

Enhancement of Collision Mitigation Braking System Performance Through Real-Time Estimation of Tire-road Friction Coefficient by Means of Smart Tires

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ABSTRACT

In the case of modern day vehicle control systems employing a feedback control structure, a real-time estimate of the tire-road contact parameters is invaluable for enhancing the performance of the chassis control systems such as anti-lock braking systems (ABS) and electronic stability control (ESC) systems. However, at present, the commercially available tire monitoring systems are not equipped to sense and transmit high speed dynamic variables used for real-time active safety control systems. Consequently, under the circumstances of sudden changes to the road conditions, the driver's ability to maintain control of the vehicle maybe at risk. In many cases, this requires intervention from the chassis control systems onboard the vehicle. Although these systems perform well in a variety of situations, their performance can be improved if a real-time estimate of the tire-road friction coefficient is available. Existing tire-road friction estimation approaches often require certain levels of vehicle longitudinal and/or lateral motion to satisfy the persistence of excitation condition for reliable estimations. Such excitations may undesirably interfere with vehicle motion controls. This paper presents a novel development and implementation of a real-time tire-road contact parameter estimation methodology using acceleration signals from a smart/intelligent tire. The proposed method characterizes the terrain using the measured frequency response of the tire vibrations and provides the capability to estimate the tire road friction coefficient under extremely lower levels of force utilization. Under higher levels of force excitation (high slip conditions), the increased vibration levels due to the stick/slip phenomenon linked to the tread block vibration modes make the proposed tire vibrations based method unsuitable. Therefore for high slip conditions, a tire-road friction model-based parameter estimation approach is proposed. Hence an integrated approach using the smart/intelligent tire based friction estimator and the model based estimator gives us the capability to reliably estimate friction for a wider range of excitations. Considering the strong interdependence between the operating road surface condition and the instantaneous forces and moments generated; this real time estimate of the tire-road friction coefficient is expected to play a pivotal role in improving the performance of a number of vehicle control systems. In particular, this paper focuses on the possibility of enhancing the performance of collision mitigation braking systems.

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INTRODUCTION

A vehicle's interaction with the road surface initiates at the contact patch of the tires. This small patch dictates the resulting motion of the vehicle and is a major governing factor of the vehicle's stability and control, especially under severe maneuvers. This underscores the importance of developing a tire contact patch monitoring system, capable of providing real-time estimates of the tire-road contact parameters to the vehicle control system. By having a thorough understanding of the tire-road interaction forces and

other parameters at the contact patch, the state of the road surface can be derived which can be play in pivotal role in improving the performance of a number of vehicle control systems [1]. Examples of vehicle control systems that can benefit from the knowledge of tire-road friction include anti-lock braking systems (ABS), electronic stability control (ESC), adaptive cruise control, and collision warning or collision avoidance systems. The quality of traffic management and road maintenance work (e.g., salt application and snow plowing) can also be improved if the

