The Effects of Vehicle Speed and Type of Road Surface on the Longitudinal Slip of Tires and the Brake Stopping Distance

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ABSTRACT

The effects of vehicle speed and type of road surface on tire longitudinal slip and on brake stopping distanceare investigated.The experimental work for measuring the tire longitudinal slip involved driving a passenger car for a distance of 500m on asphalt and earth roads at five different speeds varying from 20-100km/h. The number of wheel revolutions to travel this distance at each speed and on both roads was measured using a wheel revolution counter specially developed for this purpose. This data was used to calculate the tire longitudinal slip at each speed and on both roads.

The experimental work also involved measuring the brake stopping distance at five different vehicle speeds(similar to above) and on both roads. In addition to that, the effect of using Anti-lock Brake System (ABS) on the brake stopping distances was also investigated.

Test results indicate that the tire longitudinal slip and brake stopping distance are both directly proportional to vehicle speed, and they are significantly higher on earth road than they are on asphalt.

The increase of vehicle speed from 20 km/h to 100 km/h resulted in a massiveincrease in tire slip by approximately 3.6 times.For the same increase in vehicle speed, the increase in stopping distance is even more significant;it increased by approximately 15 and 18times on asphalt and earth roads respectively.

The effect of type of road surface is indicated by the fact that at 100 km/h the tire longitudinal slip and the brake stopping distance on earth road are higher than those on asphalt by 54% and 29% respectively.

Finally, test results indicate that the use of ABS has adverse effects on the brake stopping distance. At 100 km/h the stopping distance increased by 6.7% and 11.3% on asphalt and earth roads respectively as a result of using ABS.

Keywords: Tire Slip, Stopping Distance, Vehicle Speed, ABS.

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تأثير سرعة المركبة ونوع الطريق على الإنزلاق الطولي للعجلات وعلى مسافة التوقف عند استخدام الفرامل

خلاصة

تمت دراسة تأثير سرعة المركبة ونوع سطح الطريق على الإنزلاق الطولي للعجلات وعلى مسافة التوقف عند أستخدام الفرامل. التجارب العملية لتحديد الانزلاق الطولي للعجلات تضمنت قيادة سيارة لمسافة ٥٠٠ م على طريق أسفلتي واخر ترابي وبخمسة سرع مختلفة للسيارة تراوحت بين ٢٠-١٠٠ كلم/ساعة. عدد دورات عجلة السيارة اللازمة لقطع تلك المسافة عند كل سرعة للمركبة وعلى الطريقين تم قياسها بإستخدام عداد لدورات العجلة طور خصيصاً لهذا الغرض. هذه البيانات إستخدمت في حساب الإنزلاق الطولي للعجلات عند كل سرعة ولكلا الطريقين.

التجارب العملية تضمنت كذلك قياس مسافة التوقف بإستخدام الفرامل وبنفس سرع السيارة المذكورة أعلاه ولكلا الطريقين. إضافة لذلك فقد تمت دراسة تأثير إستخدام منظومة منع قفل العجلات (ABS) على مسافة التوقف.

نتائج التجارب العملية أظهرت إن إنزلاق العجلات ومسافة التوقف يتناسبان طردياً مع سرعة المركبة وكلاهما أكبر بكثير على الطريق الترابي منهما على الطريق الأسفلتي.

إن زيادة سرعة المركبة من ٢٠ الى ١٠٠ كلم/ساعة أدت الى زيادة كبيرة في إنزلاق العجلات بلغت حوالي ٣,٦ ضعفاً. ولنفس الزيادة في السرعة فإن الزيادة في مسافة التوقف كانت أكبر بكثير حيث بلغت حوالي ١٥ و١٨ ضعفاً عل الطريق الأسفلتي والترابي على التوالي.

