

Scaled Vehicle Electronic Stability Control

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Introduction

Electronic Stability Control (ESC) is the current buzz technology in automotive industry, and rightly so. NHTSA has published that ESC reduces single vehicle crashes by 67% and fatal crashes by 64%. With 10,376 rollover related fatalities in 2003 and 8,476 of those being single vehicle rollover fatalities, the numbers reveal the potential ESC has to save lives. ESC's effectiveness is so impressive that Daimler, Ford, and GM have announced that ESC, once only an option on SUVs, will be a standard feature in all of their 2007 SUV models. Though ESC's ability to prevent single vehicle rollover is already high, there is room for even more improvement by using an intelligent vehicle model. This study uses simulation in conjunction with an ESC on a scaled vehicle testbed to determine the effectiveness of the ESC as vehicle properties change. More specifically, the simulation is used to determine the vehicle's stability threshold at different vehicle properties. The ESC with the intelligent vehicle model is aware of the property changes to the vehicle model and the controller gains are adjusted to keep the vehicle within the stability threshold which is known from the simulation. This is different from a regular ESC where the vehicle model does not change, and only one stability threshold is known. Vehicle loading conditions are the most common way vehicle properties are varied. This study will focus on studying two of those parameters; the center of gravity (CG) height and weight split, and compare the effectiveness of ESC with and without an intelligent vehicle model.

Vehicle Simulation

The vehicle is simulated via MATLAB code. The simulation model has 4 degrees of freedom and was developed by deriving the equations of motion (EOM) using the free body diagrams (FBD) in Figures 1, 2, and 3. The primary dynamics that are of concern are those associated with the yaw and roll motions. Pitch dynamics (which include longitudinal weight transfer) are neglected since longitudinal accelerations were kept small.

The transient yaw equations are derived from the "bicycle model" free body diagram as seen in Figure 1. The 2-wheel bicycle model is the most commonly known version. However, for the purposes of this research, a 4-wheel bicycle model is used so that lateral weight transfer can be included in the yaw dynamics. It is assumed that the slip angles are symmetric along the x-axis of the vehicle, which is valid at high speeds.

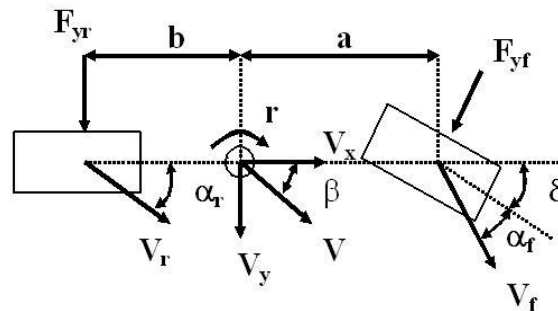


Figure 1. Bicycle Model, Yaw FBD

Summation of moments about the center of gravity yields the yaw acceleration:

$$\dot{r} = \frac{1}{I_z} \cdot [-F_{yr} \cdot b + F_{yf} \cdot a \cdot \cos(\delta)] \cdot [rad/s^2]$$

Summation of the forces in the y-axis direction yields dynamics in the y-axis:

$$\dot{V}_y = (F_{yf} + F_{yr}) \cdot \frac{\cos(\delta)}{(M + m)} - V \cdot r \cdot \cos(\beta) \cdot [m/s^2]$$

The Roll Equations are derived by separating the sprung and un-sprung masses as shown in Figure 2 and Figure 3, and applying Newton's second law (as formulated for rigid bodies). 'Inside' and 'Outside' represent the sides of the car that correspond to the inside and outside of a turn. Increasing roll angle towards the outside of the vehicle is positive.

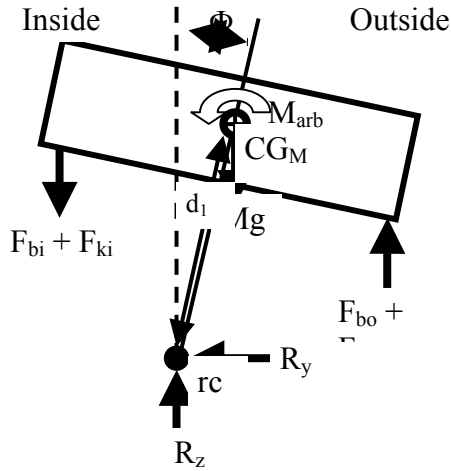


Figure 2. Roll FBD Sprung Mass

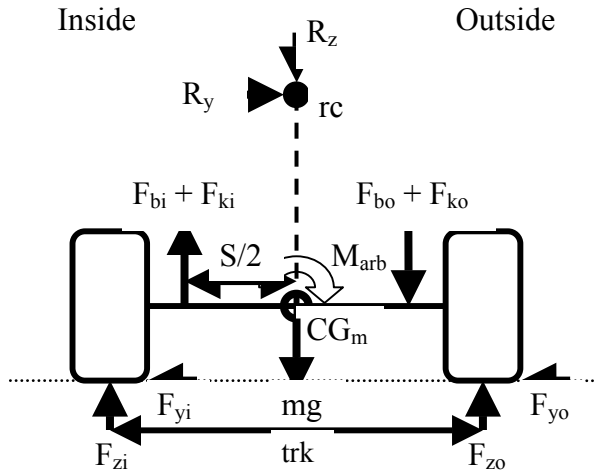


Figure 3. Roll FBD Un-Sprung Mass

Roll Equation of Motion:

