Real Driving on Under-inflated Rear Tire on Horizontal Curves: A Road Experimental Study

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Abstract: An under-inflated tire represents a high risk of accidents for vehicle occupants and other users. Publications have previously been directed toward monitoring tire pressure and its influence on several driving-controlled experiences. However, little has been written about their impact on a real road trip, for example driving on curves, grades, or unfavourable weather conditions. This study aims to evaluate the relationship between the stability variables on the vehicle in curves of the road when driving on the under-inflated rear tire on wet pavement. In this interesting experience, the left rear tire of a pickup truck was under-inflated to 10 psi (-33%). The vehicle travelled more than 50 km of a mountain road. As a result, an average reduction in speed (-6.5%) was found in the right curves and an average increase in lateral acceleration (+ 8.5%) in the right curves in relation to the left ones. As a secondary result, the radius of the curve had a statistical relationship on lateral acceleration and the grade had not. The results of this study, would help to create a new indirect pressure method and in accidents reconstructions.

1 INTRODUCTION

Driving on under-inflated or deflated tires cause damage very quickly. Inadequate tire inflation can shorten the tire life or damage the rim, it may lead to a tire blow-out, affect the passenger's comfort, or even negatively affect the vehicle's stability (Motrycz et al., 2021; Toma et al., 2018). Those effects could induce the driver's loss of control and subsequent vehicular accidents (Fancher et al., 1974; Liqiang et al., 2018). A properly inflated tire that distributes the vehicle weight could provide good contact with the road, passenger comfort, responsive handling, and uniform tire wear (Varghese, 2013). Nowadays, modern vehicles are equipped with systems that monitor vehicle safety problems.

The tire-pressure monitoring system (TPMS) is one of those systems. There are two approaches to perform this monitoring: direct and indirect. The first method has higher precision but is more expensive. While the second one has more errors but is cheaper (Goharimanesh et al., 2016). The direct method uses a tire pressure sensor to measure the tire pressure directly. The indirect one, such as the rotation radius procedure, employs effective tire rotation to monitor the tire pressure (Liqiang et al., 2018). In both cases, the idea is to warn drivers when the tire has lost air pressure. For them to act, they need to know the effects of driving with an under-inflated tire.

Under-inflated tires increase forward drag and lateral steering effects on vehicles which are frequently an issue in an accident reconstruction (Robinette et al., 1997). Since the under-inflation tire increases the contact patch length, the tire would have a higher rolling resistance (Varghese, 2013). And with lower speeds, the rolling resistance will be higher (AASHTO, 2011). Also, the tire pressure affects the vehicle handling, such as lateral force, self-aligning moment, and longitudinal force (Pacejka, 2012). What happens if drivers, despite warnings or knowledge, do not act. What would happen?

Several studies were conducted to answer this question. One of the experiments had six passenger cars and a pickup truck (Robinette et al., 1997). With all four tires deflated to 10 psi, acceleration and vehicle control results were similar to the tires' pressure in the regular conditions. When one tire was deflated (either the front or rear axle), the driver controlled the vehicle. These results are applicable up to 72 km/h (45 mph). Another investigation, between

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5-7 km/h, found the tire pressure did not influence the maximum braking rate (Toma et al., 2018). One study using laboratory and field equipment found that a decrease in inflation pressures reduces the cornering and camber stiffness and increases the aligning stiffness of the tire (Fancher et al., 1974). Based on these results, well-adjusted mathematical relationships have been carried out with simulators for road accident reconstruction (Zębala et al., 2014; Zebala & Wach, 2014).

Most of the studies carried out in the field have not related the variables of the vehicle stability when it has an under-inflated tire with geometric variables on the road, such as a curve. In addition, they have been in a relatively controlled environment, for example, in good environmental conditions. Therefore, the objective of this study is to evaluate the relationship between the stability variables on the vehicle on curves, when driving on an under-inflated rear tire on wet pavement. It analyzed the speed, lateral and longitudinal acceleration, the vertical velocity with the radius of the curve and the grade.