تأثير نوع الطريق أوضحته نتائج التجارب العملية التي أظهرت أنه عند سرعة ١٠٠ كلم/ساعة فإن الأنزلاق الطولي للعجلات ومسافة التوقف على الطريق الترابي يكونان أكبرمن قيمتهما على الطريق الأسفلتي بمقدار ٥٤% و٢٩% على التوالي.

اخيراَ، فأن نتائج التجارب العملية دلت على إن إستخدام منظومة منع قفل العجلات له تأثير سلبي على مسافة اتلتوقف، فعند سرعة ١٠٠ كلم/ساعة إزدادت مسافة التوقف بمقدار 6.7% و11.3% على الطريق الأسفلتي والترابي على التوالي نتيجة إستخدام منظومة منع قفل العجلات.

List of symbols

Symbol	Definition	Unit
a	deceleration of vehicle	m/s^2
A_f	frontal area of vehicle	m^2
C_D	aerodynamic drag coefficient	__
d	distance traveled	m
f_r	coefficient of rolling resistance	__
g	acceleration of gravity	m/s^2
i	longitudinal slip	%
L	circumference of free rolling tire	m
m	vehicle mass	kg
n	number of wheel revolutions	rev

N	rotational speed of driving wheels	rpm
r	free rolling radius of the tire	m
r_e	effective rolling radius of the tire	m
s	brake stopping distance	m
t	braking time	s
v	linear speed of tire (vehicle)	m/s
v_1	initial vehicle speed	m/s
W	vehicle weight	N
η_b	brake efficiency	%
μ	coefficient of road adhesion	__
θ	angle of road gradient	°
ρ	density of air	kg/m^3
ω	angular speed of tire	rad/s

INTRODUCTION

The longitudinal forces that produce acceleration and braking on ground vehicles with pneumatic tires arise due to deformation and sliding in the contact patch. While the actual motion that takes place in the contact patch are somewhat complex, the force generation can generally be described with sufficient accuracy in terms of wheel slip [1].

When a driving torque is applied to a pneumatic tire, a tractive force is developed at the tire-ground contact patch. At the same time, the tiretread in front of and within the contact patch is subjected to compression. Acorresponding shear deformation of the sidewall of the tire is also developed. As tread elements are compressed before entering the contact region, the distance that the tire travels when subject to a driving torque will be less than that in free rolling. This phenomenon is usually referred to as longitudinal slip[2]. In fact it is reported that tire slip occurs whenever pneumatic tires transmit forces [3].

According to the Society of Automotive Engineering longitudinal slip is defined as "the ratio of the longitudinal slip velocity to the spin velocity of the straight free-rolling tire expressed as a percentage." The longitudinal slip velocity is taken as "the difference between the spin velocity of the driven or braked tire and the spin velocity of the straight free-rolling tire." Both spin velocities are measured at the same linear velocity at the wheel center in the longitudinal direction. Apositive value of slip results from a driving torque [4].

Tires are made to grip the road surface (road adhesion) when the vehicle is being steered, accelerated, braked and/or negotiating a corner and so the ability to control the tire to ground interaction is of fundamental importance. Road grip or adhesion is a property which resists the sliding of the tire over the road surface due to a retardant force generated at the tire to ground contact area [5].

The parameters influencing the maximum road adhesion (and consequently tire slip) can be divided into three groups: vehicle parameters e.g., speed and wheel load, tire parameters e.g., tire material and tread depth and road parameters e.g., road type, presence of lubricants and temperature. The most influencing parameters on the maximum road adhesion are road parameters [6].

Generally as the speed of the vehicle rises, the time permitted for tread to grip the road surface is reduced so that the coefficient of adhesive friction declines [5].

A load on the tire causes the peaks of road irregularities to penetrate the tire and the tire drapes over the peaks. Higher load increases the penetration of the irregularities in the tire and therefore increases the friction force [7].

A previous investigation into the effect of tire tread depth on some vehicle performance parameters indicated that the longitudinal slip is inversely proportional to tire tread depth, since new tires with deeper tread has better road grip (and consequently lower slip) than worn-outtires[8].