$$\ddot{\Phi} = \left(\frac{1}{I_x} \right) \cdot [-RSM - RDM + (R_z \cdot d_1 \cdot \sin(\Phi)) + (R_y \cdot d_1 \cdot \cos(\Phi))],$$

$\ddot{\Phi}$ is the roll acceleration, RSM is the torque from the roll stiffness, and RDM is the torque from the roll damping.

Simulation Experiments

Vehicle simulation is used to determine the stability threshold for different vehicle loading conditions. This is done by varying individual parameters and recording the lateral acceleration at which two wheel lift (2WL) is detected. For these experiments, a Fishhook steering profile was used with a maximum steer angle of five degrees at the wheels and a maximum steering rate of 40 degrees per second. The vehicle model is that of a scaled car. Velocity is held constant for each maneuver. For a given property setup the maneuver is repeated with a different velocity until 2WL occurs. 2WL is defined as the instance that either the inside or the outside wheel loads of the vehicle go to zero. For this experiment, 2WL over a duration of 0.4 seconds is declared to be a rollover event. The stability threshold is defined as the lateral acceleration at which a rollover event occurs. This is calculated for variations of different a vehicle properties.

The first experiment varied the CG height with a weight split of 50:50. Figure 4 shows the stability threshold for the RC car as a function of CG height. The vehicle requires a higher lateral acceleration to rollover as the CG height is lowered, which follows intuition and the results of the static stability factor. Eventually, as the CG height is lowered, the vehicle no longer rolls, but begins to slide because the lateral force of the tires saturate before becoming large enough to roll the vehicle. It is important in this experiment to note that there is a 0.2615g lateral acceleration difference in the extremes of the rollover threshold. The vehicle requires 0.349g of lateral acceleration to roll at a CG height of 0.1m, while .0875g will roll the vehicle with a CG height of 0.35m.

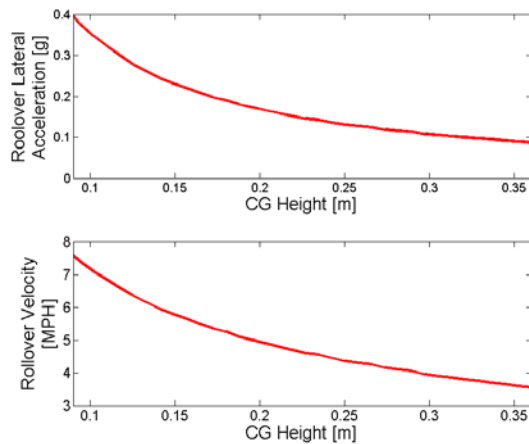


Figure 4. CG Height Variation

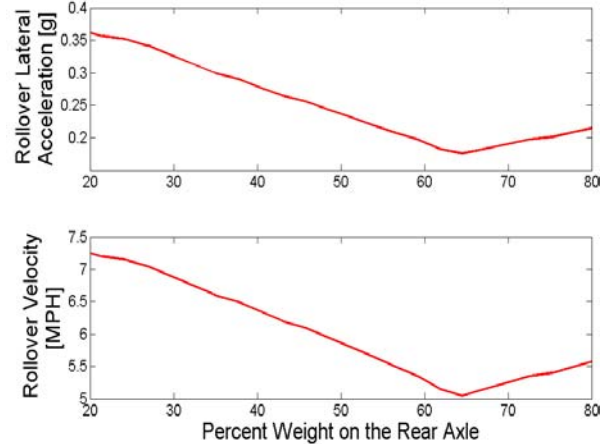


Figure 5. Weight Split Variation

The second experiment varied the vehicle's weight split from 20:80 to 80:20, front to rear axle weights respectively and the CG height was held constant at 0.15 meters. A higher lateral acceleration is required for vehicle rollover as the weight is shifted towards the front axle. It is interesting to note that the vehicle understeer gradient also increases as the weight split is shifted to the front. Therefore a generalization can be made that an understeer vehicle has a higher stability threshold than an oversteer vehicle. The stability threshold extremes of the weight split experiment vary by 0.186g lateral acceleration; 0.362g for an 80:20 weight split, and 0.176g for a 36:64 weight split.