To present these findings of this unique experimental study, the materials and methods details the selection of the road and the vehicle, measurement tool. Also, it presents the road geometric design estimation, and data collection procedure and data processing. Then, the results are presented in section 3, where four analyses are performed: curve radii, grade, descriptive statistics, and linear regression. Each section discussed the influence of the geometric features on speed, vertical velocity, and accelerations.

2 MATERIALS AND METHODS

2.1 Road Selection

The selected road for the study was in a mountainous topography (see Figure 1). Considering its geometric design limitations, this type of road allows it to have a high number of horizontal curves. Also, combine them with other geometric elements, such as steep grades. The evaluated road section has a length of more than 50 km. The longitudinal profile of the road is shown in Figure 2. In this profile, the sections with homogeneous grades have been shaded. This profile was obtained from the GPS data of the VBOX tool.

The selected road is located in the Ecuadorian Amazon between Palanda and Yangana town. This road belongs to the "Eje Vial No. 4" that communicates Ecuador with Peru. The road has a rigid pavement roadway and has a lane width of 3.65 m. The road crosses several protected forests: Podocarpus National Park and Tapichalaca Reserve. The mountain forests and paramos of the region are considered "super-humid" since rainfall over 6000 mm has been recorded (Richter, 2003).

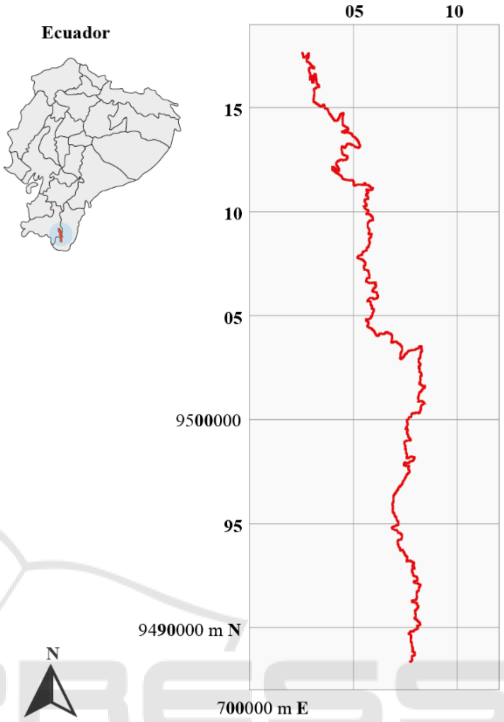

Figure 1: Planimetry of the selected road for this experimental study (Ecuador).

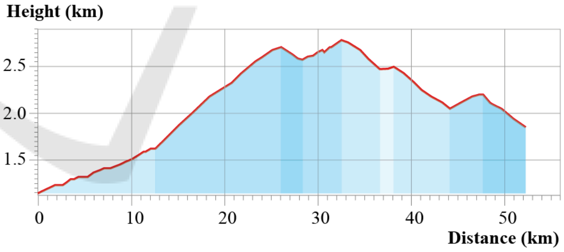

Figure 2: Road vertical profile of the selected road.

2.2 Test Vehicle Selection

The vehicle selected was a Chevrolet D-Max diesel pickup. The truck has the characteristics shown in Table 1. This car is practical in the case of small landslides, small rock falls, among others, which are frequently on these roads. The vehicle has ABS + EBD brakes, traction control, and stability control.

2.3 Measurement Tool

The selected measurement tool was the Video VBOX Lite. This device collects the following data: time, distance, satellites, speed (km/h), heading (degrees), latitude, longitude, height (m), vertical velocity (km/h), longitudinal and lateral acceleration (m/s²).

Table 1: Technical specifications of the test vehicle.

Characteristic	Condition
Motor	2,5L turbo diesel
Net Power (Hp @ rpm)	34 @ 3600
Torque (Nm @ rpm)	320 @ 1800
Traction	4x4
Front suspension	Independent Double Wishbone Type
Rear suspension	Rigid with Crossbow
Gross vehicle weight (kg)	2950
Front axle capacity (kg)	1350
Rear axle capacity (kg)	1870
Tire size	245/75/ R16
Rated press	30 psi
Height (mm)	1790
Width (mm)	1860
Length (mm)	5295

It allows recording geo-referenced digital images through high-resolution cameras and the GPS antenna. The antenna was placed on the roof of the vehicle. The Video VBOX Lite has an accuracy of 0.05% for distance travelled, 0.2 km / h for speed, and ± 10 m for height. Accuracy acceleration: 0.50% (resolution = 0.01 g and max = 20 g). The device has a sampling frequency of 10 Hz.

