TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

INTERNATİONAL BACCALAUREATE

PHYSICS EXTENDED ESSAY

Investigation of the Effect of Various Tire Pressures and Surfaces to the Coefficient of Rolling Resistance

Candidate's Name: Batu İnal

Candidate Number: D1129075

Supervisor's Name: Mine Gokce Sahin

Batu İnal

D1129075

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Abstract:

This essay serves to answer the question “What effects do varying tire pressures and surfaces have on the coefficient of rolling resistance?” The investigation attempts to solve the question in hand through the means of experimentation and theoretical models, by three means. Firstly by answering the question “Is the coefficient of rolling resistance reduced if the material of the surface is more compact and smooth”. Secondly by answering “Is the coefficient of rolling resistance reduced if the tire pressure increases?” This is then further elaborated by combining the two, “What are the best conditions of surface and tire pressure to obtain the optimum rolling resistance coefficient?” For the experiment a car was speeded up to exactly 60 km/h every time and the gear was slipped into neutral at a certain point. Then the time and distance for the car to stop was measured with the help of a chronometer and check points set next to the experimentation road.

The conclusion leads to the inevitable fact that there are very important correlations between the surfaces compactness and the tires pressure to the coefficient of rolling resistance. It is inferred from the drawn conclusion that the coefficient of rolling resistance is inversely proportional to the compactness of the material on the surface and the pressure of the tires. However there is an optimum level for the *coefficient* of rolling resistance as the wheels are impossible to displace the car without it.

Word Count: 239 words

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Introduction:

Minimizing the force of rolling resistance acting on the tires of a car is a phenomena which is considered highly important these days. In a world where there is limited amount of natural resources it is a vital subject to minimize some of the forces working against and wasting our spent natural resources. To reduce fuel consumption, the impact of the forces opposing the movement of vehicles must be reduced (gravity due to vehicle weight, air resistance, mechanical friction, inertia, vehicle accessories).Tire rolling resistance is very often under-estimated and is however the cause of one third of fuel consumption for trucks[6]. As there is no significant information about the phenomena in the high school physics books, it came to mind interesting to investigate the factors that had significant effects on rolling resistance.

This essay is an attempt to investigate the factors that increase and decrease the coefficient of rolling resistance. Specific attention is given to the type of surface the tires are travelling on and the varying pressures of tires that affect the coefficient of rolling resistance. The tests are conducted on an ongoing motorway project in Romania. The surfaces have been set accordingly to the layers of the motorways surface such as Crushed Stone Base (CSB), Ballast Base (BB) and Asphalt Binder Course (ABC). During the experiment the slopes of the surfaces are taken in record accordingly with the varying tire pressures and surfaces. An evaluation on the success of the experiment and its backing up supports are made valid in the conclusion of the experiment.

Background Information – Literature:

Rolling resistance occurs starting the moment when the wheel begins spinning. On a horizontal road, it is the most significant resistance up to speeds of 60-80 km/h. Due to the rolling resistance, the tires heat up, which affects the tires wear resistance and the bending fatigue resistance of the tire material. [1]

The following are the phenomena generating the rolling resistance:

1. loss of energy by the phenomenon of hysteresis at the deformation of the sidewalls and tire tread;

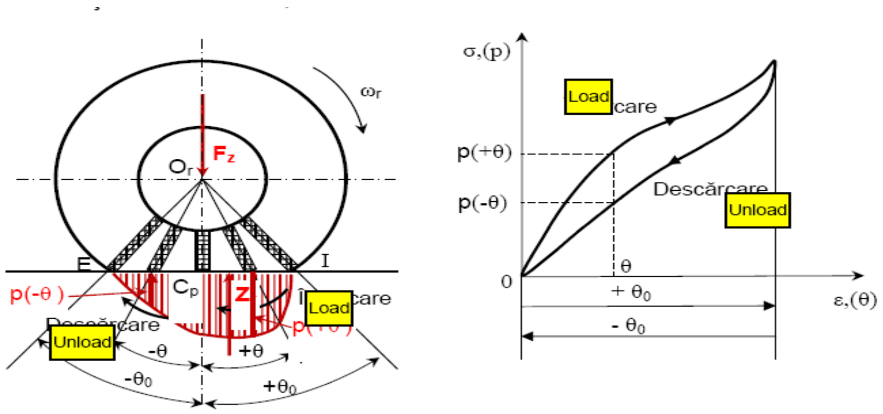


Figure 1: Diagram and Graph of deformation of the sidewalls and tire tread[3]

For two points which are symmetrical as to the center of the contact spot the deformations are equal, but the pressures differ. (The length of the tire element is identical between point I and point E.)

2. Deformation of the rolling track

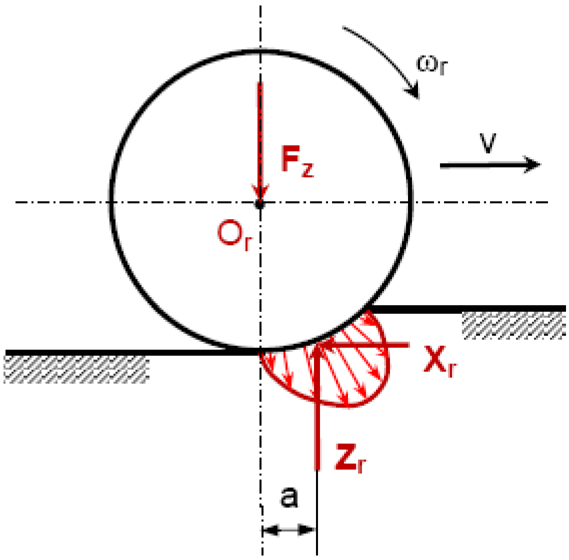


Figure 2: Forces acting on tire by the rolling track that cause deformation[3]

3. the unbalance between the values of the longitudinal tensions between the rear and front areas of the contact spot in the case of moving wheels

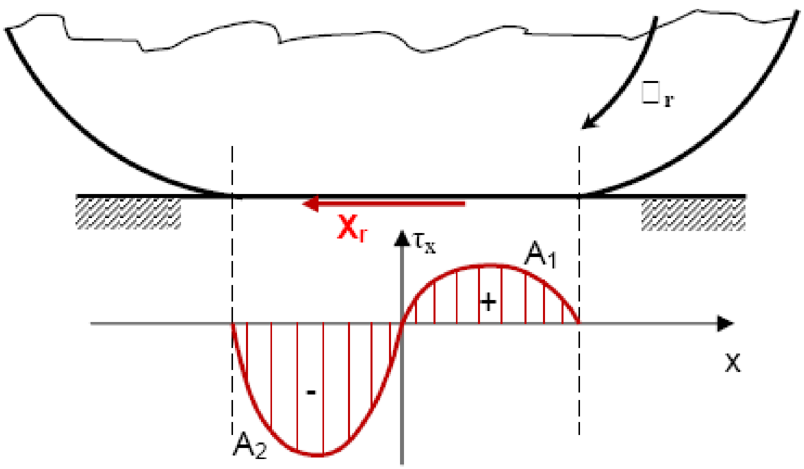


Figure 3: Diagram and Graph of the unbalance between the values of the longitudinal tensions between the rear and front areas of the contact spot[3]