Braking performance of motor vehicles is undoubtedly one of the most important characteristics that affect vehicle safety. Stopping distance is an important parameter widely used for evaluating the overall braking performance of a road vehicle [2].

In general, the main parameters affecting the brake stopping distance are:

1. Vehicle weight: The weight and the center of the gravity affect the stopping distance. The larger the total mass of the vehicle, passengers and luggage, the more kinetic energy it will have at a given speed. This increases the braking distance as it is harder to slow down.
2. Vehicle speed: The higher the vehicle speed gets the longer stopping distanceresults.
3. Coefficient of road adhesion: The adhesive coefficient of friction between the tires and road surface varies according to the type of road surface and weather conditions. The higher coefficient of road adhesion results in shorter stopping distance.

Other factors affecting the brake stopping distance are [9]:

- The type of braking system
- Brake pad material
- Wheel alignment
- Tire pressure, tread and grip
- Suspension system
- Wind speed
- Slope of road
- The braking technique applied by the driver
- Weather conditions

Several investigations have been carried out previously to determine the vehicle brake stopping distance of various vehicles on dry and wet surfaces.

Data provided by Wheels Magazine [10] indicate that the stopping distances of five new cars from a speed of 100 km/h to complete stop on dry road, with good tires and good skills drivers were 41.7 to 57.1m.

The Transportation Research Institute of Oregon State University[11] reported that at 100 km/h on dry surface the emergency stopping distance was 39m and on wet surface it was 72m.

Nicklin[12] reported that the stopping distances for 55 new cars (1991-1995) from a speed of 97 km/h (60 miles/h) on dry asphalt road ranged from 35 to 55 m with an average of 43m.

As for the effect of using Anti-lock Brake System (ABS) on the brake stopping distance, the investigations' results were not conclusive.

Burton et al[13] indicated that ABS will not substantially reduce stopping distances in dry conditions. However, in wet slippery conditions, ABS is very effective in reducing stopping distances. A locked wheel may provide higher deceleration than ABS on surfaces such as gravel and snow that allow a build up of material in front of a sliding wheel.

Marshek et al[14, 15]conducted track tests on six vehicles and found that deceleration in ABS-fitted vehicles was a significant function of vehicle speed. The results showed that both ABS and locked wheel braking varied significantly between vehicles, indicating that ABS degrades braking performance at speeds lower than 35 km/h and improves braking performance at higher speeds.

Strickland and Dagg[16] also performed ABS track tests on dry asphalt. Straight line braking tests were completed on asphalt surfaces with different coefficients of friction (0.61 – 0.87) and at initial speeds from 38 km/h to 74 km/h. The data indicated that at speeds below 50km/h the average deceleration of ABS-equipped vehicles may drop to as low as 82% as that of standard braking system with locked wheels. Similar toMarshek[15] they found that as initial speed increased so did the braking efficiency of an ABS equipped vehicle.

Macnabb et al [17]investigated the relative stopping distance of seven vehicles fitted with ABS on gravel roads. They demonstrated that ABS significantly increased (up to 60%) stopping distances on gravel. The average deceleration with the ABS deactivated was between 0.59 and 0.66g and with the ABS operational, the average deceleration range was between 0.37 and 0.52g.

Eddie[18]performed maximum braking tests on snow and ice surfaces with and without ABS. It was found that the average deceleration of the ABS equipped vehicle was slightly greater on ice than the non-ABS vehicle. However, in pavement tests in snow, the deceleration of the non-ABS equipped vehicle was slightly greater than the same vehicle equipped with ABS. It was noted that loss of control of the vehicle occurred in several tests with vehicles not equipped with ABS but never with any ABS equipped vehicle.

The objectives of this work are to investigate:

1. the effects of vehicle speed and type of road surface on tire longitudinal slip of a passenger car.
2. the effects of vehicle speed and type of road surface on the brake stopping distance.
3. the effect of using ABS on the stopping distance of a passenger car at different vehicle speeds and on different road surfaces.

