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ABSTRACT

Sudden tire deflation, or blow-out, is sometimes cited as the cause of a crash. Safety researchers have previously attempted to study the loss of vehicle control resulting from a blow-out with some success using computer simulation. However, the simplified models used in these studies did little to expose the true transient nature of the handling problem created by a blown tire. New developments in vehicle simulation technology have made possible the detailed analysis of transient vehicle behavior during and after a blow-out. This paper presents the results of an experimental blow-out study with a comparison to computer simulations. In the experiments, a vehicle was driven under steady state conditions and a blow-out was induced at the right rear tire. Various driver steering and braking inputs were attempted, and the vehicle response was recorded. These events were then simulated using EDVSM. A comparison between experimental and simulated results is presented. The research was extended by simulating blow-outs at other wheel locations and observing how various driver inputs affect the vehicle's response.

TIRE BLOW-OUT was cited as a factor in more than 300,000 crashes between 1992 and 1996, according to the National Center for Statistics and Analysis [1]*. These crashes resulted in over 2,000 deaths and several times that many serious injuries. Clearly, a thorough understanding of how a tire blow-out affects the potential for loss of vehicle control and subsequent crash is important to motor vehicle safety researchers.

Simulation has been used to study tire blow-outs by previous researchers (e.g.,[2]). The typical approach is based on research [3] showing a blown tire has a significant loss of cornering stiffness. By simulating a maneuver with both normal and reduced cornering stiffness, the researcher is able to show the difference in behavior for a vehicle with normal tires and the same vehicle performing the same maneuver with a flat tire.

The approach described above provides some insight regarding vehicle handling characteristics while driving on a flat tire. However, the authors felt this approach may be too simplistic: It essentially describes how a vehicle would handle if it left the driveway with a flat tire and was driven down the street. Greater detail and flexibility are required to perform a complete, three-dimensional analysis of the *transient* effects of blow-out on vehicle behavior during and after a sudden pressure loss while performing normal driving maneuvers. To meet this requirement, the EDVSM vehicle simulator [4] was extended to allow the user to simulate the transient effects of a tire blow-out at any wheel at any given time during the simulation. This capability has been named the EDVSM *Tire Blow-out Model.*

This paper describes the EDVSM Tire Blow-out Model. The paper includes a validation of the model by direct comparison with experiments conducted at the Transportation Research Center (TRC), in East Liberty, Ohio. The paper also provides a parameter study wherein a pre-defined maneuver is simulated and the wheel location for the blow-out is varied in order to assess the relative danger for loss of control from blow-out at each wheel location. Finally, EDVSM simulation results for front and rear tire blow-outs are reviewed to describe in detail the blow-out process and how that process affects vehicle handling.

* Numbers in brackets designate references found at the end of the paper.

EDVSM Program Overview

The following is a brief description of the EDVSM simulation model. For a complete description, see references 4 and 5.

Description

EDVSM is an HVE-compatible [6-8], 3-dimensional simulation analysis of a single vehicle. The model includes 15 degrees of freedom: six degrees for the sprung mass (body X,Y,Z, roll, pitch, yaw), two degrees for each wheel (spin and jounce/rebound) and one degree for the steering system (steer angle). The suspension model supports solid axle and independent suspensions, and accommodates ride and damping rates, anti-sway bars, jounce and rebound stops, camber change, half-track change, anti-pitch and roll steer at each wheel (lateral spring spacing is required for solid axle suspension systems). The tire model includes load-and speed-dependent friction vs longitudinal slip, cornering stiffness and camber stiffness. The tire model also includes radial stiffness and pneumatic trail. The brake system model includes master cylinder pedal ratio, proportioning, push-out pressure and brake torque ratio at each wheel.

Driver control parameters include time-dependent steering, braking, throttle and gear selection. Various user options are available for entering driver controls (*At Driver*, *At Wheel*, *Percent Available Friction*, and so forth). A steer degree of freedom option allows the user to simulate active steering from external inputs, such as curb impacts and other forces generated at the tire-road interface.

Complex, three-dimensional terrain interaction is modeled automatically. During execution, the current terrain conditions beneath each tire are obtained using the HVE Developer's Library function, GetSurfaceInfo()[8]. Complex road geometry, such as bumps, curbs, ditches or virtually any other surface geometry, as well as variation in surface friction, is thus handled efficiently and transparently to the user.

Validation

EDVSM was validated by direct comparison of simulation results with experimental handling studies performed by Calspan [9] and the University of Missouri [10]. The five handling studies used in the validation were as follows:

- Sinusoidal Steer
- Braking in a Turn
- Alternate Ramp Traversal
- Turning Maneuver Into Curb (Rollover)
- Wet Pavement Skid Into Soil (Rollover)

The validation revealed an excellent agreement between simulated and experimental results. See reference [5] for details regarding the validation study.

Table 1. Relationship between key tire parameters and decreasing inflation pressure [3].

Parameter	Effect
Cornering Stiffness, C_α	Decreases
Camber Stiffness, C_γ	Decreases
Radial Tire Stiffness, K_t*	Decreases
Rolling Resistance, R_r	Increases
Self-aligning Torque, A_t	Increases

**Initial radial tire stiffness only; does not apply to secondary radial tire stiffness that begins after 80% of maximum tire deflection.*

Description of Blow-out Model

Table 1 shows the relationship between several tire parameters and inflation pressure.