The change in the stability threshold during these experiments shows how important vehicle loading data is to the ESC. As an example, the stability threshold changes from 0.279g to 0.1927g as the vehicle's weight split is changed 60:40 to 40:60. If the ESC is not updated with this loading condition, it will still assume the stability threshold is 0.279g, which is 44.8 percent more than the actual stability threshold. Knowing the stability threshold as a function of loading condition gives the ESC better ability to keep the vehicle within this stability threshold.

Scaled Vehicle Description

In order to verify the simulation and test the ESC's robustness, a scaled testbed was developed (Figure 6). The scaled testbed is a 1/10th scale radio controlled car modified to include an inertial navigation unit (INS), a roll cage and a center of gravity relocater. The vehicle is controlled through driver inputs via a steering wheel and pedal assembly. These inputs are sent to a controller which determines if these inputs keep the vehicle within the stability region and modifies them accordingly to maintain the driver's

intended path. The CG relocater enables the vehicle's center of gravity to be changed in the vertical and longitudinal axis in order to simulate various loading configurations. The roll cage protects the INS and wireless data acquisition. The INS measures the vehicle's dynamics via an inertial measurement unit (IMU) and samples GPS measurements, while the wireless data acquisition sends the INS information to the vehicle controller to enable wireless feedback control. Figure 7 is the layout of how the vehicle is controlled.



Figure 6. Scaled Vehicle Testbed

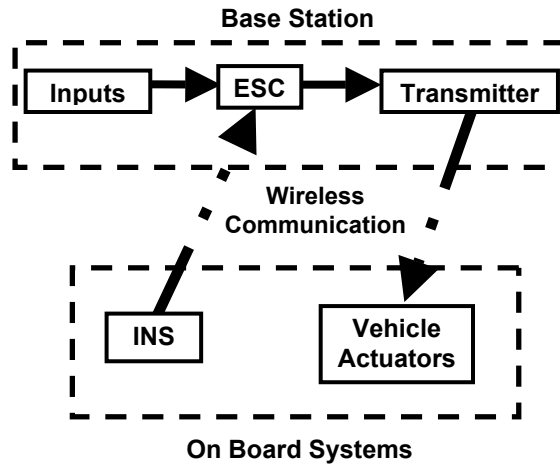


Figure 7. Control Layout

Inertial Navigation System (INS)

The INS board on the scaled rollover vehicle includes an accelerometer and gyroscope package, GPS receiver, wireless receiver, Rabbit 2000 microprocessor, and power management components (Figure 8). It is used to collect inertial and position data for analysis of vehicle's dynamics. The components are mounted on a printed circuit board and then placed in a protective box which is then mounted to the vehicle.

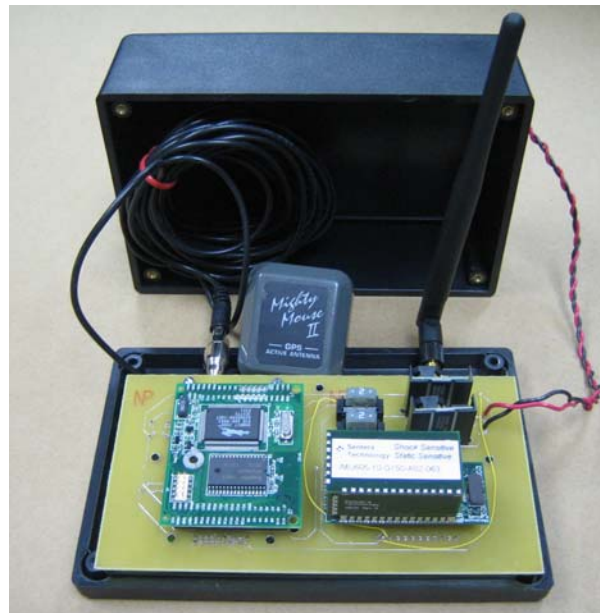


Figure 8. Wireless INS Package

All data sampling is controlled by the microprocessor, which uses C code to compile and transmit data. The microprocessor begins by collecting GPS and IMU data to be sent to the base station. It then prepares a package to be sent through the wireless receiver which then transmits the data to the base station. This package can be either literal data received from the GPS and IMU units or raw data parsed from their messages and processed onboard. The data is received by a wireless receiver plugged into the base station, and is further processed by the ESC to determine the vehicle's stability. Figure 9 includes the specifications of the INS.

