Intelligent systems

Intelligent tires-and-vehicle systems involving tire-mounted sensors and powertrain control will be essential for sustainable transportation in the future

by Mukul K Verma and Vladimir V Vantsevich, University of Alabama at Birmingham, USA

Several challenges exist for present-day and near-future automotive transportation. They arise from changing patterns in worldwide mobility demands as well as through the necessity to reduce energy consumption and emissions. These are economic and societal challenges, often implemented as regulatory requirements by governments of nations with large or growing numbers of vehicles.

Problems associated with solid-waste disposal have also received attention, and consequently the recyclability standards for tires and other vehicle components will continue to increase in all parts of the world. These and other factors lead to near-future projections of increasingly stringent regulations governing automotive transportation and tire manufacturers, even though several factors (e.g. petroleum availability and price) cannot be forecast reliably.

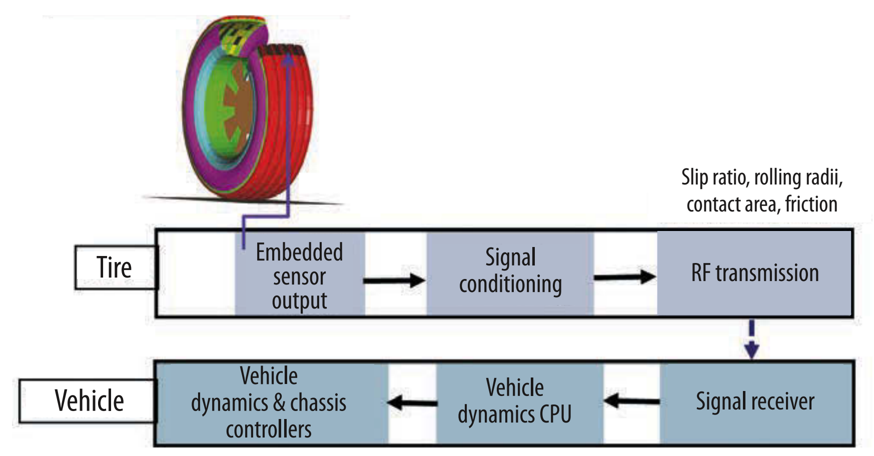
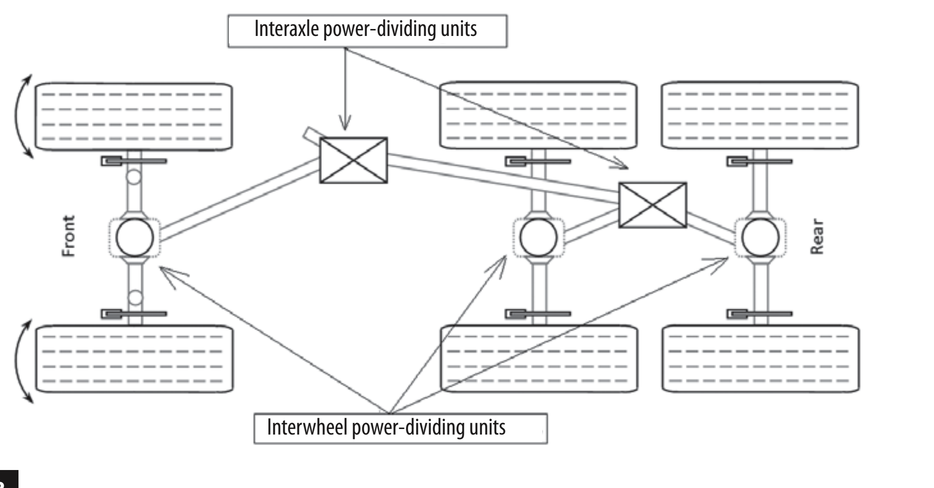


Figure 1: Schematic diagram of an intelligent system where tire data is used as control input for vehicle functions

Figure 2: Tires interact through the vehicle chassis and the driveline system

As an example, US laws require that in the period 2017-2025, the average fuel efficiency of all new passenger vehicles must reach 54.5mpg versus the estimated 24.1mpg achieved by US automobiles in 2012. This is a major problem demanding urgent, practical solutions because the design and development of tires and vehicles are conducted several years in advance of market introduction. Intelligent tires-and-vehicle technologies are one of the possible engineering solutions for meeting these rising standards for vehicles' energy efficiency and safety performance and are briefly discussed in this article.