In this investigation the types of road surfaces considered are dry asphalt and dry earth roads which are believed to be more representative of local environment than the wet and snow surfaces considered in investigations carried out abroad.

THEORETICAL CONSIDERATION

The longitudinal slip of the vehicle tire when a driving torque is applied is usually expressed by the following formula [2]:

$$\boldsymbol{i} = \left(\mathbf{1} - \frac{\boldsymbol{v}}{\boldsymbol{r\omega}}\right) \times \mathbf{100}\% = \left(\mathbf{1} - \frac{\boldsymbol{r_e}}{\boldsymbol{r}}\right) \times \mathbf{100}\% \qquad \ldots(\mathbf{1})$$

The free rolling radius of the tire is determined by dividing the free rolling circumference of the tire by 2Π as expressed by the following equation [2]:

$$\boldsymbol{r} = \frac{\boldsymbol{L}}{\mathbf{2}\boldsymbol{\pi}} \qquad \ldots(\mathbf{2})$$

The effective wheel radius of the tire is obtained from the relationship between the linear speed and rotational speed of the tire as expressed by [2]:

$$\boldsymbol{v} = \frac{\mathbf{2}\boldsymbol{\pi N r_e}}{\mathbf{60}}$$

When the above formula is rewritten in terms of the effective wheel radius it yields the following:

$$\boldsymbol{r_e} = \frac{\mathbf{60}\boldsymbol{v}}{\mathbf{2}\boldsymbol{\pi N}} \qquad \ldots\ (\mathbf{3})$$

The relationship between the rotational speed of the driving wheels and the number of wheel revolutions for a given distance at a constant linear speed can be expressed by the following equation [2]:

$$\boldsymbol{N} = \frac{\mathbf{60}\boldsymbol{nv}}{\boldsymbol{d}} \qquad \ldots.(\mathbf{4})$$

When the above equation is substituted in eq. (3), an expression for the effective wheel radius in terms of distance traveled and number of wheel revolutions is obtained:

$$\boldsymbol{r_e} = \frac{\boldsymbol{d}}{\mathbf{2}\boldsymbol{\pi n}} \qquad \ldots(\mathbf{5})$$

By substituting eqs.2 and 5 into eq.1, a formula for the tire longitudinal slip as a function of distance traveled, number of wheel revolutions and circumference of free rolling tire is obtained:

$$i = \left(1 - \frac{d}{nL}\right) \times 100\% \quad \ldots(6)$$

Theoretically, the stopping distance may be predicted by the following equation [2]:

$$S = \frac{W}{g\rho C_D A_f v_1^2} ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{\eta_b \mu W + f_r W cos\theta \pm W sin\theta}\right) \ldots(7)$$

For a level road θ=0 and the above equation is reduced to:

$$S = \frac{W}{g\rho C_D A_f v_1^2} ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{\eta_b \mu W + f_r W}\right) \quad \ldots.(8)$$

It should be mentioned that atmospheric conditions affect air density ρ. In performance calculations, the mass density of the air ρmay be taken as1.225 kg/m^3 [2].

The vehicle frontal area A_f may be calculated using its relationship with vehicle mass(m) as expressed by the following relationship which can be used for passenger cars with mass in the range of 800-2000 kg [2]:

$$A_f = 1.6 + 5.6 \times 10^{-4}(m - 765) \quad \ldots(9)$$

The brake efficiency $\eta_b$is defined as the ratio of the maximum deceleration rate in $g$units $(^a/_g)$ achievable prior to any tire lock-up to the coefficient of road adhesion $\mu$and is given by [2]:

$$\eta_b = \frac{^a/_g}{\mu} \quad \ldots(10)$$

The deceleration during braking is calculated by [19]:

$$a = \frac{v_1}{t} \quad \ldots.(11)$$

EXPERIMENTAL WORK

Longitudinal slip

A wheel revolution counter was developed specially for the purpose of counting the number of wheel revolutions required to travel a distance of 500m on dry asphalt and dry earth roads. This device as shown in Fig.(1) consists of the following components:

1. U-shaped fixture (1) bolted on the wheel hub.
2. A threaded rod (2) with one end bolted to the wheel center and the other end bolted on the U-fixture (1).

