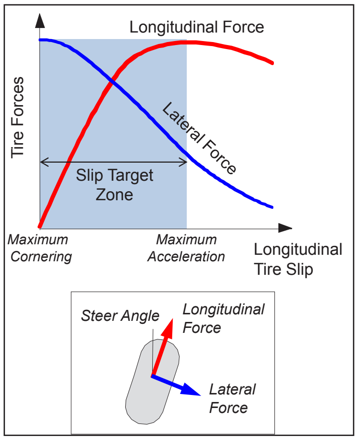
# Automotive Engine-Based Traction Control

The availability of inexpensive embedded controllers and sensors has enabled an ever-increasing number of advanced functions for automotive safety, driver comfort, and convenience. After microprocessor-based engine controls were introduced, anti-lock brakes (ABS) provided the first instance of embedded controls for chassis and vehicle dynamics. Shortly thereafter, traction control (TC), the tractive analog to ABS for vehicle acceleration, appeared. Continuous improvement of traction systems led to Ford Motor Company's in-house development of engine-only traction control. This system provides the majority of the safety-related TC function with improved refinement at a greater value for the vehicle buyer.

## The Traction Challenge

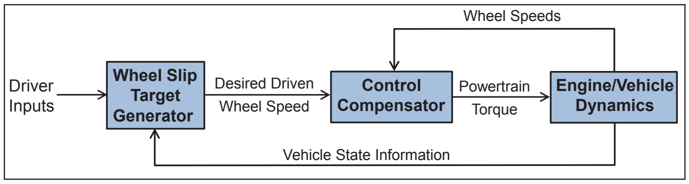
Vehicle motion is caused almost entirely by forces generated at the tire/road interfaces, and these forces provide the greatest nonlinearity and uncertainty in vehicle dynamics control problems.

The figure at right depicts typical tire forces generated as a function of longitudinal tire slip for a given steering angle and road surface friction. Longitudinal tire force initially increases with slip (the difference between the driven and nondriven wheel speed) but falls off at high slip. Lateral force capability decreases with slip. In the high slip range, accelerating and steering both diminish. The purpose of a traction control system is to manage vehicle acceleration and steerability by targeting an appropriate driven wheel slip, based on driver control inputs and vehicle state, and meeting this target using closed-loop control through powertrain torque modulation.




*Tire characteristics*

The following figure depicts the generalized TC structure with powertrain torque as the control actuation. The wheel speed (slip) target is based on vehicle speed, steering wheel angle, accelerator pedal position, and estimated road surface friction. When the vehicle is cornering, low longitudinal tire slips are targeted to produce the necessary higher lateral tire forces. When large accelerator pedal positions are present and the driver's steering input is low, larger slip levels are targeted to produce the larger longitudinal forces required for better acceleration.




*Traction control system structure*

Traction control design is challenging due to the torque production dynamics of the powertrain, which exhibits sizable variation in transport lag depending on engine speed and torque level. Further complicating the problem is the variability of the tire force/slip relationship that is strongly dependent on the road surface condition (ice, snow, gravel, etc.). This effect can lead to a locally unstable plant. Powertrain output torque is modulated using electronic throttle control, spark advance, cylinder cutting, cylinder air/fuel ratio, and transmission shifting. Each of these actuation methods operates with its own bandwidth, limited authority, and in some cases transport delay.

## Development Process

Control system development in an industrial setting begins with appropriate control-oriented plant modeling and controller design, including stability analysis. For automotive applications, great care is taken to guarantee closed-loop robustness across a wide range of operating conditions. This is followed by work to ensure that the resulting control design is compact, computationally efficient, and fail-safe.

The initial control analysis for the Ford Traction Control system modeled the powertrain as a lumped rotating mass with significant transport delay to account for the intake-to-power delay in the engine. A state feedback controller with optimal target tracking and actuator use was constructed with linear quadratic (LQ) design. The resulting control structure was then realized in the form of a classical proportional-integral structure with a cascaded lead filter (dubbed "PI+") tuned through gain scheduling to address the varying engine transport delay. This form preserves all the elements of the LQ design while fitting into the familiar classical PID-type control structure and

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***Contributors: Davor Hrovat and Michael Fodor, Ford Motor Company, USA***

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"Traction control on the V-6 test car was just right—perhaps unique in all the industry. It allowed tire spin when starting forcefully on slick roads and gradually eased the spinning without trying to stop it, allowing the car to keep moving forward as traction was gained. It should be unusually effective in winter and whenever some spinning helps forward progress."