In engineering terms, an 'intelligent system' is defined as one that can sense its current state, can compute the difference from a desired state and can modify its parameters to achieve the desired system state.

Tires with embedded pressure-monitoring systems are often referred to as 'intelligent', but they do not meet the above criteria for an intelligent system since the measured pressure data is used only to inform the driver of a drop in inflation. Sometimes the term 'intelligent tire' is taken to imply that such individual units can be purchased off-the-shelf and installed on vehicles to replace today's tires, thereby gaining energy efficiency and other advantages.

A more relevant approach for achieving near-future goals is to view 'intelligent tires-and-vehicle' as one system with integrated mechanical properties, sensing capabilities and control mechanisms so as to optimize the performance and safety of the vehicle at each instant of its operation.

This 'design synthesis' approach generates the requirements for tire design as 'subsystem specifications', which are a set of numerical values for three things: the tires' mechanical properties (such as rolling resistance, friction coefficients etc), the required measurement of tires' dynamic parameters by embedded sensors, and the required level of integration with the vehicle dynamics control system. These principles and methods were discussed in the short course entitled *Intelligent Vehicle-and-Tire Design for Energy Efficiency and Safety* presented in conjunction with the 2014 Tire Technology Conference.

In vehicle systems, the desired (or optimal) state is measured in terms of the vehicle's performance, and all parts of the intelligent tires-and-vehicle system interact with each other to achieve this. Even without fully intelligent vehicles, the tires in a vehicle do talk to each other, interacting through the vehicle chassis by sharing the 3D forces, and through the driveline system (i.e. a set of power-dividing units, PDUs), which distributes the engine power among the driven wheels. The number of PDUs is usually equal to the number of the driven wheels minus one. For example, a 6x6 truck has five PDUs (Figure 2). In fully electric vehicles, coordinated control of individual electric motors plays the role of the driveline system.

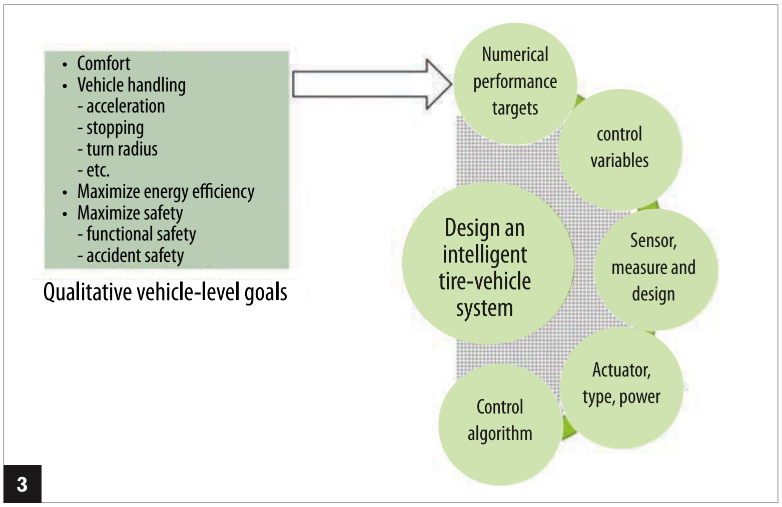


Figure 3: The flow-down of vehicle-level specifications can be applied to obtain each subsystem's specification

The tire 'talk' through a driveline system is coupled/fused wheel-driveline dynamics. It affects the power distribution between the wheels and thus the slip power loss in the vehicle's tires due to the longitudinal deflections of the tires (or of tires and soil on deformable terrain), and due to the power loss in the driveline system itself. Different combinations of PDUs in a driveline system will lead to different longitudinal deflections of tires and hence cause different slip power loss. Additionally, power distribution between front and rear, and/or left and right, wheels also influences the lateral tire forces. Thus, the same vehicle with a different set of PDUs will demonstrate different characteristics in its fuel consumption, terrain mobility, turning ability, stability of motion and handling.