2.4 Road Geometric Design Estimation

The VBOX Lite also collects the heading data. This variable helped to estimate the horizontal geometry of the road. The use of heading direction for recreating the horizontal alignment of an existing road (Camacho-Torregrosa et al., 2015) is well extended in the field. The heading remains constant when traveling along a tangent and varies its slope when traveling along a horizontal curve. After this procedure, a check of the radii of the curves was carried out using the calculation method based on three known points. With this procedure, 327 horizontal curves were determined. This value means that there are 6.29 curves per kilometre. The radii of these curves were between 20 to 558 m.

On the other hand, to determine the grades of the section, the total length was divided into sub-sections that have the same slope. In these homogeneous sub-sections, the average slopes of each section were: -9%, -8%, -7%, 2%, 4%, 5% and 8%.

2.5 Data Collection Procedure

The Video VBOX Lite was placed inside the test vehicle, as seen in Figure 3. The device has a GPS antenna and a high-resolution camera.

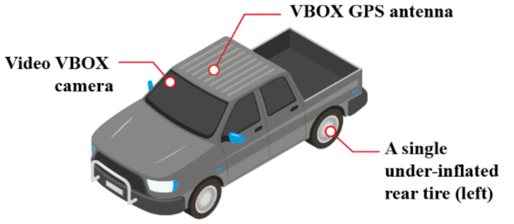

Figure 3: Details of data collection on the test vehicle.

The antenna was placed in the central part of the vehicle roof, and the camera was placed on the front windshield facing the road. Data were collected in poor weather conditions: light rain, wet pavement, and daylight. The test vehicle was unloaded. The rated press of the tire suggested by the manufacturer in the unloaded state is 30 psi. The air pressure of the left rear tire was reduced to 10 psi. This value was taken from the previous literature (Robinette et al., 1997). A single trip was made considering the risk of the test. As a precaution, emergency and mechanical units were located in the middle and end of the route. After finishing the experiment, the mechanical team checked the tire and the operation of the entire vehicle and its components. During the test, the driver was always able to easily maintain control of the test vehicles and steer them in the road test.

2.6 Data Processing

After the data collection, video and data were obtained employing the VBOX Test Suite ® of the equipment manufacturer. It eliminated all the following data: the vehicle was not in free flow, overtaking maneuverer, in an urban or suburban area, or when the road deteriorated. The acceleration data were subjected to a smoothing process using a

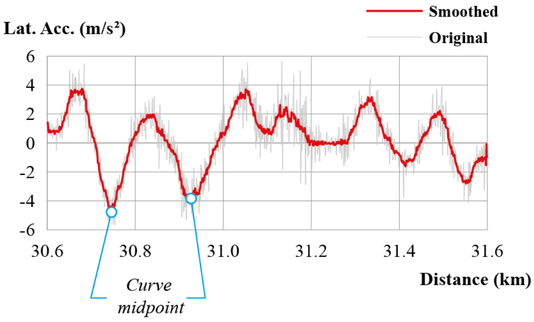

Figure 4: Example of lateral acceleration smooth.

moving average with a window width of 7. Figure 4 shows as an example, the original and smoothed profile of lateral acceleration. After this procedure, the data was extracted in the midpoint of the horizontal curve, also shown in Figure 4.

3 RESULTS

The number of satellites registered on the route was between 6 and 13, with an average of 10. The minimum speed was 5.03, and the maximum was 69.37 km/h. Previous studies reached 72 km/h (Robinette et al., 1997). The under-inflated rear tire could mainly affect the speed, vertical velocity, longitudinal acceleration, and lateral acceleration. It would have very little relevance to analyse all the acceleration values without considering the geometry of the road. Therefore, these are discussed below for the road grades and the radii of the curves.