Component	IMU605 - Accelerometer	IMU605 - Gyroscope	RCB-LJ - GPS
Update Rate (Hz)	Up to 256 (default 60)	Up to 256 (default 60)	4
Range	+/- 2g	+/- 150 deg/sec	n/a
Output format	Digital UART	Digital UART	Digital UART

Figure 9. INS Specifications

ESC I Logic

The first generation of our ESC is implemented open loop. ESC I monitors the driver's inputs to determine the driver's desired path, and uses actuators on the vehicle, steer angle and throttle, to track this path. The controller evaluates the lateral acceleration that is caused by these inputs. If this lateral acceleration is within the stability region, the controller does not intervene; however, if these inputs cause the vehicle to leave the stable region, the throttle and steer angle are adjusted to keep the vehicle within the stability region threshold.

Simulation and Experiment Comparison

The simulation has been previously validated for full scale passenger vehicles via comparison of experimental data from NHTSA's Phase IV with simulation data (Figure 10). Figure 11 shows data from a scaled vehicle experiment compared with a simulation of that same vehicle and maneuver. The maneuver is the Fishhook 1a, at a maximum steer angle of 5.0 degrees and a velocity of 7.2 MPH. The RC car simulation closely follows the experimental data; however, there is more error between these two than in the Blazer data comparison. The error is due to sensor noise and unknown vehicle properties, most notably the tire curve. Small discrepancies in the scaled vehicle model cause more error than those in the full size vehicle model.

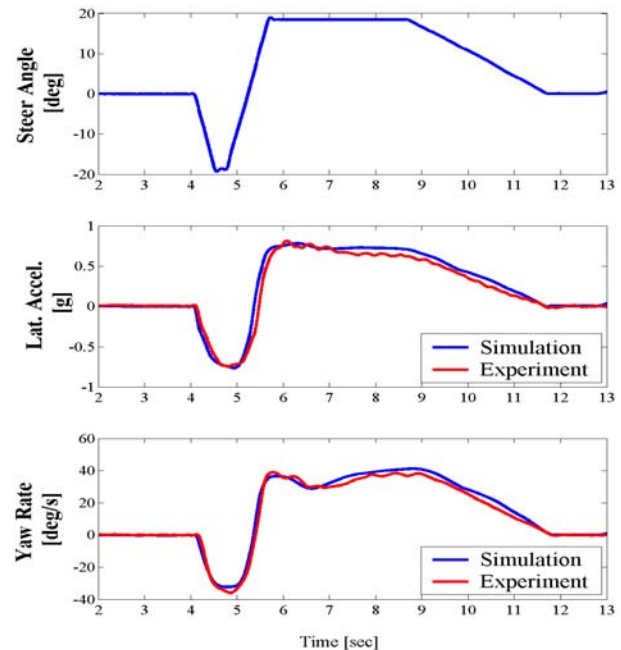


Figure 10. NHTSA Phase IV data vs. Simulation

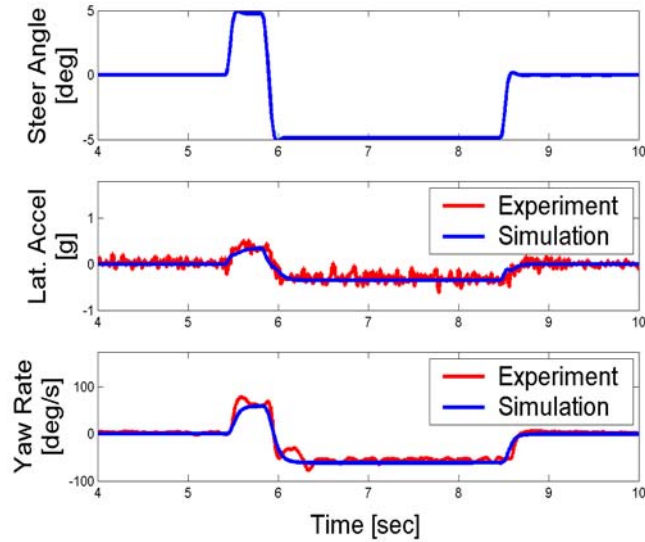


Figure 11. Scaled Vehicle Experiment vs. Simulation

On-Going Work

Currently we are developing a closed feedback ESC, ESC II. It uses the same project layout as the ESC I such as driver interface, vehicle configuration, and actuators; however, ESC II uses data from the INS to monitor the vehicle's dynamics and stability. Once the ESC II is developed, it will be tested by simulations and experiments to determine how an intelligent vehicle model affects performance. Vehicle properties that will be varied to test the ESC include tire stiffness, roll center height, wheelbase length, un-sprung mass, and roll and yaw inertias. These tests will yield understanding to the characteristics of the stability threshold as a function of the vehicle parameters tested. These tests will also reveal the effectiveness of an ESC that monitors vehicle properties and adjusts the controller's knowledge of the vehicle's stability threshold accordingly. These results will allow designers to make an evaluation on how adding sensors that monitor the vehicle loading conditions will make ESC more effective in reducing rollover fatalities. Finally, this testbed of a scaled vehicle and simulation gives ability to test and validate new control methods and ideas with experiments while being cost effective at the same time.

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