The transition to fully electric vehicles will give further flexibility in controlling individual wheel torques to generate appropriate longitudinal forces (leading to optimum distribution of tire/soil deflections) in order to minimize tires' slip power losses. It is therefore evident that tire slip sensors are an immediate requirement for 'talk' intelligence and for providing agile – pre-emptive, fast and exact – interaction with the environment and between the tires.

As the first step in designing an intelligent tires-and-vehicle system, the required characteristics for the tires are derived from the vehicle's performance targets. The current state-of-the-art in tire design involves trade-offs among many competing variables, including rolling resistance, traction and tread wear. It also poses difficulties, such as preventing designs with the lowest possible rolling resistance (e.g. by maximizing rigidity) as they may result in unacceptably low traction and reduced safety in some driving situations.

In fully integrated intelligent systems there are other subsystems whose parameters can be varied, such as engine power, to achieve the goal of optimal vehicle safety. This provides more flexibility in meeting the tire's performance criteria without compromising any of its mechanical properties. An intelligent tires-and-vehicle system is thus an 'optimal system' rather than a grouping of optimized subsystems. The principles of systems engineering, for example the flow-down of vehicle-level specifications, can then be

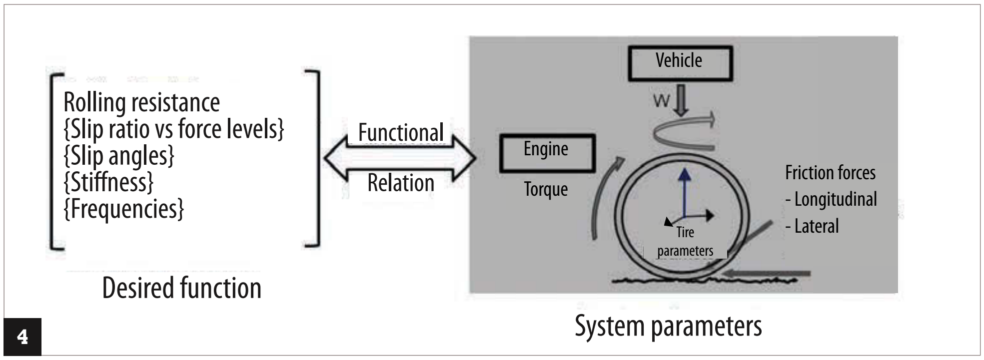


Figure 4: The tire's technical specifications are functionally related to its structural properties and to the operating parameters from the powertrain and the terrain

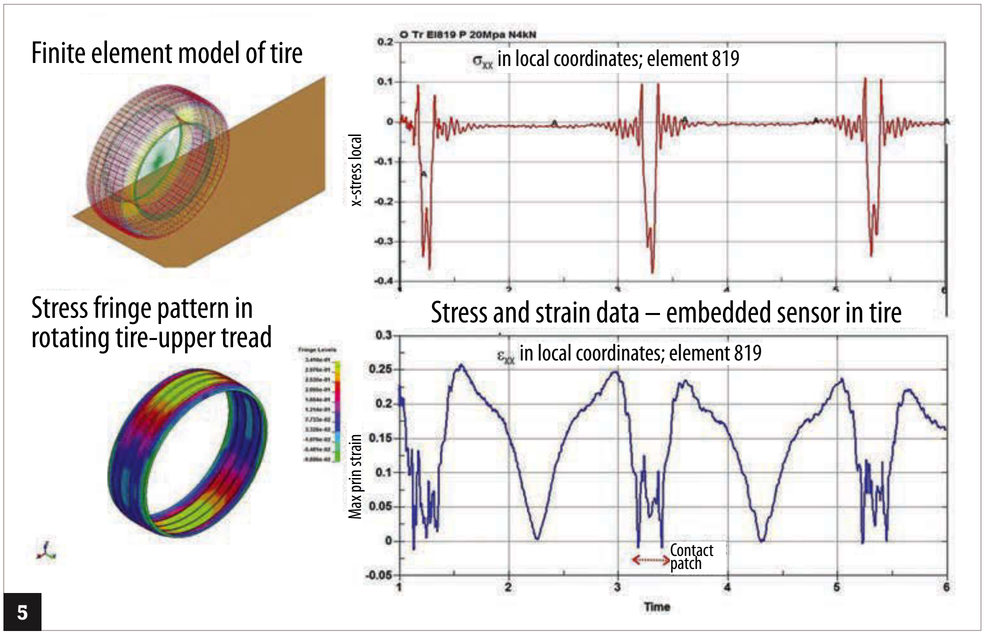


Figure 5: Example of stress and strain distributions in a rotating tire (inflation pressure 0.20MPa, vehicle mass 1,630kg)