3. A rotor (3) fixed on the U-shaped fixture (1) via the threaded rod (2); the rotor rotates with the wheel.
4. A shielded steel wire (4) with one end fitted to the rotor (3) and the other end fitted to the counter display unit (5), the steel wire transfers the number of wheel revolutions to the counter display unit.
5. A four-digit mechanical counter display unit (5).

A passenger car type Suzuki model Forenza 2008 was used in the experimental work to determine the longitudinal slip. This car is front-wheel drive and has automatic transmission. The car has tires size 195/55 R 15, all tires are of the same type, they have identical tread pattern, good tread depth and standard inflation pressure. The wheel revolution counter was fitted on the front driving wheel as shown in Fig.2. The curb car mass (full tank without the driver) is 1240kg [20]. During the tests a driver and a front seated passenger whose combined mass was 190 kg were in the car which resulted in a total car mass of 1430 kg.

Figure (1)Components of wheel revolution counter.

Figure (2) The wheel revolution counter mounted on the front wheel of passenger car.

The circumference of free rolling tire L was measured by pushing the car on a level road until the front tires rotate one revolution and the distance traveled on the ground is marked and measured. The free rolling radius of the tire is then calculated using eq. (2).

The experimental procedure involved driving the car for a distance of 500m on asphalt and earth roads at five different vehicle speeds; 20, 40, 60, 80 and 100 km/h. At each speed the wheel revolution counter was initially set to zero and the number of wheel revolutions to travel the distance of 500m as displayed by the revolution counter was recorded.

This procedure was repeated several times to ensure repeatability of readings. The car speed was maintained constant during test procedure. In addition to that, the tests were carried out on level dry roads with good surface conditions which did not have irregularities, curves or bends.

Brake stopping distance

A new passenger car type Hyundai model Elantra 2011 equipped with ABS on all tires was used in the experimental work to determine the brake stopping distance (Fig.3). This car is also a front-wheel drive with automatic transmission and its curb mass (full tank without driver) is 1160 kg [21]. During the tests a driver and a front seated passenger whose combined mass was 190 kg were in the car which resulted in a total car mass of 1350 kg.

(a)

(b)

Figure (3) Brake stopping distance tests on (a) Asphalt road (b) earth road.

The brake stopping distance test procedure involved driving the car on similar roads and at similar speeds to those adopted in longitudinal slip tests. At each speed when the front wheels cross a marked line on the road the brakes were applied simulating an emergency stop. The distance between the marked line and the position of the front wheels where the car completely stops, represents the brake stopping distance and it is measured by a measuring tape. In addition to that the passenger in the front seat measured the brake stopping time using a digital stop watch. This procedure was repeated several times to ensure repeatability of results.

The brake stopping distance test procedure described above was repeated twice, once with the use of ABS and the second withthe ABS disabled; by removing itsfuse in the fuse box.

RESULTS AND DISCUSSION

Longitudinal slip

The circumference of free rolling tire (L) was measured and found to be 1.81m. The numbers of wheel revolutions (n) required for traveling a distance of 500m on the asphalt and earth road at each vehicle speed are given in Table (1).

By substituting the values of numbers of wheel revolutions given in Table-1, the distance traveled (500m) and the circumference of free rolling tire (1.81m) into eq.6, values of tire longitudinal slip on the two roads and at each speed are obtained. The effect of vehicle speed on the tire longitudinal slip is shown in Figure (4). Using least squares regression, the best fit between the vehicle speed and tire slip is found to be linear. As shown the tire longitudinal slip is directly proportional to vehicle speed and it is significantly higher on earth road than asphalt road.