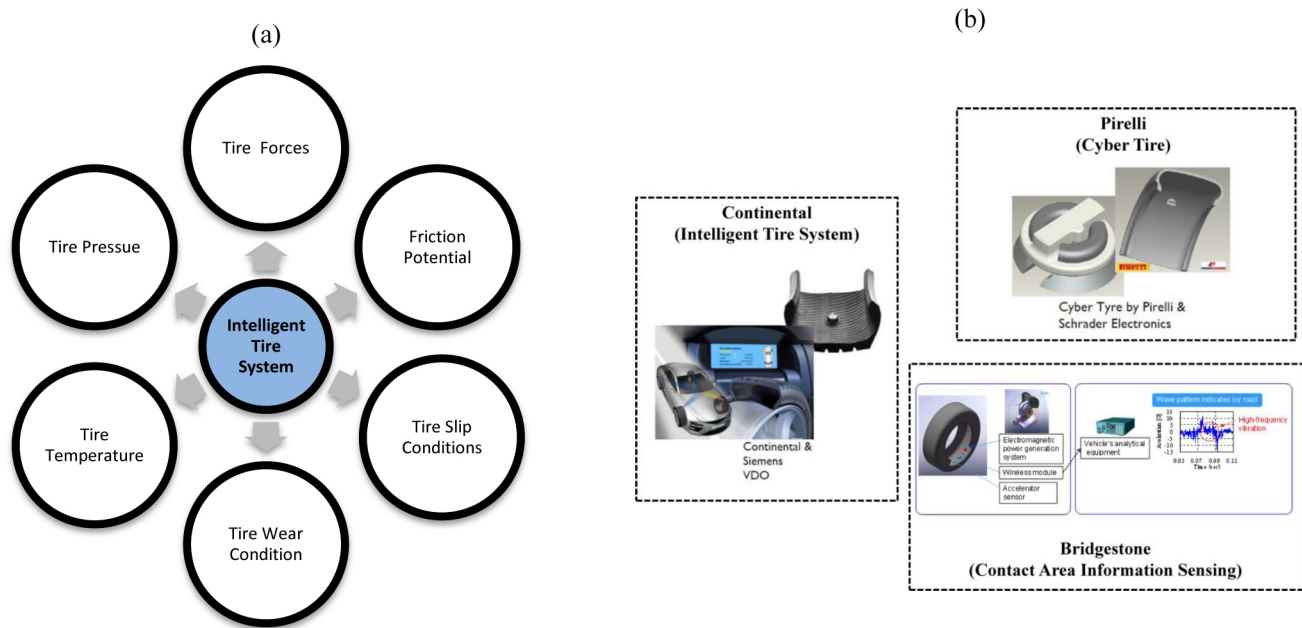


Figure 1. Intelligent tire system: (a) sensor output, and (b) products and concepts

estimated friction value is communicated to the traffic and highway authorities.

The new terms “Intelligent Tire” and “Smart Tire”, which mean online tire monitoring are thus enjoying increasing popularity among automotive manufacturers and formed the motivation for this study to explore the possibility of developing an intelligent tire system. These next generation intelligent tires are expected to play a cardinal role in improving the overall drivability of a vehicle and contributing significantly in improving the performance of a number of active safety systems on board today's vehicles [2,3,4,5,6]. The stimulus for increased research into intelligent tires is attributed to the Bridgestone/Firestone recalls in 2000 [7]. As a result of the recalls, United States Transportation Recall Enhancement, Accountability, and Documentation (TREAD) legislation has mandated that every new automobile be equipped with a tire pressure monitoring system (TPMS) [8,9,10]. This legislation has given impetus to the development of advanced tire technologies for improved tire safety.

The Intelligent tire concept as envisioned by the tire researchers will have the capability to monitor in real time, the forces at tire-road interface, friction coefficient, slip conditions, temperature/pressure and tire wear (Figure 1a). The potential of this system can be judged by its ability to give exhaustive information about a tire in motion in terms of the sensor outputs. Being able to leverage the plethora of information about the contact patch dynamic properties, an intelligent tire system is expected to stimulate the development of a new generation of traction (TCS), braking (ABS) and stability (ESP) control systems for improving vehicle safety and performance [11,12,13]. Moreover, as compared to a classical tire-pressure monitoring system

(TPMS) mounted to the valve stem in the wheel, an intelligent tire sensor module being attached directly to the tire tread would allow the sensor to collect temperature and pressure data more accurately. This being achieved by making the sensor module less vulnerable to impacts during tire changes and heat radiated from the brakes and wheel, as in the case of valve mounted TPMS units [14].

Most of the research over the past few decades in the field of advanced tire systems has been focused on developing techniques for both offline and online tire inspection. Intelligent tire system, which primarily consists of online tire monitoring systems, has garnered a lot of interest from both industry (Figure 1b) and academia, and there have been several architectures proposed in the past few years pertaining to these systems. Some of the concepts which have shown great potential include:

- i. The APOLLO program - Developed a 3-in-1 intelligent tire [15];
- ii. The FRICTI@N program - On-board system for measuring and estimating tyre-road friction[16];
- iii. Contact area information sensing (CAIS) system being developed by Bridgestone [17];
- iv. Cyber Tire being developed by Pirelli Tires [18];
- v. Intelligent tire systems being developed by Continental AG [19].