applied to obtain each subsystem's specification, as illustrated in Figure 3.

A vehicle's overall performance goals (fuel efficiency, safety, cost, etc) are determined by various regulations and other socioeconomic factors, as described earlier. Translated into engineering quantities, these goals become system-level specifications – mass, engine power, stopping distance, NOx levels, etc. The next step is to expand these – flow down – into each subsystem's technical specifications. For mechatronic systems, such as an automobile, these specifications include mechanical, electrical and control-system criteria. Each subsystem is then designed to its specified criteria and synthesized into an intelligent vehicle system.

The usual tire subsystem specifications consist of numerical targets for functions, such as those shown in Figure 4. For current pneumatic tires, these values depend on dynamic properties, such as tire-to-ground contact forces, horizontal and angular velocities, loading, ground friction, etc, and have to be achieved within the tire itself by appropriate structural and material compositions. However, subsystem specifications for intelligent tires-and-vehicle systems are an integrated set among all parts of the vehicle and by assigning part of its stability and safety to the powertrain, the tires themselves can be designed to have much lower values of rolling resistance than currently possible.

An essential factor in achieving this goal is the availability of real-time data on tire-to-ground contact dynamics. Thus, sensing requirements are an integral part of tire subsystem specifications. Generally it has been difficult to implement the required sensing in tires because of the continuously moving tire-to-ground interface, and many attempts have involved indirectly estimating the required parameters from measurements of the tire's deformed geometry. However, this poses several problems and no production-worthy solutions yet exist.

Recent explorations of feasible sensing technology have been conducted by various researchers by applying non-linear finite element analysis methods to the tires of a moving vehicle. Correlation thus demonstrated between the dynamic strains and the tire-to-ground contact dynamics (shown by Matsuzaki and others) makes it possible to use strain gauges for reliable estimation of required parameters. The example in Figure 5 is for tires with an inflation pressure of 0.20MPa on a 1,630kg vehicle. Several locations in the tire are studied.

This method enables the evaluation of alternate mounting locations and sensor parameters for meeting tires' sensing specifications. Current sensors require an external power supply, but recent developments of sensors based on surface acoustic wave technology and zinc oxide nanowire technology may eliminate this requirement.

With tires designed to meet the necessary sensing specifications for an intelligent vehicle, the next step is the integration of this data with the vehicle dynamics control systems. As shown in Figure 1, the present state-of-the-art involves tire data as control input for varying the engine power as well as for varying a vehicle's linear and angular velocities and accelerations.

Overall, this implementation of intelligent tires-and-vehicle systems promises many advances in automotive transportation. Such systems appear even more desirable when one considers that several present-day safety systems in vehicles, such as ESC, use indirect estimates of tire-to-ground contact. Intelligent tires-and-vehicle systems with tire-embedded sensors will likely provide cost and performance benefits by using real-time measurement and eliminating the need for TPMS or other sensors and CPUs.

Of course, several difficulties still remain in implementing the above technical solutions, one of the most important being that these implementations of intelligent tires-and-vehicle systems will require joint development by tire manufacturers and automobile companies. **tire**

Several of the technical issues related to vehicle design for the immediate future will be discussed on July 13-18, 2014, at the Advanced Study Institute organized jointly by the University of Alabama at Birmingham (USA), Coventry University (UK, hosting the event) and KTH (Sweden), with the support of NATO. This event provides an avenue for young researchers to meet with world-class professionals to learn and discuss leading-edge engineering accomplishments and future trends. Readers can check their eligibility for full or partial financial support to attend this Institute by going to www.coventry.ac.uk/asi