Table(1) Number of wheel revolutions on asphalt and earth roads.

Vehicle speed (km/h)	No of wheel revolutions	
	Asphalt	Earth
20	283	287
40	288	296
60	296	307
80	302	321
100	310	334

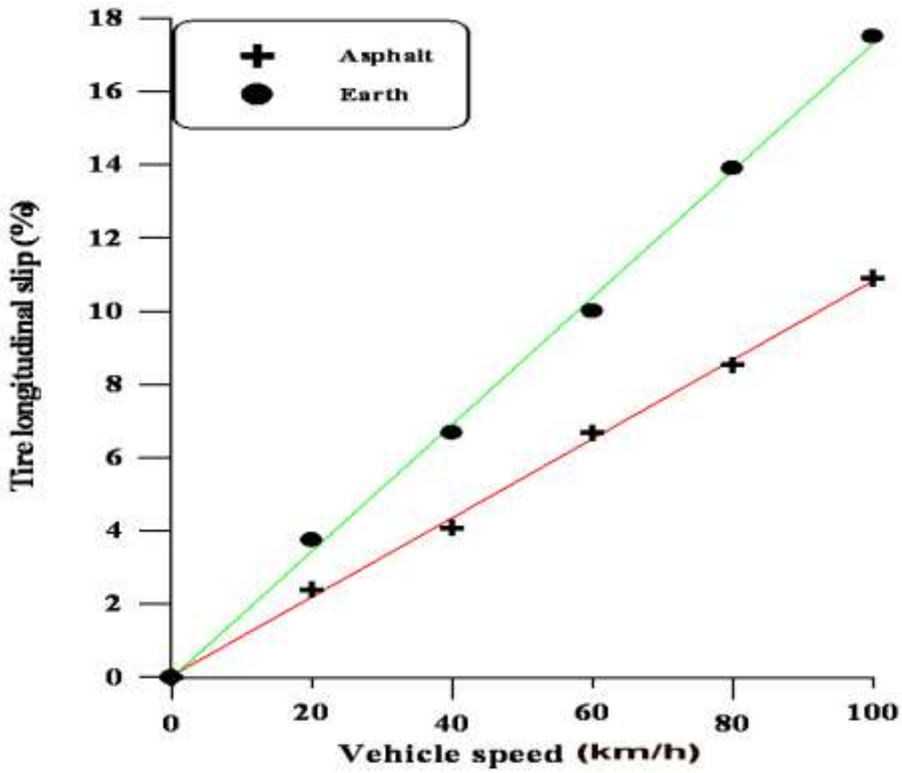

Figure (4) The effect of vehicle speed on tire longitudinal slip.

The increase of vehicle speed from 20 km/h to 100 km/h resulted in a massive increase in tire slip from 2.4% to 11% on asphalt and from 3.7% to 17% on earth road. These results imply that tire slip increased by approximately 3.6 times with the abovementioned increase in vehicle speed.

The effect of type of road surface on tire longitudinal slip is indicated by the fact that at 100 km/h the slip on earth road is higher than that on asphalt by approximately 54%.

Stopping distance

The experimental results verified the fact that the stopping distance is directly proportional to vehicle speed as shown in Fig.(5). This is due to the fact that vehicles travelling at higher speeds possess more kinetic energy and thus require longer stopping distances to dissipate it. Least squares regression was employed to determine the best curve fit between the vehicle speed and brake stopping distance and it is found to be parabolic (2^{nd} degree polynomial).

The increase of vehicle speed from 20 to 100 km/h resulted in increasing the stopping distance on asphalt by approximately 15 times while on earth road it increased by approximately 18 times.

The brake stopping distance on earth road is found to be significantly higher than that on asphalt. At a speed of 100km/h, the brake stopping distances on asphalt and earth roads are 41.8 and 54.1m respectively. These results imply that the brake stopping distance on earth road is 29% higher than that on asphalt. This is attributed to the fact that the coefficient of road adhesion on earth is significantly lower than that on asphalt.