4. The adhesion processes between the tire and rolling track surfaces

5. The hysteresis processes from the rubber produced upon moving over the micro-irregularities of the road

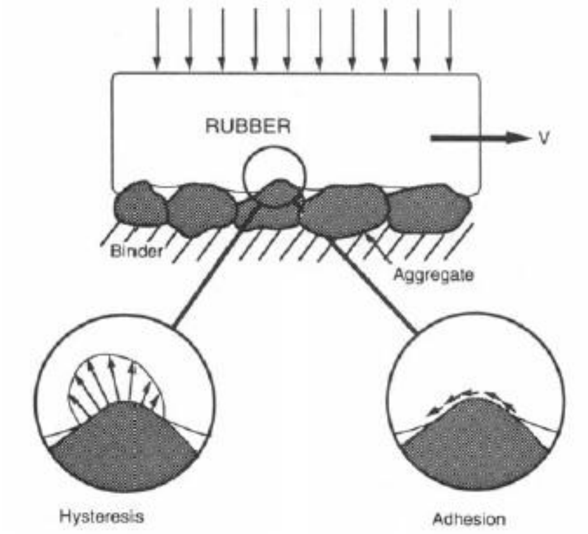


Figure 4: Diagram of the hysteresis process from the rubber[3]

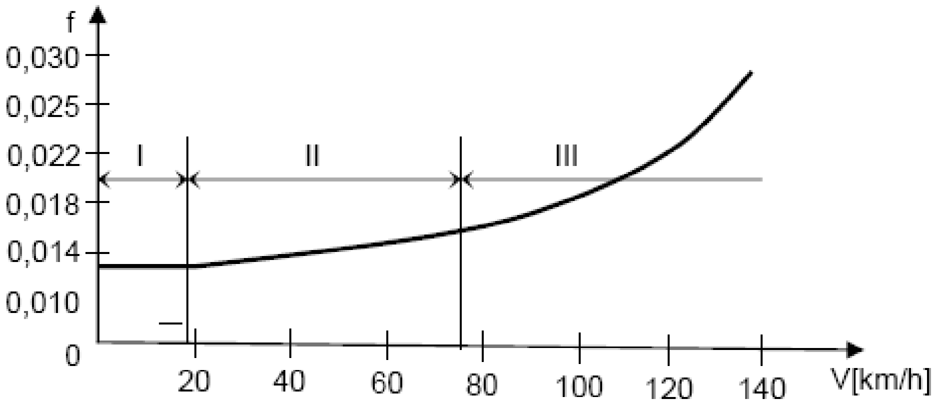
6. Friction with the air inside and outside the tire

When moving on a dry and rigid rolling track, the energy loss by rolling[3]:

- 90....95% - hysteresis
- 5.....10% - superficial friction
- 1...3% - aerodynamic loss.

Factors that influence the rolling resistance

- Forward speed

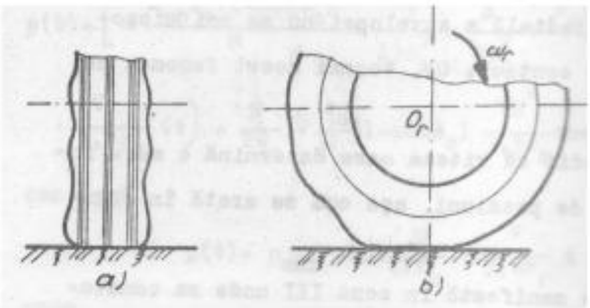


Zone I – f ≈ continuous; losses by static hysteresis;

Zone II – f increases linearly with the speed; the asymmetry of the distribution of pressure in the contact spot increases; losses by hysteresis increase;

Zone III – rapid increase of the F with the speed; at high speeds, the bounce back of tire elements to its initial form, after exiting the contact spot, produces with delay due to lag, resulting in tire oscillation under the elastic and lag forces. The result is additional energy consumption by hysteresis. First, there is transversal oscillation, and then the radius oscillation, at the exit from the contact spot.

<u>Critical speed = </u>speed at which the peripheral oscillation covers half a wave length. At even higher speeds, the deformation increases and is conveyed to the tire cover perimeter, the tire heats up and the rolling resistance increases exponentially with the speed. The speed marked on the tire cover is 80…90% of the critical speed. The increase in pressure stiffens the tire increasing the critical speed. When rolling on the motorway at high speed, it is recommended to use a pressure of 0.2 …0.4 bars higher than at lower speeds.



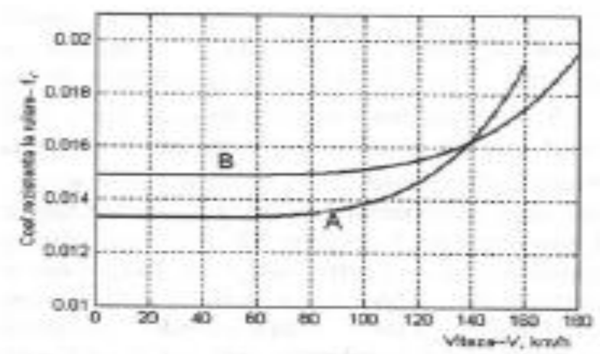


Fig. 3.82. Influenţa vitezei asupra coeficientului de rezistenţă la rulare (Anvelope 185/70 R 13:
A – pentru viteza maximă de 160 km/h;
B – pentru viteza maximă de 180 km/h).

Figure 5 & 6: The influence of speed on the rolling resistance coefficient[4] (tire covers 185/70 R 13

A – for a maximum speed of 160 km/h;

B – for a maximum speed of 180 km/h).

- <u>The air pressure in the tire</u>

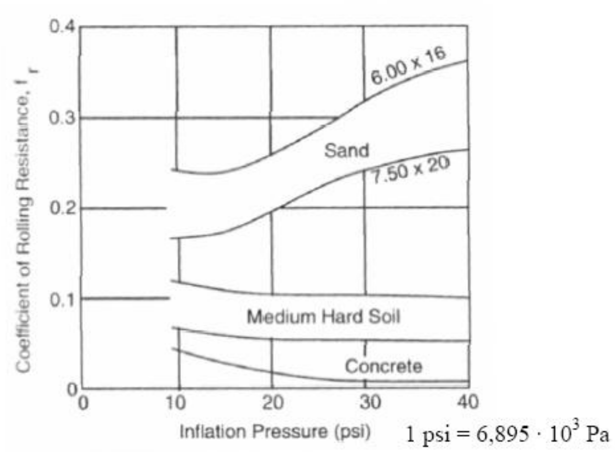


Figure 7: Varying Coefficient of rolling resistance on different surfaces with respect to different inflation pressures[4]

On deformable roads, the reduction of pressure leads to the reduction of the rolling track, but a too drastic pressure drop leads to exaggerated tire deformation and, thus, to the increase of the rolling resistance on such type of soil, as well.