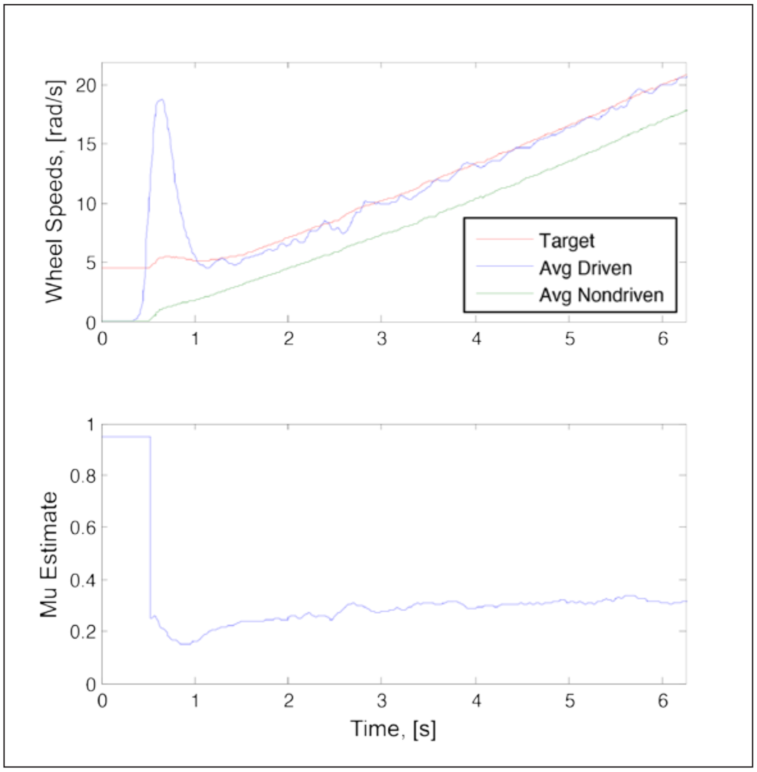
—James R. Healey, *USA Today*,
2006 Ford Fusion Review,
"Fusion Charges Off the Blocks,"
October 28, 2005

## Development Process (continued)

providing tuning based primarily on the desired closed-loop bandwidth for the system.

In addition to the core control law, the controller includes a mu-estimator for surface friction detection and corresponding PI+ control gain adaptation, a wheel speed target generator, and a state machine for control initiation and error handling. The figure at right above shows a typical TC event initiated by full accelerator pedal application on snow with the accompanying mu-estimator response.

Computer code for implementation was written to minimize memory footprint, stack size, and computation time (chronometrics). Furthermore, the entire system design was scrutinized using the Boundary Diagram, P-Diagram, a full failure mode and effects analysis, and thorough in-field testing.




*Typical traction control operation on snow—angular velocities of driven and nondriven wheels and mu-estimator (friction detection) response*

## Benchmarking and Market Reception

To provide assurance of its performance capability, the previously described controller was benchmarked against a hybrid model predictive controller (MPC) designed using the same plant model. The MPC system was implemented using the "explicit" form, which prestores all possible control actions in a searchable collection of piecewise affine control regions. The PI+ controller compared favorably, losing approximately 10% target tracking performance compared to the benchmark MPC system while employing a significantly smaller control structure and tuning that is familiar to present calibrators.

For straight-line acceleration, data collected for several drivers driving with and without TC show that with TC an inexperienced, perhaps less agile, driver will perform at least as well if not better than test drivers experienced at driving on slippery surfaces without TC. Similar improvements in vehicle steerability and stability are also evident with traction control engaged.

The Ford Engine-Only Traction system was introduced in 2006 on the Ford Fusion and the F150 light truck. It has been well received in the market as evidenced by favorable reviews (see the sidebar) and high customer take rates where it is offered as an option. It has since been introduced on several other Ford and Lincoln vehicles, including Ford's large and commercial truck lines.

*Awards: Best Paper of Automotive Track, 1998 Digital Avionics Systems Conference, Seattle, WA; 2004 Henry Ford Technology Award, Ford Motor Company, Dearborn, MI.*

*For more information: D. Hrovat, J. Asgari, and M. Fodor, Automotive mechatronic systems, in Mechatronic Systems, Techniques and Applications: Vol. 2—Transportation and Vehicle Systems, C.T. Leondes, Ed., Gordon and Breach Science Publishers, 2000.*