3.1 Road Grades Analysis

In order to analyse the variations of the variables concerning the grade, the homogeneous sections with similar slopes were grouped. Then, it calculated their average grade in every section. Then, it plotted the boxplots of the speed, vertical velocity, longitudinal and lateral acceleration versus the grade of the road (see Figure 5). In Figure 5, it can be seen just the logical relationship between vertical velocity and slope. Vertical velocity has a direction associated, is positive when climbing, and is negative when descending. Regarding speed, there are no significant variations between positive or negative slopes that have been reported in previous research (García-Ramírez & Alverca, 2019). Previous studies found higher speeds on descending slopes and lower them on ascending slopes. This situation could be a result of a mountain topography with consecutive curves, where the grade could be less important than the curvature itself.

3.2 Curve Radii Analysis

The scatterplot of the speed, vertical velocity, longitudinal and lateral acceleration is seen in Figure 6. The scatterplot of the speed, vertical velocity, longitudinal and lateral acceleration is seen in Figure 6. In this figure, when the radius of the curve is lower, speeds go down, and vice versa. This relationship is well documented in previous speed prediction models. Regarding the vertical velocity, the Figure 5 does not show any trend with the grade or the radius of the curve. On the other hand, the longitudinal acceleration does not present any visible trend, unlike the lateral acceleration, where the highest values are found in the radii smallest and the lowest at the largest radii. This relationship is consistent with the highway geometric design philosophy (AASHTO, 2011).

In Figure 6, the direction of the curve has also been placed. This was done because the driver, during

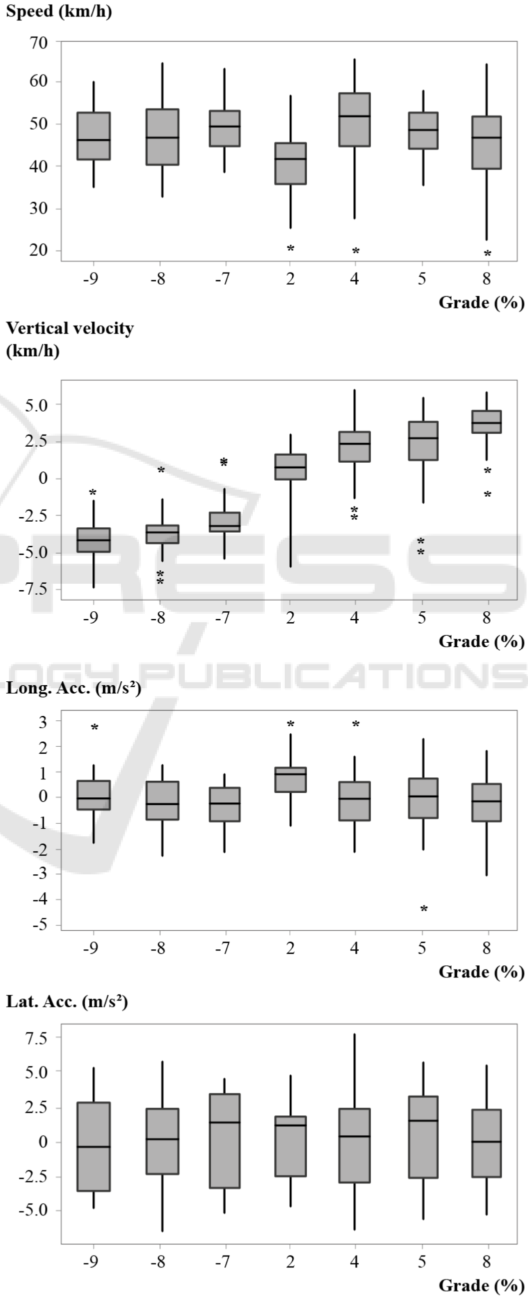

Figure 5: Boxplot of speed, vertical velocity, longitudinal and lateral acceleration versus the grade of the road.

the test, reported skidding in the left curves. The grade and vertical speed were discarded since there were no significant differences. Table 2 shows the average speed, acceleration, and radius. This table confirmed the trends in Figure 6, and, other two interesting elements appear, the speeds generally are lower in the right curves; while the lateral accelerations are lower in those curves. In the next section, this element will be analysed in deep.