- <u>Temperature</u>

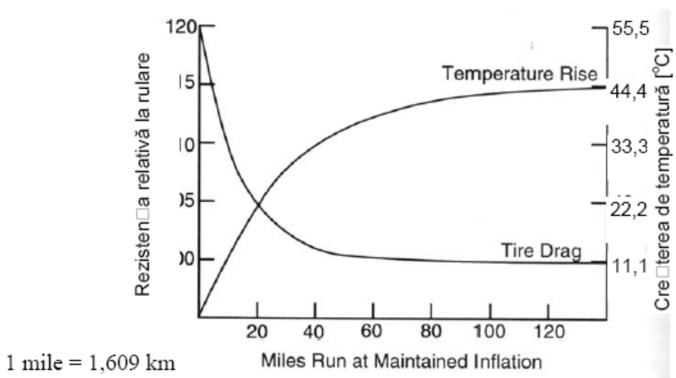


Figure 8: Temperature influences the friction inside the tire cover material[4].

Testing Surfaces

In the test, three types of rolling surfaces were used. Motorway construction site was used for testing area.

Paving structure of motorway consist of 3 types of paving layers.

- Ballast base (BB)
- Crushed stone base (CSB)
- Asphalt layer (ATB,ABC,AWC)

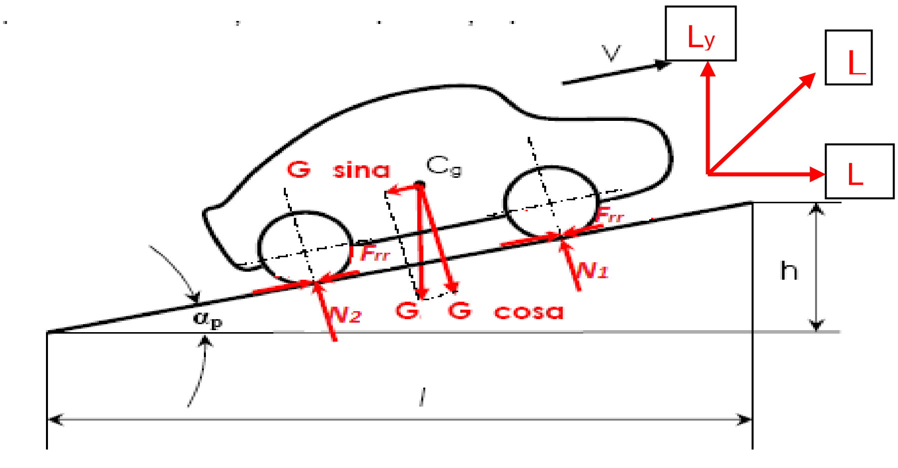
Ballast base (BB) is the first and lowest bottom layer of paving construction with lower compaction relative to the above layers. The source of this material is river aggregate with the gradation to 0 to 63 mm aggregate particles. Required compaction is achieved by 15 ton steel drum rollers. The surface roughness of this layer is comparably higher than the above layers.

Crushed stone base (CSB) is the second layer of pavement with higher compaction ratio compared to the Ballast base layer. The source of this material is Rock Mountains. Rock extracted from the mountain is crushed and screened to achieve required gradation. Surface roughness is less than the Ballast base layer but higher than the Asphalt layer. Required compaction is achieved by 25 ton rubber tired and 15 ton steel drum rollers. Gradation of this material is again 0 to 63 mm screened aggregate.

Asphalt is the last layer of pavement. Asphalt also placed in three different layers as asphalt treated base (ATB), asphalt binder course (ABC) and asphalt wearing course (AWC). We were able to perform our tests on the first lowest layer of asphalt since the motorway construction was at that level. ATB is produced by composition of 0 to 25 mm size crushed aggregate and 6% (in weight) bitumen. The required compaction is achieved by Asphalt pavers, Rubber Tired Rollers and oscillatory vibrating steel drum rollers. This layer is much smoother than the previous layers of Ballast base (BB) and crushed stone base (CSB). Of course the smoother surface is aimed to be achieved at the AWC layer of the asphalt where vehicles are driven on. There are special test required by road construction specifications to achieve this rolling surface smoothness [8].

Theoretical Mathematical Hypothesis:

Let us consider a vehicle climbing up a constant sloped road as represented in Diagram 1 below:



With:

G: Weight of the car (mg)

N_1/N_2: Normal force from the road acting on the tires perpendicular to the plane

F_{rr}: Force of the rolling resistance acting on the tires.

L: Distance the car travels

L_y

Figure 9: Theoretical car on a theoretical inclined road

If we assume that L_x is the distance the car travels in horizontal and that the car started from a certain speed, by the help of a rough v-t graph we can determine the Formula of displacement of the car in horizontal (L_x).

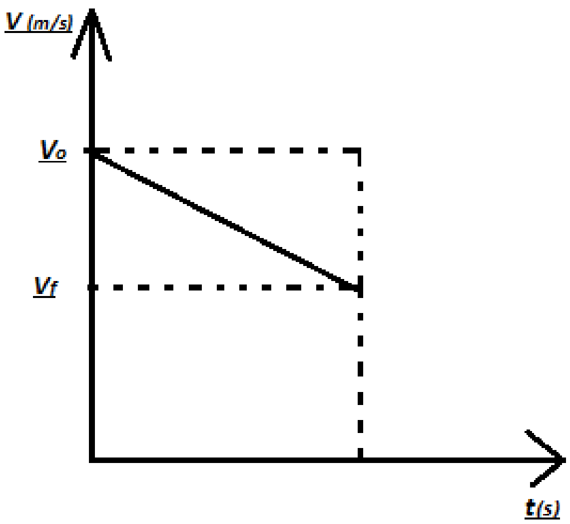


Figure 10: Simple sketch of a v-t graph

The area under the graph gives the total displacement.

As a result we obtain the following formula for L_x:

$$\underline{L_x = V_0 t - \tfrac{1}{2}(at^2)}$$

For a vehicle in motion, there are several forces which act up on the vehicle. The vehicle in return would have to overcome these forces in order to reach a certain point elsewhere. These forces can be categorized into 2 factors which are;

1. The retarding force due to rolling resistance friction (F_{rr})
2. The retarding force due to aerodynamic drag (F_w)

The total force acting on the vehicle in motion is $F_t = F_{rr} + F_d$ (9). These two forces work in corporation to bring the vehicles motion to an end. When we look back at the formula for L_x it is seen that these forces can be placed in acceleration (a). This results in the following way:

$$\underline{L_x = V_0 t - \tfrac{1}{2}(a_{rr} + a_w)t^2}$$

Where a_{rr} is the negative acceleration of rolling resistance and a_d is the negative acceleration due to aerodynamic drag.