The APOLLO program consortium, consisting of several tire and vehicle companies, performed a study to evaluate the potential benefits of using an intelligent tire system and its effects on accident free traffic [20]. Table 1 presents their findings on which control and driver assistance systems stand

Table 1. APOLLO program findings on how information gained from an intelligent tire will affect vehicle control systems [20]

		Friction Information	Slip Angle	Wheel Forces	Tire Condition	Road Parameters
Vehicle Control	ABS					
	TCS					
	ESP					
	Rollover Avoidance					
Advanced Driver Assistance System	ACC					
	Emergency Braking					
	Collision Avoidance					
Driver Information	Information Level					
	Warning Level					
The application would benefit from the availability of the tire information		Greatly		Somewhat		Little

to benefit from information gathered from the tire. Advanced Driver Assistance Systems (ADAS) are expected to significantly benefit from a more continuous friction estimation system. Also, some of the existing systems could be supported with high quality real-time information about tire-road friction coefficient. Tire-road friction coefficient information would enable, for example, ABS to start braking with the optimal brake pressure based on the current maximum coefficient of friction, meaning the early cycles of operation are more efficient, resulting in shorter stopping distance. In addition, it may be useful to present the driver with friction information.

Some more recent studies [3,4,5] have evaluated the possibility of enhancing the performance of the ABS (Antilock Braking System)/EBD (electronic braking distribution) control systems by using the tire normal load and the tire-road friction coefficient information from the intelligent tire system. [4], examines the integration of accelerometer based tire sensors with lateral stability control system (ESP) and presents a preliminary study on potential performance improvements.

In this paper, an adaptive intelligent tire based collision mitigation braking System (CMBS) is proposed as a procedurally viable option to address the problem of unpredictable road surface conditions. The proposed system is capable of differentiating various types of road surfaces, and accordingly adapting its critical distance (warning/braking distance) definitions as a function of the tire-road surface conditions. Once it has been established that a collision is unavoidable, a classical collision mitigation braking system activates autonomous emergency braking to reduce the collision speed and consequently reduce the severity of a collision. To ensure optimum brake performance, this paper focuses on the possibility of using the additional information provided by the intelligent tire to enhance the performance of the brake system (ABS). In order to achieve the aforementioned objectives, the design and implementation of a Fuzzy/Sliding Mode/Proportional

Integral (Fuzzy-SMC-PI (FSP)) control methodology is proposed. Improvements in the system performance have been evaluated by means of numerical simulations carried out with a validated 8 degrees of freedom (DOF) vehicle model.

ROAD SURFACE CONDITION ESTIMATION ALGORITHM

Knowledge of the friction coefficient of the road is important for the design and analysis of vehicle control systems. Lack of knowledge about friction leads to conservative design rules for the controller, resulting in reduced performance. In normal driving conditions the frictional force is not fully utilized and the developed tire force will be somewhere in the interior of the circle. When force is applied to a tire, a relative motion arises between the tire structure and the road. This relative motion is referred to as tire slip. The relation between the resulting tire force and the slip depends on many factors, namely, tire inflation pressure, vertical load, tire wear, temperature, etc., and contains information about the available friction. When the tire is exposed to excitation with high utilization, beyond the point corresponding to the maximum available friction force, the tire is sliding and the resulting tire force directly corresponds to the friction coefficient. Hence, determination of friction coefficient is straightforward in cases where tire forces are saturated, such as under hard braking. The difficulty lies in obtaining a friction estimate under more normal driving circumstances, in which the tire slip is smaller (lower utilization conditions).

The implementation strategy for a road surface condition estimation algorithm that utilizes sensor signals from an instrumented tire is presented in this section. A method that characterizes the terrain using the measured frequency response of the tire vibrations has been developed. To do this, the tire vibration signals in a predetermined domain were extracted. The predetermined domain represents a certain portion of the tire signal per tire revolution. The vibration



Figure 2. Intelligent tire application: (a) sensor mounting location, (b) instrumented tire assembly, (c) mobile tire test rig, and (d) test rig attached to the towing vehicle

