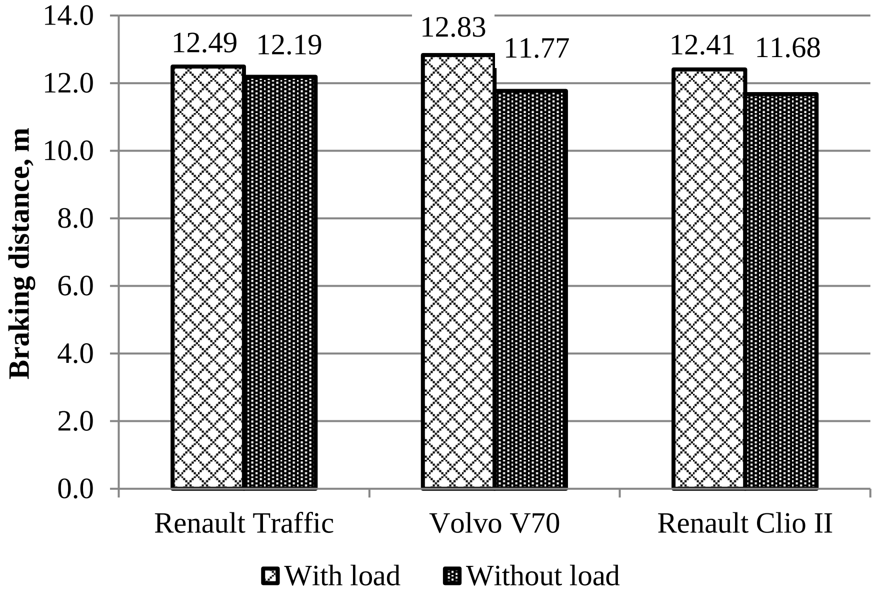

Fig. 4 Comparison of braking distances for the experimental automobiles

Fig. 5 presents data on braking decelerations for all the experimental automobiles. The braking deceleration for Renault Traffic with a load was 0.1 m s^{-1} or 1.25% slower than that without a load, but for Volvo V70 the braking deceleration with a load was 0.51 m s^{-1} or 5.99% slower than that without a load. The braking deceleration for Renault Clio with a load was 0.65 m s^{-1} or 7.59% slower than that without a load. The Volvo V70 had the fastest deceleration, 8.6 m s^{-2}, and the lighter Renault Clio II had almost the same deceleration, 8.57 m s^{-2}, regardless of its simpler rear brake system. With a load, however, the Renault Clio II had a considerably slower deceleration and almost reached that of the Renault Traffic (7.92 and 7.91, respectively).

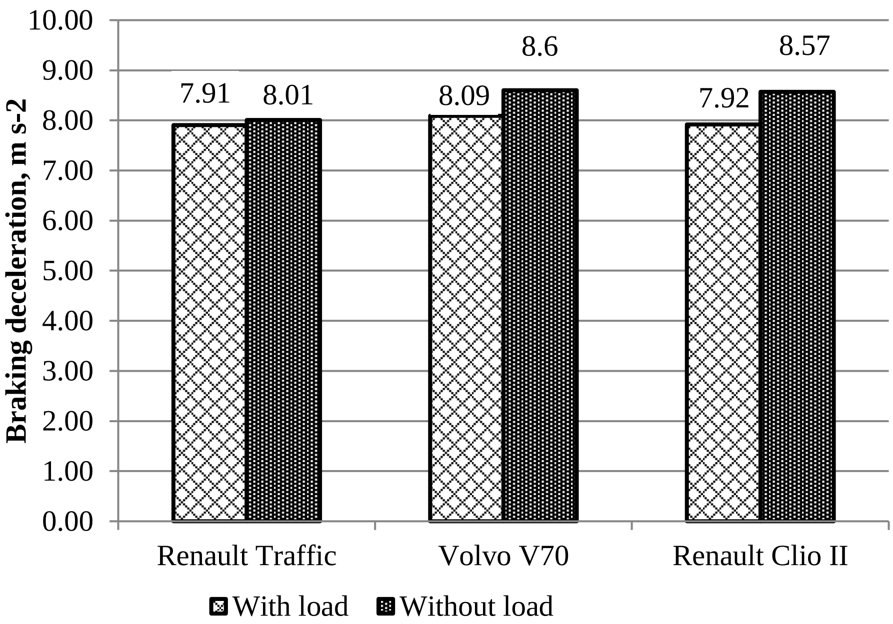

Fig. 5 Comparison of braking distances for the experimental automobiles

The small differences of parameters for Renault Traffic could be explained by the fact that the automobile was in good condition and intended for carrying loads as well. The automobile was initially designed as a freight van, and later it was industrially redesigned into a passenger automobile.
The larger differences of Volvo V70 parameters could be explained by corrosion on rear brake discs. However, the automobile performed the best in terms of force of braking (Table 3).
The decelerations identified in the experiment were similar to those established in investigations by other authors – in the range of 7.91-8.6 m s^2 for automobiles with an ABS *(Sokolovskij, 2017).* An analysis of average braking parameters for all the automobiles tested revealed that the differences in braking time, distance and deceleration between loaded and non-loaded automobiles were 1-2% less than those reported by other authors *(National, 2003).*

CONCLUSIONS

1. The research designed and approbated an experimental methodology for identifying braking parameters by use of a scientific radar Stalker ATS.
2. The braking systems of all the experimental automobiles were in good technical condition because the differences in force of braking among the wheels were less than 19.8%.
3. The braking distance of the Renault Traffic was only 2.46% longer with a load than without. The braking time was 1.15% longer, while the deceleration was 1.25% slower. Among all the automobiles, the Renault Traffic performed the best, which could be explained by the appropriateness of it for transporting large loads.
4. The Volvo V70 had a 0.11 s or 6.83% longer braking time, a 9% longer braking distance and a 5.99% slower braking deceleration with a load than without.
5. The Renault Clio II had a 7.36% longer braking time, a 6.25% longer braking distance and a 7.59% slower braking deceleration with a load than without.
6. All the experimental automobiles had, on average, a 5.12% longer braking time, a 5.9% longer braking distance and a 4.94% slower braking deceleration with a load than without. Overall, the changes in braking parameters were relatively small.
7. The experiment demonstrated that without a load, the Renault Clio II had the shortest braking distance – 11.68 m, whereas the Renault Traffic had the longest one – 12.19 m. With a load, the Renault Clio II had the shortest braking distance – 12.41 m, whereas the Volvo V70 had the longest braking distance, 12.83 m.
8. Braking a fully loaded automobile on high-adhesion roads requires applying more force to the brake pedal than necessary for an automobile without a load. This aspect causes a false impression that it takes a longer braking distance and time for the automobile to stop, yet the experiment demonstrated that not a single braking parameter deviated by more 6%.

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