Factor 1:

- The retarding force due to rolling resistance friction (F_{rr})

The retarding force due to rolling resistance friction is given by:

$$\mathbf{F_{rr} = C_{rr}N}$$

Where Crr is is the (unitless) coefficient of rolling resistance and N Normal force from the road acting on the tires perpendicular to the plane (mg).

As there is also angle of elevation of the road cosα also has to be included because has a direct effect on the Normal force from the road acting on the tires perpendicular to the plane (N).

$$\mathbf{F_{rr} = C_{rr}N = C_{rr}W\cos\alpha = C_{rr}g\cos\alpha m}$$

From Newton's second law of motion, F=ma, a_{rr} can be derived from the formula by dividing it all by the mass (m).

$$\mathbf{a_{rr}= C_{rr}g\cos\alpha\cancel{m} = \quad C_{rr}g\cos\alpha}$$

Factor 2:

- The retarding force due to aerodynamic drag (F_w)

The retarding force due to aerodynamic drag (F_w):

$$\mathbf{F_w= ½(\rho C_d A V^2)}$$ [9]

Where C_d is the coefficient of drag, which can take values of 1 for a non-recumbent bicycler to 0.5 for a truck to 0.3 for an aerodynamic car to 0.1, ρ is the density of air (1.2 kg/m³ at standard conditions), A the frontal area (projected) of the vehicle, and V the average velocity of the vehicle.

If we assume that:

$$\mathbf{V_{avrg} = (V_0+V_f)/2= V_0/2}$$

F_w would equal:

$$\mathbf{F_w=(½)\rho C_d A (V_0/2)^2 = (1/8)\rho C_d A V_0^2}$$

Hence acceleration a_w would be dividing it all by mass (m)

$a_w=(1/8_m)\rho C_d A V_0^2$

To derive our formula lets replace the accelarations we figured out in Factor1 and Factor2 in the displacement formula.

$$L_x = V_0 t - ½(at^2)$$

$$\Downarrow$$

$$L_x = V_0 t - ½(a_{rr}+a_w)t^2$$

$$\Downarrow$$

$$L = V_0 t – ½\ [C_{rr} g\cos\alpha + (1/8m)\rho C_d A V_0^2]t^2$$

$$\Downarrow$$

$$C_{rr} = [16m(V_0 t-L_x) - t^2(\rho C_d A V_0^2)]/[8mgt^2\cos\alpha]$$

Experimental Variables :

1. Independent

   - Total tire pressure of the car
   - Surface Type

2. Controlled

   - Same car and all physical properties of the car
   - Frontal area (projected) of the vehicle (2.75 m²) [10]
   - Initial-Final Velocity of the car (60 km/h – 0km/h)
   - Angle of elevation of the road (%0.3)
   - Mass of the car (2340 kg)[11]
   - the route of the car
   - Type of tire
   - Temperature of the Weather
   - Weight of the people in the car

3. Dependent

   - Time of travel of the vehicle up to stopping point
   - Distance Taken by the vehicle until stopping point

Overall Experimental Apparatus

- 1 car of constant weight (2340 kg) ,Frontal surface area (2.75 m²) and tires,(Figure 11)
- 10 meter long tape measure (± 1 cm)
- Chronometer (± 0.01 s)
- 1 Visible Color Spray Paint (Phosphoric pink, orange etc.)
- 34 Metal Rods (at least 70 cm in height), (Figure 2) Long stretch of at least 800m,
- 3 different surfaces with constant slope
- Paper and a Pen
- Manometer (±0.01 bar)

Figure 11: The vehicle

Figure 12: Sample Metal Rod

Experimental Methods:

Before Test Day:

1. 3 different roads (Crushed Stone Base, Ballast Base, Asphalt Binder Course), at least 800 meters in longitude, with the exact same slope value, %0.3 are decided.
2. The car (with the driver, co-pilot and any objects inside) is weighed and the initial pressures of all tires are measured, to make sure they all have the same value.
3. A starting point is appointed and a metal rod is placed next to it.
4. The spray paint is painted horizontally starting from the stick till the end of the width of the surface, to indicate the start point.
5. Taking regard of the curves and dents in the road, 3 metal rods 100 meters one after another are stuck, with accordance to the displacement of the car
6. Again, taking regard of the curves and dents in the road, 30 metal rods are stuck 10 meters one after another, with accordance to the displacement of the car.

Key Note: *The rods are placed one after another because to measure stretched distances such as 800 meters with a measure every time is a long, tiring process. With the help of the rods the process is easier and more pragmatic. When placing the rods one after another it is very important to calculate and then place them with respect to the displacement of the car in the arc, not a simple, straight, perpendicular measurement (figure 13).*

Figure 13: The metal rods placed 10 meters apart with respect to the arc

During Testing:

1. The vehicle is started from a spot which has enough distance to reach 60 km/h once on the drawn start point. (Be careful that the vehicle includes the same people and objects from before the test day)
2. The car is sped up to exactly 60 km/h and the gear is slipped into neutral once the start point has been reached. At the same time the chronometer is started.
3. Do not turn the steering wheel or interfere anyway with the car (let still).

Figure 14: Numbered points during the experiment

4. Once the motion is ended, immediately the chronometer is stopped and the time is recorded.
5. The point reached is numbered with the spray paint (start numbering from 1), not to lose track. (Figure 14)

6. With respect to the metal sticks placed and the 10 meter calculating ruler, the displacement is calculated and recorded (The displacement should be calculated with respect to the front wheels as in figure 14)
7. At least 3 trials are done for the same surface and same tire pressure.
8. Everything is moved to one of the other roads, selected earlier, with a different surface but constant slope from the first road. Steps 1-7 are repeated.
9. Everything is moved to the last road, with a different surface but constant slope from the first and second road. Steps 1-7 are repeated.

10. With the manometer the pressure of all the tires are decreased at least 0.3 bar and steps 1-7 are repeated (Figure 17).
11. All equipments are moved to one of the other roads, selected earlier, with a different surface but constant slope from the first road. Again steps 1-7 are repeated.

Figure 15-16: Measuring the Stopping Distance

12. All equipments are moved to the last road, with a different surface but constant slope from the first and second road. Once again steps 1-7 are repeated.
13. Again with the manometer the pressure of all tires is decreased at least 0.3 bar and repeat steps 1-7.
14. All equipments are moved to one of the other roads, selected earlier, with a different surface but constant slope from the first road. Again steps 1-7 are repeated.
15. All equipments are moved to the last road, with a different surface but constant slope from the first and second road. Once again steps 1-7 are repeated.