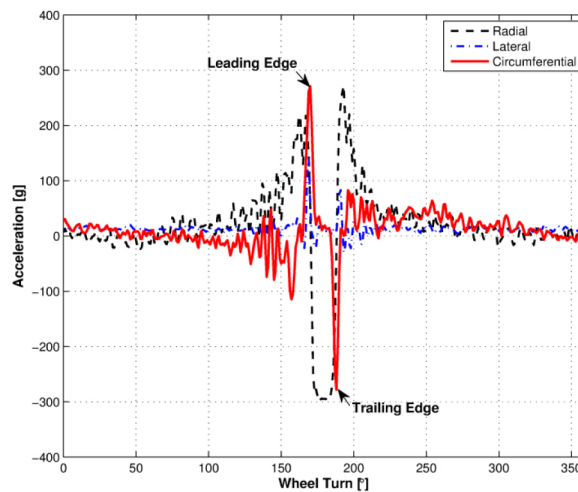


Figure 3. Measured acceleration signal for one rotation

levels of a predetermined frequency band within these domains are then calculated using the frequency spectrum of the time signal by passing the signals through a band-pass filter. Based on the calculated vibration level, the road surface condition can be estimated. Details regarding the procedure adopted to instrument the tire, outdoor tire testing, methodology for sensor data analysis and the classification algorithm are explained in the sections to follow.

TIRE INSTRUMENTATION AND TESTING

The instrumented tire system was developed by placing accelerometers on the inner liner of a tire (Figure 2a).

Figure 2b shows the final assembly of the instrumented tire with a high speed slip ring attached to the wheel. Extensive dynamic tests of the tire were conducted using the in-house mobile tire test rig shown in Figure 2c and Figure

2d. An example of the acceleration signal is shown in Figure 3.

SENSOR DATA ANALYSIS AND ALGORITHM DEVELOPMENT

The effect of tire load, translational speed, varying pressure conditions, and road surface roughness on the tire vibration spectra were studied by varying each of these parameters by carrying out extensive outdoor testing of the instrumented tire under free-rolling, traction/braking and steering conditions (Figure 4).

The power spectrum of each accelerometer signal from these tests was computed using Welch's averaged modified periodogram method [12] for spectral estimation (Figure 5). Analyzing the dynamic test results, it was concluded that, a marked difference was noticed in the concentration of the higher frequencies on the spectrum of the circumferential acceleration signal of the tire tested on different surface

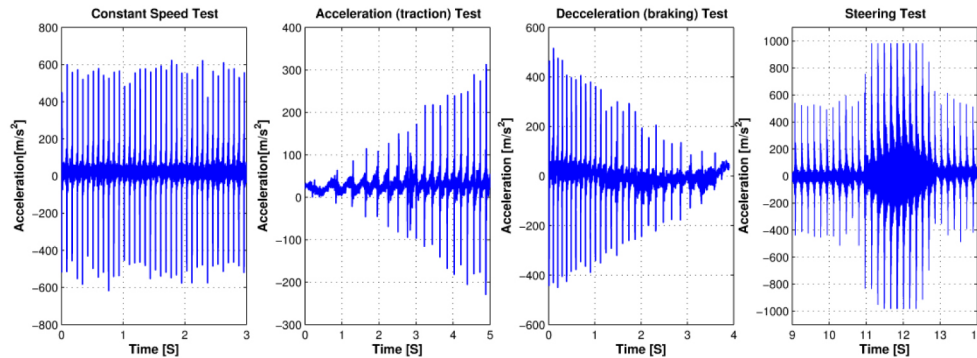


Figure 4. Measured circumferential acceleration signal under free-rolling, traction, braking, and steering conditions

conditions (Figure 5d). This variation in the circumferential acceleration signal PSD on different road surface conditions presented an opportunity to characterize the road condition using the tire vibration pattern information.

The proposed intelligent tire based road surface condition estimating algorithm consists of detecting the circumferential vibration of a tire of a running vehicle; dividing the detected tire vibration into vibration in a pre-trailing domain, the domain existing before a trailing edge position; and vibration in a post-trailing domain, the domain existing after a trailing edge position as shown in Figure 6a. Thereafter extracting signals of tire vibration only from the pre-trailing domain; obtaining a time-series waveform of tire vibration including only the frequencies in a predetermined frequency band by passing the extracted signals through a band-pass filter of the predetermined frequency band; calculating a vibration level in the predetermined frequency band; and estimating a road surface condition based on the calculated vibration level.