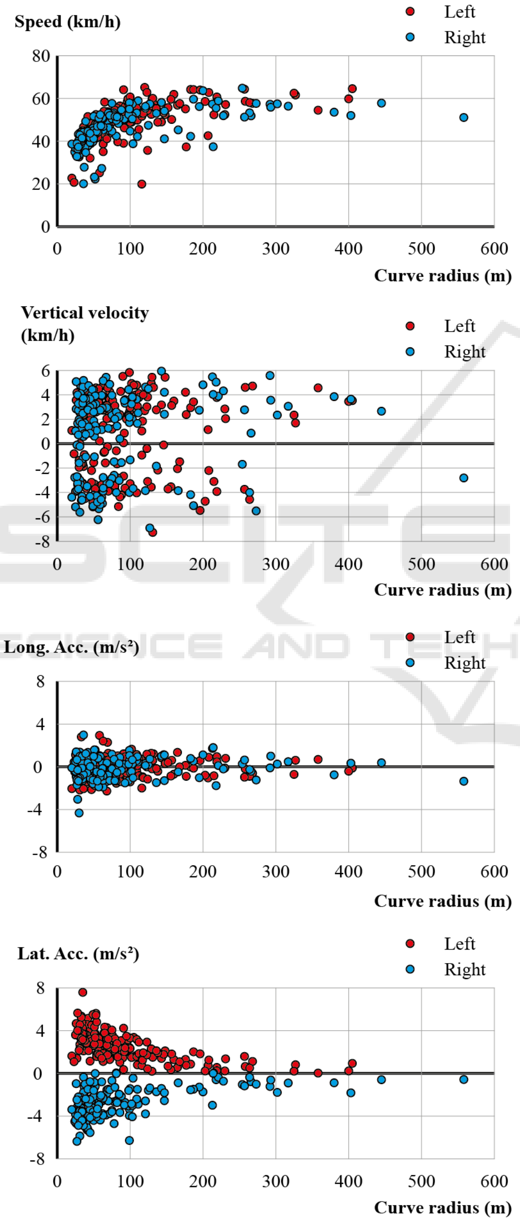

Figure 6: Scatterplot of the speed, longitudinal and lateral acceleration versus the radius of the curve and considering the direction of the curve.

3.3 Descriptive Statistics Analysis

Table 3 presents the descriptive statistics of the variables previously detected. This table shows the mean longitudinal acceleration in the right curve is greater than in the left. The rest of the statistics are very similar to each other, except for the minimum value. Regarding the mean lateral acceleration, the value of the right curve is also greater than the left.

Table 2: Descriptive statistics of speed and acceleration with the ranges of the radii of the curves.

Radii of curves (m)	N	Mean Speed (km/h)	Mean long. acc. (m/s^2)	Mean lat. acc. (m/s^2)
All data				
20-50	110	40.1	-0.233	3.518
51-100	123	48.9	-0.145	2.707
101-150	43	52.1	0.188	1.981
151-200	16	55.9	0.090	1.218
201-250	13	54.4	0.155	0.719
>250	22	57.4	-0.151	0.856
Right curves				
20-50	66	39.7	-0.242	-3.461
51-100	52	48.0	-0.321	-2.671
101-150	16	51.6	0.144	-2.305
151-200	5	53.4	0.188	-1.382
201-250	5	52.2	0.336	-0.934
>250	13	55.5	-0.057	-0.980
Left curves				
20-50	44	40.6	-0.219	3.604
51-100	71	49.5	-0.015	2.735
101-150	27	52.3	0.214	1.790
151-200	11	57.0	0.045	1.143
201-250	8	55.7	0.041	0.585
>250	9	60.2	-0.288	0.677

Regarding the speeds, in general, higher values were obtained in the left curves than in the right curves. The driver was expected to slow down in the right curves since with the under-inflated rear tire, the possibility of outward skidding was a consequence. This behaviour does not occur on left curves. This particularity also impacts the lateral acceleration, since although the left curves have higher average speeds, they have lower lateral acceleration values than the right ones. The same happens in longitudinal acceleration. In conclusion, the presence of an under-inflated left rear tire impacts a reduction in average speed in left curves and an increase in average lateral acceleration and average longitudinal acceleration. The variations are -6.5%, + 8.5% and + 78% for speed, lateral acceleration and average longitudinal acceleration, respectively.