Figure 17: Adjusting the tire pressure

Recorded Data:

Having carried out the above steps for the experiment, the following data were collected:
For Crushed Stone Base (CSB):

Measurement ID	Time	Weather Condition	Distance reached	Duration	Tire pressure
			l	t	p
		C°	± 0.1 (m)	±0.01 (s)	±0.10 (bar)
1	11:08	Cloudy 27°	574,0	77,97	2,20
2	11:22	Cloudy 27°	602,5	77,42	2,20
3	11:30	Cloudy 27°	594,9	75,30	2,20
16	13:58	Cloudy 27°	507,5	72,03	1,85
17	14:04	Cloudy 27°	522,3	73,36	1,85
18	14:10	Sunny/Cloudy 27°	502,8	73,27	1,85
25	14:58	Sunny/Cloudy 27°	499,3	68,71	1,50
26	15:03	Sunny/Cloudy 27°	494,9	68,80	1,50
27	15:07	Sunny/Cloudy 27°	495,2	68,64	1,50

Table 1: Represents the raw data recorded during the experiment on CSB with varrying tire pressures.

For Ballast Base (BB):

Measurement ID	Time	Weather Condition	Distance reached	Duration	Tire pressure
			l	t	p
		C°	± 0.1 (m)	±0.01 (s)	±0.10 (bar)
4	11:43	Cloudy 27°	504,0	69,52	2,20
5	11:47	Cloudy 27°	503,3	71,09	2,20
6	11:57	Cloudy 27°	511,2	69,52	2,20
13	13:48	Cloudy 27°	495,0	71,92	1,85
14	13:51	Cloudy 27°	487,9	72,58	1,85
15	13:55	Cloudy 27°	501,0	70,73	1,85
19	14:21	Sunny/Cloudy 27°	436,2	62,53	1,50
20	14:25	Sunny/Cloudy 27°	469,2	63,18	1,50
21	14:34	Sunny/Cloudy 27°	454,3	64,03	1,50

Table 2: Represents the raw data recorded during the experiment on BB with varrying tire pressures.

For Asphalt Binder Course (ABC):

Measurement ID	Time	Weather Condition	Distance reached	Duration	Tire pressure
			l	t	p
		C°	± 0.1 (m)	±0.01 (s)	±0.10 (bar)
7	12:15	Cloudy 27°	667,1	92,46	2,20
8	12:20	Cloudy 27°	658,9	90,67	2,20
9	12:23	Cloudy 27°	648,5	89,99	2,20
10	13:34	Cloudy 27°	594,8	81,97	1,85
11	13:39	Cloudy 27°	611,4	82,91	1,85
12	13:43	Cloudy 27°	594,2	85,72	1,85
22	14:37	Sunny/Cloudy 27°	570,3	78,53	1,50
23	14:41	Sunny/Cloudy 27°	565,7	78,10	1,50
24	14:43	Sunny/Cloudy 27°	563,4	80,10	1,50

Table 3: Represents the raw data recorded during the experiment on ABC with varrying tire pressures.

The uncertainities in the carried out experiment was recorded suitably and will be processed accordingly in the rest of the essay.

Data Processing:

After having derived the formula for the coefficent of rolling resistance and having collected data by conducting the experiment, the relationships between tire pressure and surfaces to the coefficient of rolling resistance can be determined. For the rest of the essay's calculations the literary constants in table 6 was used. To find the coefficient of rolling resistance let's start from our general equation which is $L_x = V_0 t - ½(a_{rr}+a_w)t^2$. As the vehicles, displacement (L_x), average velocity V_0, and time of travel (t) is known the accelerations of rolling resistance friction and aerodynamic drag can be determined. This process can be split up into 2 parts:

Literary Constants	Values
ρ(air) (t=27 C°) kg/m³	1,174
g (gravitational acceleration) m.sn²	9,807
tan(α)	0,003
cos(α)	1,000
sin(α)	0,003
Car Drag Coefficent, Cd (2004 Nissan Navara)	0,430
Car Frontal Area, Af (2004 Nissan Navara)	2,750

Table 4: Literary Constants[12]

Part 1:

- Determining the acceleration due to aerodynamic drag (a_w):

Fundamental Assumption:

The only obvious weakness in the conducted experiment can be seen as the fundamental assumption of the average velocity was made to be $V_{avrg} = (V_0+V_f)/2= V_0/2$. The velocity was regarded as a linear correlation.

⟺ The acceleration due to aerodynamic drag can be determined by $a_w= (1/8m)\rho C_d A V_0^2$ where:

- Mass of the vehicle (m): 264,02 ± 1,02 kg
- The coefficient of drag (C_d): 0,43
- The density of air at 27°C (ρ): 1,174 kg/m³
- The frontal area (projected) of the vehicle (A): 2,75 m²
- The start velocity of the vehicle (V_0): 16,67 ± 0,28 m/s

As all the values are considered as constants the overall acceleration of the vehicle for each trial is considered to be:

$a_{w=}$ 12726,46 m/s² ± %2,05

The uncertainty for acceleration due to aerodynamic drag was calculated by calculating the percentage errors for all values with uncertainty and then adding them all up.

- Percentage of uncertainty of the mass of vehicle(1.02/264.02)X 100 = 0.39 %
- Percentage of uncertainty of the start velocity of vehicle(0.28/16.67)X 100 = 1.67 %

When the exact values found were added up roughly %2,05 was found.

Part 2:

- Determining the coefficient of rolling resistance friction (**C**rr):

In the previous part we had found the general equation of $L_x = V_0t - ½(a_{rr}+a_w)t^2$. The equation shows us that the distance travelled by our vehicle is determined by, its displacement (in a case where there are no forces against it) V_0t, minus the forces acting against our vehicle which are friction of rolling resistance and aerodynamic drag - $½(a_{rr}+a_w)t^2$. In the conducted experiment all the values except acceleration due to rolling resistance friction (a_{rr}) is known, therefore by substituting the values we have found a_{rr} can be determined. As a_{rr} is known to be $C_{rr}g\cos\alpha$, Coefficient of rolling resistance (C_{rr}) can be found by $a_{rr}/g\cos\alpha$.

The tables below represent the processed data for the three type surfaces:

For Crushed Stone Base (CSB):

Measurement ID	Distance reached	Duration	Tire pressure	Displacement due to initial velocity	Uncertainity of V_0t	Coefficent of rolling resistance	Uncertainity of Crr
	l	t	p	V_0t	±	C_{rr}	±
	± 0.1 (m)	±0.01 (s)	±0.10 (bar)	(m)	(m)		
1	574,0	77,97	2,20	1299,50	21,99	0,0057	0,0005
2	602,5	77,42	2,20	1290,33	21,84	0,0048	0,0005
3	594,9	75,30	2,20	1255,00	21,25	0,0051	0,0005
16	507,5	72,03	1,85	1200,50	20,33	0,0086	0,0006
17	522,3	73,36	1,85	1222,67	20,70	0,0079	0,0005
18	502,8	73,27	1,85	1221,17	20,68	0,0087	0,0005
25	499,3	68,71	1,50	1145,17	19,40	0,0093	0,0006
26	494,9	68,80	1,50	1146,67	19,43	0,0095	0,0006
27	495,2	68,64	1,50	1144,00	19,38	0,0095	0,0006

Table 5: Represents the processed data for the experiment on CSB with varrying tire pressures.