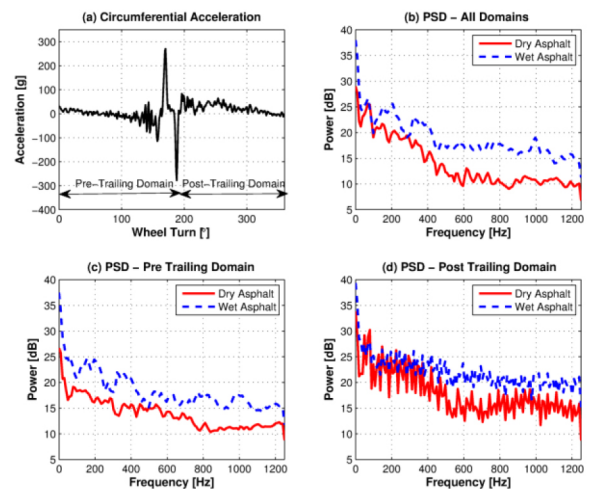


Figure 6. (a) Accelerometer signal domains; PSD waveforms using: (b) all the domains, (c) only the pre-trailing domain, and (d) only the post-trailing domain

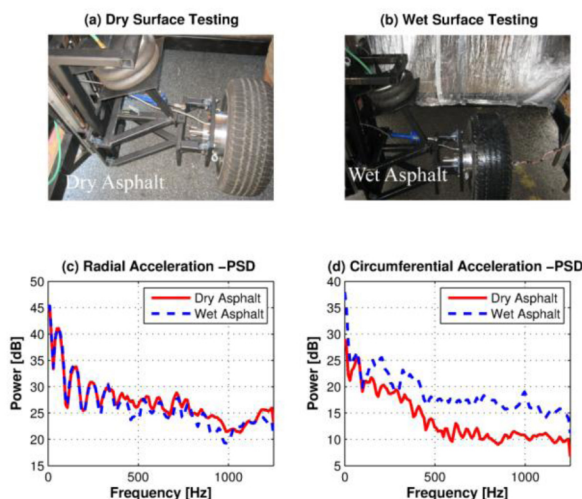


Figure 5. Tire tested on different road surface conditions: (a) dry surface testing, and (b) wet surface testing; Roughness dependence study: (c) radial signal PSD, and (d) circumferential signal PSD

The predefined frequency domains being a low frequency band (e.g. 10-500 Hz band) and a high frequency band (e.g. 600 to 2500 Hz), as shown in Figure 7. The motivation for only using the pre-trailing domain signal is the larger difference in the PSD of the pre-trailing domain signal as shown in Figure 6c, as compared to the PSD's obtained using the entire signal (Figure 6b) or using the signal from the post-trailing domain (Figure 6d). To determine these differences, the instrumented tire was first driven on a dry surface and then on a wet road surface at different speeds and the change in the vibration level ratio (R) was measured, where R is the ratio of the aforementioned high frequency band and the low frequency band vibration level. It is evident from Figure 8 that the vibration level ratio R increased as the tire was tested on the wet road surface. This change in the vibration level ratio can be attributed to the increased slippage of the tire, and thus it has been confirmed that the slipperiness of a road surface can be decided by setting a proper threshold value.