Table 3: Descriptive statistics of speed and acceleration for the direction of the curve.

Variable	Curve type	N	Mean	StDev.	Min	Max
Long. acc. (m/s^2)	Right	157	-0.182	0.997	-4.320	2.98
	Left	170	-0.040	0.942	-2.27	2.94
Lat. acc. (m/s^2)	Right	157	2.729	1.420	0.000	6.360
	Left	170	2.496	1.397	0.030	7.590
Speed (km/h)	Right	157	45.803	8.166	20.110	64.840
	Left	170	48.981	8.610	19.940	65.200

3.4 Linear Regression Analysis

Due the differences between the direction of the curves, the following linear regression analysis was carried out as shown in Table 4.

The regression analysis was done with the Stepwise function of Minitab ® (State College, 2005). These equations are referential and should be explored further in future research.

Table 4 shows the models for all the data, the right curves, and the left curves. The lateral acceleration was a dependent variable. The main predictors for lateral acceleration are: the speed and the radius of the curve. It used the R^{-1} (inverse of the curve radii) in the regression process, but it was not statistically significant. The model that best fits is the one for the left curves. This outcome was expected because the under-inflated tire did not have a meaningful effect on these curves. The real impact is in the right curves, where the coefficient of determination is low. And this also affects the fit of the general model, so the R^2 adjusted is very low.

Table 4: Linear regression models for the lateral acceleration and the direction of the curve.

Predictor	Coef.	SE Coef.	T-value	P-value	R^2 adj.
All data					
Constant	-2.20	0.92	-2.39	0.018	1.5 %
Speed (km/h)	0.05	0.02	2.41	0.016	
Right curves					
Constant	-3.49	0.14	-24.96	0.000	26.4 %
Curve radii (m)	0.09	0.00	7.94	0.000	
Left curves					
Constant	3.67	0.14	26.37	0.000	39.4 %
Curve radii (m)	-0.01	0.00	-10.54	0.000	

Coef.: model coefficients, SE Coef.: standard error of the coefficient, T-value: ratio between the coefficient and its standard error, P-value: probability that measures the evidence against the null hypothesis, R^2 adj.: adjusted R-squared.

4 CONCLUSIONS

This article aimed to investigate the influence on the stability variables of the vehicle in curves of the road when the vehicle driving on the under-inflated rear tire on wet pavement. After analysing the results, the following conclusions are presented:

The speed and acceleration were the variables that were mainly affected because of a left under-inflated rear tire. However, the influence was only present in curves on the opposite side of the under-inflated rear tire. Speed decreases in these curves, while lateral acceleration increases. The radius of the curve was also statistically significant; nevertheless, the grade of the road was not. That is why equations were calibrated with this variable, where, as a result of the presence of the under-inflated tire, the right curves had less regression fit than the left curves. It is necessary to mention that differences in lateral acceleration in left or right curves are not only to the flat tire but it could also have been caused by the driver, for whom a left curve differs from a right curve since he/she sits on one side of the vehicle. This could be analysed in future studies.

This study has several limitations. First, this study employed a single vehicle and a single under-inflated rear tire. Additionally, just one trip was conducted in the experiment, with 10-psi tire pressure. Both conditions could differ in other vehicles, another tire or air pressure, or driving several trips. It did not repeat the trip due to an accident hazard. It would be interesting to compare at least 3 cases: 1) current case, 2) normal case (all tires inflated to 30 psi) 3) the right rear tire reduced to 10 psi, and other combinations. This study focused on the kinematics effects of an under–inflated tyre; therefore, we don't know what are the causes of this behaviour: rolling resistance, the contact area tyre, among others. These causes could be modelled as seen in Varghese (2013). With this procedure, it could predict the effect of more under–inflated tires and complement the presented experiment that involves only one under–inflated tire.

Despite these limitations, the present study helps to extend the knowledge of the consequences of an under-inflated rear tire, and their relationship with the road geometric variables. Data in this study belonged to the actual driving on more than 50 km in the mountainous road. This context was not previously analysed. Although modern vehicles include direct monitoring of the tire pressure, the present outcomes can be the basis for a new indirect pressure method in accidents reconstructions, which can be analysed in future studies.

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