For Ballast Base (BB):

Measurement ID	Distance reached	Duration	Tire pressure	Displacement due to initial velocity	Uncertainity of V_0t	Coefficent of rolling resistance	Uncertainity of Crr
	l	t	p	V_0t	±	C_{rr}	±
	± 0.1 (m)	±0.01 (s)	±0.10 (bar)	(m)	(m)		
4	504,0	69,52	2,20	1158,67	19,63	0,0090	0,0008
5	503,3	71,09	2,20	1184,83	20,07	0,0089	0,0009
6	511,2	69,52	2,20	1158,67	19,63	0,0087	0,0009
13	495,0	71,92	1,85	1198,67	20,30	0,0091	0,0006
14	487,9	72,58	1,85	1209,67	20,49	0,0093	0,0006
15	501,0	70,73	1,85	1178,83	19,97	0,0090	0,0006
19	436,2	62,53	1,50	1042,17	17,67	0,0130	0,0009
20	469,2	63,18	1,50	1053,00	17,85	0,0112	0,0007
21	454,3	64,03	1,50	1067,17	18,09	0,0119	0,0008

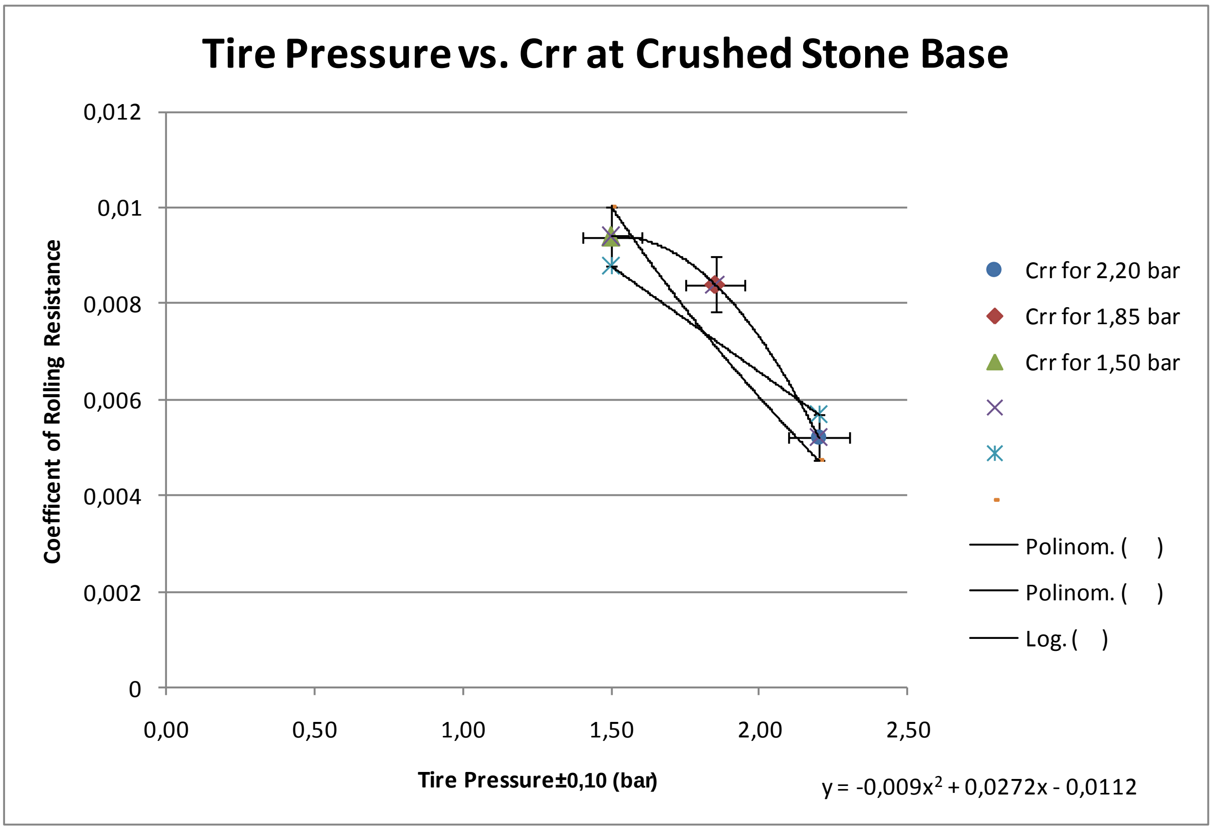
Table 6 : Represents the processed data for the experiment on BB with varrying tire pressures.

For Asphalt Binder Course (ABC):

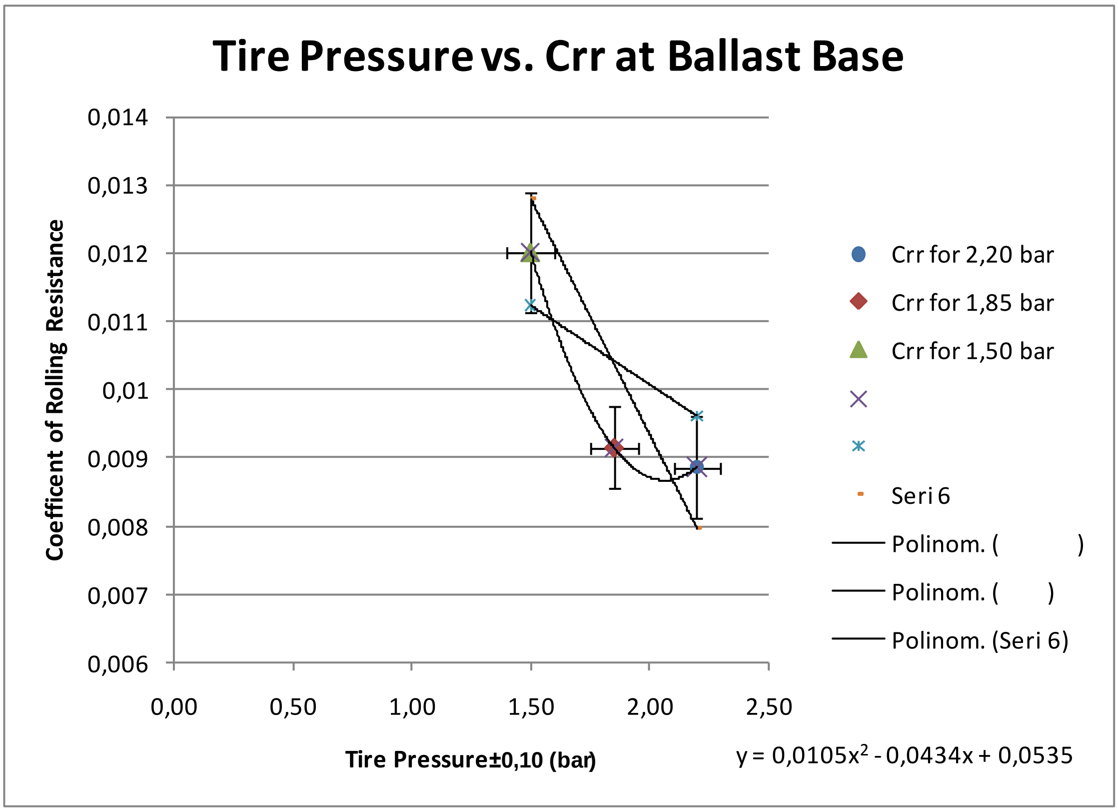
Measurement ID	Distance reached	Duration	Tire pressure	Displacement due to initial velocity	Uncertainity of V_0t	Coefficent of rolling resistance	Uncertainity of Crr
	l	t	p	V_0t	±	C_{rr}	±
	± 0.1 (m)	±0.01 (s)	±0.10 (bar)	(m)	(m)		
7	667,1	92,46	2,20	1541,00	26,05	0,0022	0,0002
8	658,9	90,67	2,20	1511,17	25,55	0,0025	0,0003
9	648,5	89,99	2,20	1499,83	25,36	0,0028	0,0003
10	594,8	81,97	1,85	1366,17	23,11	0,0048	0,0003
11	611,4	82,91	1,85	1381,83	23,38	0,0042	0,0003
12	594,2	85,72	1,85	1428,67	24,16	0,0045	0,0003
22	570,3	78,53	1,50	1308,83	22,15	0,0058	0,0004
23	565,7	78,10	1,50	1301,67	22,03	0,0060	0,0004
24	563,4	80,10	1,50	1335,00	22,59	0,0059	0,0004