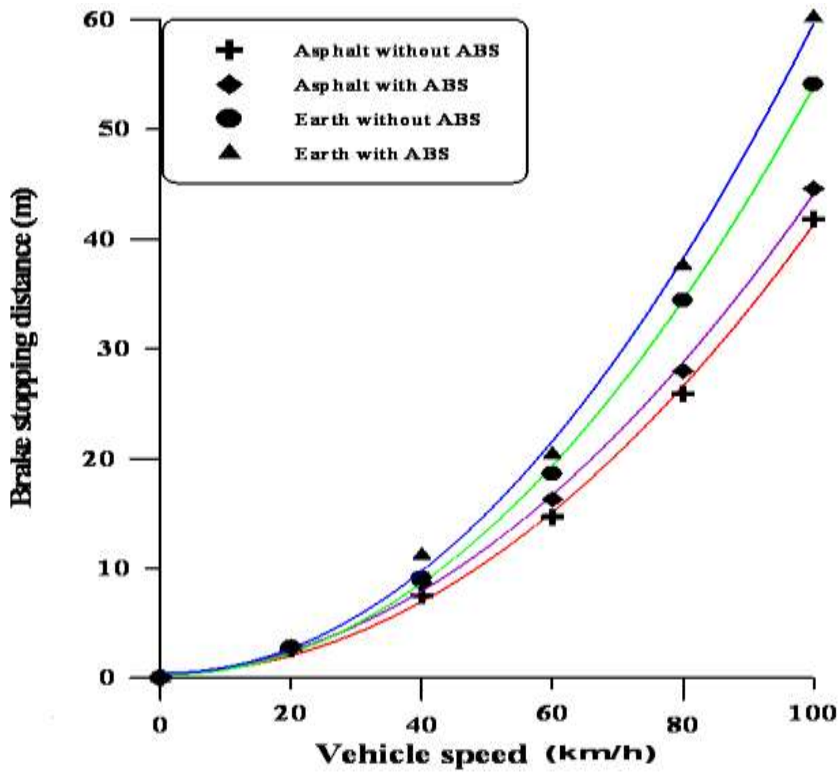

Figure (5) The effect of vehicle speed on brake stopping distance.

Test results also indicated that the use of ABS had adverse effects on the brake stopping distance on both asphalt and earth roads. At 100 km/h the stopping distance on asphalt and earth roads using ABS are 44.6 and 60.2m respectively which represent an increase in stopping distance of 6.7% and 11.3% respectively.This confirms the findings of investigations referred to earlier [14-18]. It is noteworthy to emphasize the fact that the primary function of ABSis to prevent a vehicle's wheels from locking during heavy braking, which allows the driver to maintain steering control as the vehicle rapidly decelerates[13];this does not necessarily imply reduction of stopping distance.

Results obtained in this work indicate that the stopping distances at 100 km/h on dry asphaltfor a passenger car without ABS and with ABS are 41.8 and 44.6m respectively.These values are within the range of stopping distances for passenger cars published by previous investigations referred to earlier[10-12]. As for the stopping distance on earth road there were no data available for comparison.

The relationship between the vehicle speed and the stopping time measured during the experimental work is found to be linear as shown in Figure (6).