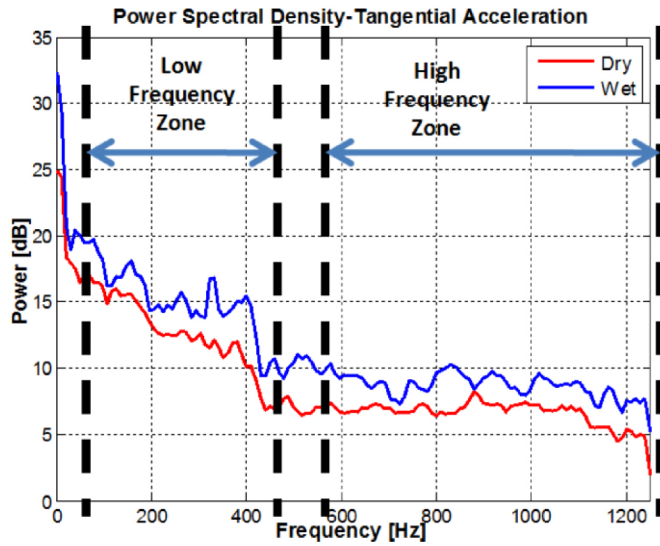


Figure 7. High and low frequency domains in the circumferential acceleration PSD

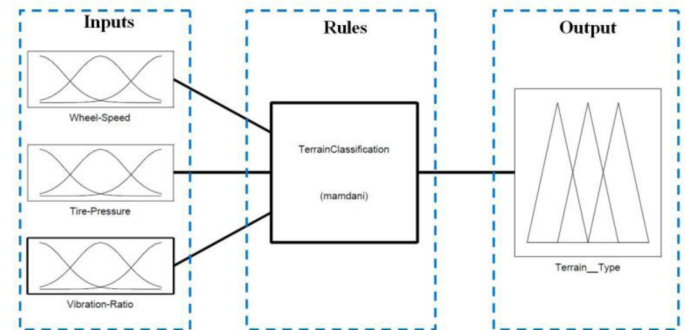


Figure 9. Fuzzy logic based controller architecture

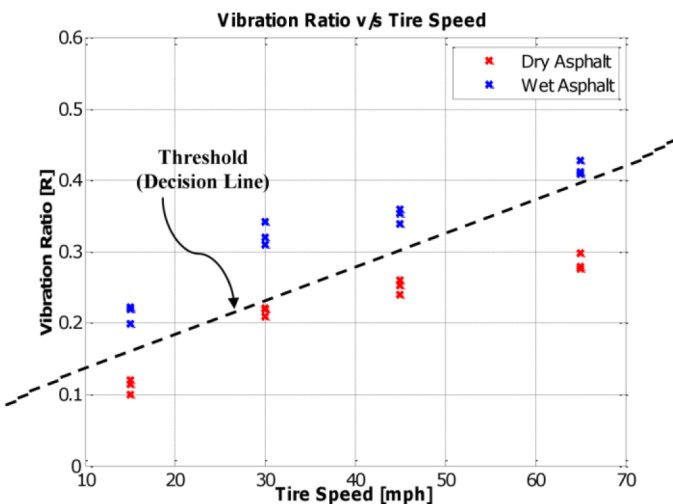


Figure 8. Vibration ratio on dry and wet surface conditions for a range of tire speeds

For this purpose, a fuzzy logic classification approach [21-22] was developed for the real-time implementation of the proposed algorithm. The application of fuzzy logic to solve the classification problem is motivated by its noise tolerance to the vibration data retrieved from sensors, and its ability for real-time implementation while ensuring robustness with respect to imprecise or uncertain signal interpretation. Figure 9 and Figure 10 show the fuzzy controller architecture.

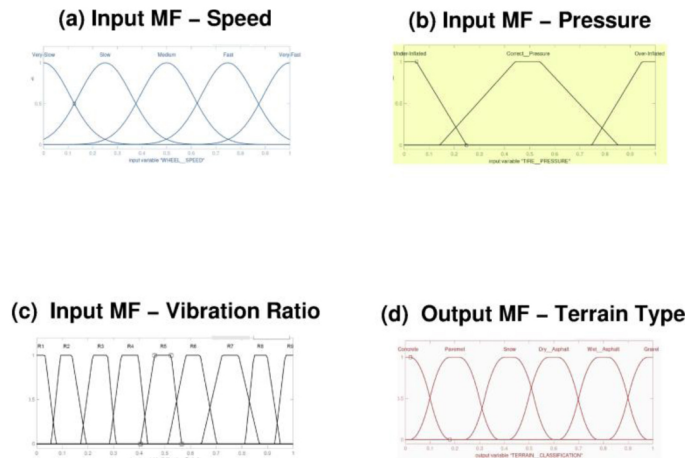


Figure 10. Input Membership Function (MF): (a) tire speed, (b) tire pressure, and (c) vibration ratio; Output Membership Function (MF): (d) terrain type

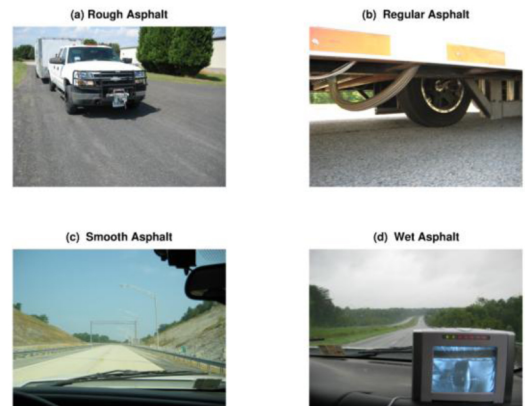


Figure 11. Tire tested on different road surface conditions: (a) rough asphalt, (b) regular asphalt, (c) smooth asphalt, and (d) wet asphalt

Based on the interdependence of all the inputs for a given road surface condition and the way they effect the vibration spectra of a tire, a set of linguistic rules were developed to