According to the proccessed data scatter graphs were drawn with the uncertainity values calculated and best fit lines ploted.

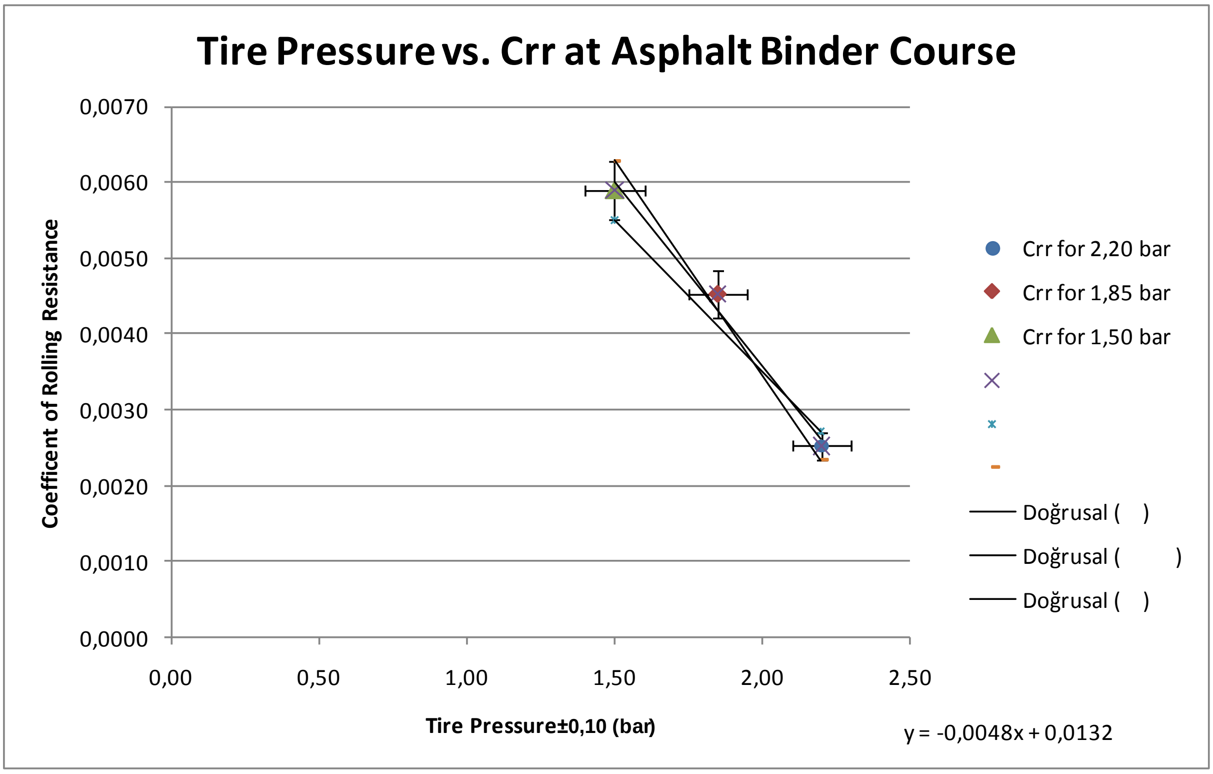
Table 7: Represents the processed data for the experiment on ABC with varrying tire pressures.



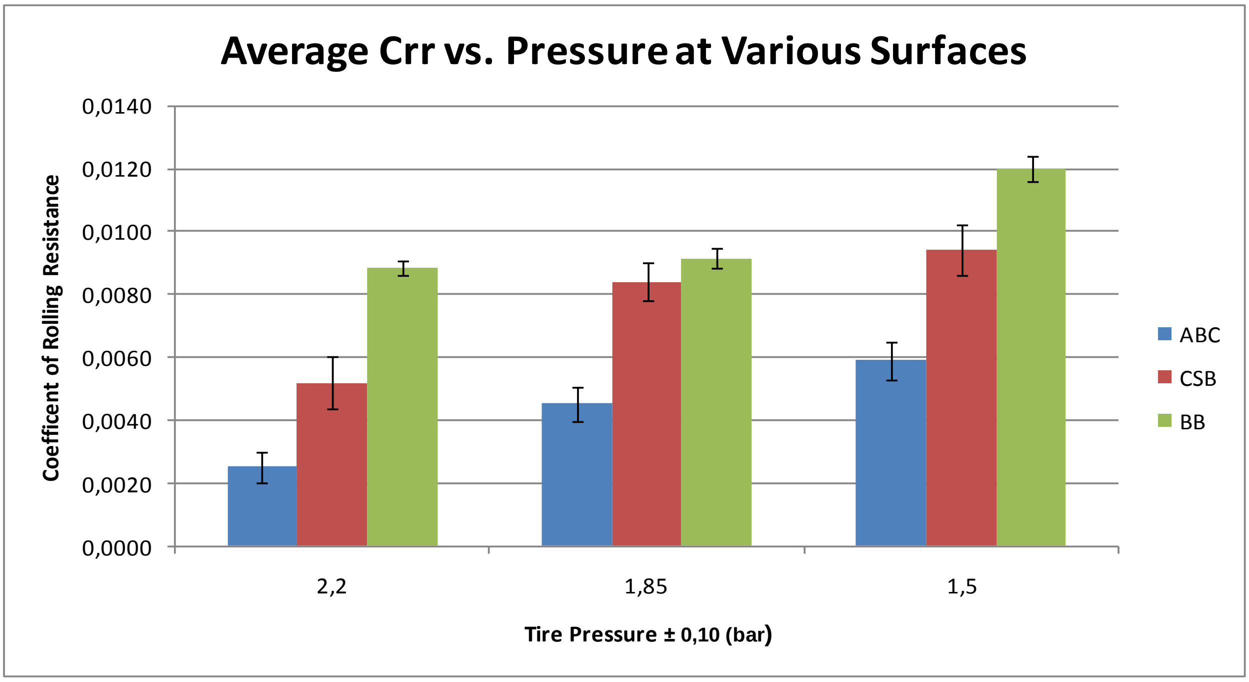
Graph 1: Represents CSB's varrying tire pressures versus the calculated coefficent of Rolling resistance with best and worst fit lines plotted.