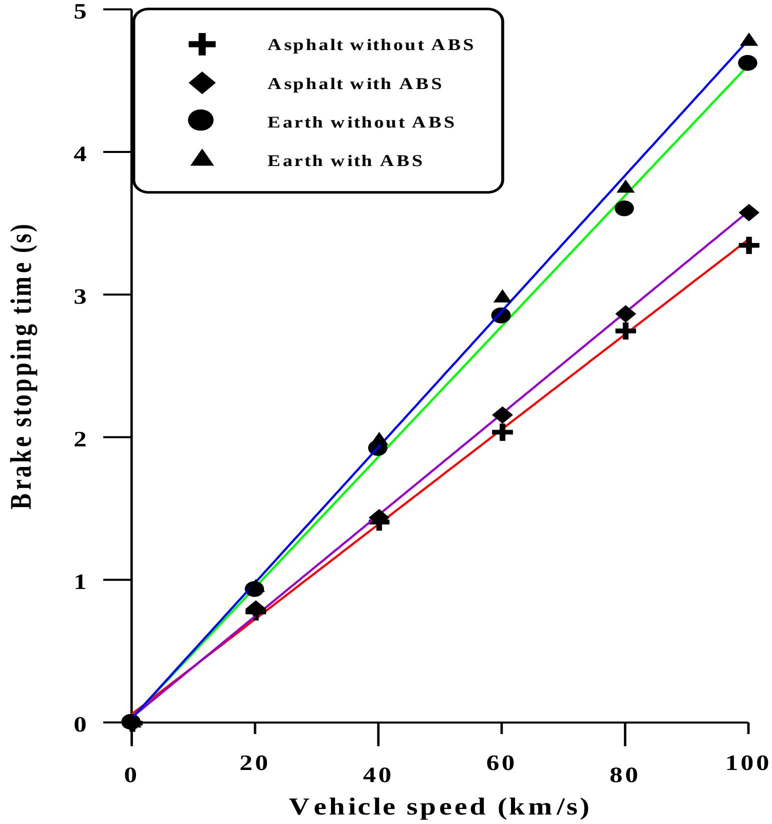

Figure (6) Vehicle speed vs. stopping time.

In order to compare the experimental results obtained in this work with the theoretical values of stopping distances expressed by eq.(8), values of several variables must be determined.

The deceleration of the car during braking (a) is determined by substituting values of vehicle speed and the corresponding stopping time in eq.(11).

The brake efficiency (η_b) is obtained by substituting the values of car deceleration and coefficient of road adhesion for dry asphalt (0.85) [2] and dry earth road (0.68) [2] in eq.(10).

The car frontal area (A_f) is determined by substituting vehicle mass (1350 kg) in eq.(9). The aerodynamic drag coefficient (C_D) as claimed by the car manufacturer is 0.28 [21].The average values of rolling resistance on dry asphalt and dry earth roads are 0.013[19] and 0.1 [22]respectively. The air density (ρ) as given earlier is 1.225 kg/m^3.

When these values are substituted in eq.(8), the theoretical stopping distanceson asphalt and earth roads without and with ABS at each vehicle speed can be obtained. The results of theoretical stopping distances calculations at vehicle speed of 100 km/h are presented in Table-2 and compared to experimental results.

These theoretical values are in good agreement with the experimental test results, which verify the validity of the experimental procedure adopted in this work. The error (or deviation between the experimental and theoretical values of stopping distance) is found to be 0.7 – 8.6%.

Table(2)Theoretical stopping distance at vehicle speed of 100km/h.

Type of road surface and brake	Asphalt without ABS	Asphalt with ABS	Earth without ABS	Earth with ABS
Theoretical stopping distance (m)	45.4	48.8	54.5	56.1
Experimental stopping distance (m)	41.8	44.6	54.1	60.2
Error (%)	8	8.6	0.7	7.3

CONCLUSIONS

1. The longitudinal tire slip and brake stopping distance are directly proportional to vehicle speed. The increase of vehicle speed five times from 20 to 100km/h led to the increase of longitudinal slip by 3.6 times and the brake stopping distance by 15 and 18 times on asphalt and earth roads respectively.
2. The longitudinal slip and brake stopping distance on earth road are higher than those on asphalt. At a vehicle speed of 100km/h the tire longitudinal slip and brake stopping distance on earth road are higher than those on asphalt by 54% and 29% respectively.
3. The stopping distance is longer for cars equipped with ABS on dry asphalt and dry earth roads. At a vehicle speed of 100km/h the use of ABS led to the increase of stopping distance by 6.7% and 11.3% on asphalt and earth roads respectively.

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