Graph 2: Represents BB's varrying tire pressures versus the calculated coefficent of Rolling resistance with best and worst fit lines plotted.



Graph 3: Represents ABC's varrying tire pressures versus the calculated coefficent of Rolling resistance with best and worst fit lines plotted.



Graph 4: Represents the mean Rolling resistance coefficents versus various surface for all tire pressures with exact uncertainity bars shown.

Conclusion and Evaluation

The investigation has lead to significant discoveries that were well-supported by theoretical values. As the investigation was to figure out the effect of the road surface and tire pressures on rolling resistance, the conducted experiments proved to validate that smoother the surface and higher the pressure less the rolling resistance.

First it was observed that as the compactness level increased on the surface, making the surface smooth, the force applied on the tires began to significantly decrease and as a result decreased the friction of rolling resistance. Ballast Base (BB) which is located in the lowest bottom layer of paving construction with lower compaction relative to the above layers and surface roughness is comparably higher than the above layers showed that the average coefficients of rolling resistance varied between, 0,009 – 0,012. Crushed Stone Base's (CSB), which is located in the second layer of pavement with higher compaction ratio compared to the Ballast base layer, surface roughness is less than the Ballast Base layer but higher than the Asphalt layer. The coefficient of rolling resistance varied between, 0,005- 0,009. The last layer Asphalt Binder Course (ABC) which was much smoother than the previous layers, Ballast base (BB) and crushed stone base (CSB) proved the following averages of rolling resistance, 0,003- 0,006. (The exact values and more accurate plotting of the entire surface's data combined may be found on graph 4)

The second observation was based on the correlation between differing tire pressures and the friction due to rolling resistance. It was observed that higher pressures in the tires turned out less friction effecting on the tires. An inverse proportionality between pressure and rolling resistance was found (see graphs 1, 2 and 3). The ideal (theoretical value) tire pressure 1,85 bar, for the vehicle that the experiment was conducted with, proved once again to be ideal because, looking back at graph 4, it can be witnessed that 1,85 was the pressure which had the least significant difference in rolling resistance values for the 3 surfaces. Where else in 1, 50 and 2, 20 there were significant gaps, differences for the values of rolling resistance in the three surfaces. The pressure value recommended in the manual, 1.85, has the least difference among all three pressures. There it can be concluded that 1,85bar really was the optimum best value, in terms of safety, for the tire of the vehicles. As there isn't as much difference in the values of rolling resistance for the 3 surfaces as the other pressures, it is thought that the stability and the dynamic of the car can be maintained more easily with the recommended 1, 85 pressure value. But on the other hand 2, 20 bar tires are the best solution to less fuel consumption.

There are certain lacking points and uncertainties in the experiment. The following could be referred to as the uncertainties in the experiment;

1. The pressure of the tires were meant to kept constant but one of the factors, temperature, which may influence modification of the basic pressures was neglected[6]:

   - From 25 to 29° C………………………i ncrease the pressure by 4%
   - From 30 to 34° C………………………increase the pressure by 6%
   - From 35 to 39° C………………………increase the pressure by 8%
   - From 40 to 45° C………………………increase the pressure by 10%

2. The uncertainty for acceleration due to aerodynamic drag a_w= 12726,46 m/s² ± %2,05 was always regarded as the same but in fact it wasn't because the weather, temperature could not be fixed to 27° C. During the experiment it was observed that acceleration due to aerodynamic drag affected the car a lot, in one false trial Accidently a window of the vehicle was left open (which increased the aerodynamic drag) and it was observed that instead of the vehicle travelling around 650 meters it only had a displacement of 567 meters. Therefore it can be thought that an uncertainty in a_w may cause major lacks.

3. The reflex arc of the driver was neglected. Once the vehicle reached the speed of 60 km/h and the gear was slipped to natural on the start line appointed there was a certain degree of lack due to a human beings reflex arc, either the gear might have been shifted slightly early or late.

Next time the experiment is conducted the following precautions should be taken in order to decrease the lacking points and uncertainties in the experiment;

1. A water bath with a constant temperature liquid such as water can be prepared and after each trial the vehicle can pass through the water bath in order to bring the temperature of the wheels to a constant degree (but of course the wheels should let dry for a while as water would bring slippery and decrease rolling resistance)

2. It is definitely very hard to keep the temperature constant at these sorts of big experiments where kilometers of road are needed. But the experiment could be conducted inside big road tunnels where the temperature does not vary as much as open air circumstances.

3. A sensor can be prepared for the car to recognize the start line so that once the car figures out that it has reached the start point, it can automatically slip the gear into natural by itself. By this way the human arc reflex time would be neglected.

As the experiment is in fact a vital issue of the present to lower the consumption of non-renewable natural sources, implementing the changes to the experiment and figuring out more precise results would surely be worthwhile.

References:

1. Hibbeler, R.C. (2007). *Engineering Mechanics: Statics & Dynamics (Eleventh ed.)*. Pearson, Prentice Hall. pp. 441–442.
2. Peck, William Guy, *Elements of Mechanics: For the Use of Colleges, Academies, and High Schools*. A.S. Barnes & Burr: New York. p. 135.
3. *Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance* -- Special Report 286. National Academy of Sciences, Transportation Research Board, 2006. http://onlinepubs.trb.org/onlinepubs/sr/sr286.pdf. Retrieved 2007-08-11.
4. Williams, John A. *Engineering Tribology*. New York : Cambridge University Press (2005)
5. Roche, Schinkel, Storey, Humphris & Guelden, "Speed of Light." ISBN 0 7334 1527 X
6. *Michelin Technical Data Earthmover Tires Handbook* (2004)
7. Goodyear, OTR data book, off-the-road tire engineering data
8. Bechtel International Inc. Reno Nevada, Cluj Napoca Sectiunea 2B, Egis Route, *Laboratory Report Savadisla* Authorization No:2078/05/07/2010
9. Jeremy Rutman ,*How to do a Roll-down test*, 8.2007 Clausthal-Zellerfeld, Germany
10. http://www.carfolio.com/specifications/models/car/?car=179641. (Retrieved 2009-10-12)
11. Cantar Auto – Fisa Cantarire Masina, SAT Valisoara F.N.COM Savadisla JUD, 31/07/2010 14:27
12. http://en.wikipedia.org/wiki/Automobile_drag_coefficient. (Retrieved 26.12.2010)