By far, the greatest effect of reduced inflation is on C_α (cornering stiffness), C_γ (camber stiffness), K_t (radial tire stiffness) and R_r (rolling resistance) [3]. Therefore, these parameters were made the dependent parameters in the blow-out model for EDVSM. Note that rolling radius is not a dependent variable in the model; this is because the reduction in rolling radius is the result of loss in the tire's radial stiffness.

To study transient effects, the blow-out model operates in the time domain (i.e., the dependent parameters are varied according to time). The model inputs are shown in Table 2. The dependent parameters are varied using linear interpolation, starting at the initiation time and lasting over the blow-out duration. The dependent parameters are multiplied (stiffness values) and divided (rolling resistance) by user-entered *blow-out factors* to create the blown tire properties. For example, if both factors are 0.1, the cornering, camber and radial stiffnesses of the blown tire are decreased to 10 percent of their normal values, while the rolling resistance is increased to 10 times its normal value. The effect is shown in Figure 1.

Table 2. EDVSM Tire Blow-out Model parameters

Parameter	Effect
T_{start}	Simulation time at start of blow-out
$T_{duration}$	Time duration of blow-out
$C\alpha$, $C\gamma$, K_t Multiplier	Multiplier for cornering, camber and radial tire stiffness
R_r Multiplier	Multiplier for tire rolling resistance

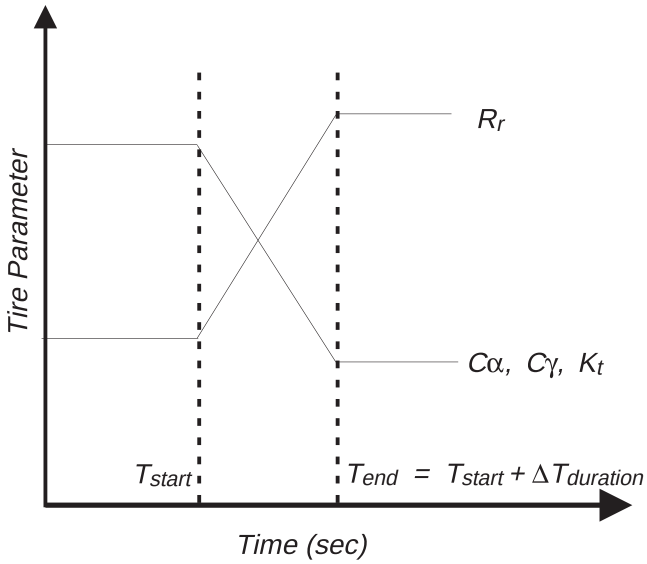

Figure 1 - Example of how tire parameters change during the air loss.

The output from the EDVSM Tire Blow-out Model provides detailed information regarding the transient nature of a vehicle's response to a tire blow-out that occurs during any maneuver. Dynamic changes in tire forces and moments are calculated and displayed, giving researchers the capability to simulate and predict the outcome for one or more driving scenarios, and to study how these transient forces affect vehicle handling.

Validation Procedure

For validation of the EDVSM tire blow-out model, four well-instrumented vehicle handling tests were selected from a series of blow-out experiments conducted at the Transportation Research Center (TRC) in East Liberty, Ohio [11]. All experiments involved the right rear tire; no front tire experiments were conducted.

Figure 2 - Test vehicle, a 1976 Ford Granada 2-Dr Sedan, fitted with outriggers.

The most successful runs (in terms of data acquisition and execution of the desired event) were selected for the current study. These tests also reflect a series of potential driver responses to blow-out at the right rear tire while driving straight ahead. These tests were described as follows:

- Experiment 7 - (63 mph, steering as required to maintain straight-ahead path)
- Experiment 8 - (63 mph, 70 degree left steer, return to zero)
- Experiment 11 - (65 mph, 50 degree left steer, return to zero)
- Experiment 12 - (65 mph, 35 degrees left steer, hold)

The test vehicle was a 1976 Ford Granada 2-Dr sedan (shown in Figure 2) fitted with lightweight, TRC-designed outriggers to prevent rollover. The vehicle was measured at TRC to determine its total weight, weight distribution and CG height. Additional measurements were taken by Engineering Dynamics Corporation (EDC) on an exemplar vehicle to determine suspension rates, roll steer characteristics and brake system parameters. Rotational inertias were estimated from measurements made on similar vehicles [12]. The vehicle was fitted with unremarkable radial passenger car tires. Tire parameters were obtained using a generic P205/75R15 from the EDC Tire Database [13]. All four tires were the same.

In performing each test, the driver accelerated the vehicle to a nominal test speed of 63 to 65 mph. The blow-out was initiated on the outer sidewall of the right rear tire using an electronically controlled detonator (see Figure 3). The driver responded by using various steering and braking inputs.

Time histories for driver inputs and vehicle response were recorded using the instrumentation package shown in Table 3. Measured time histories included:

- Velocity
- Steering Wheel Angle
- Brake Pedal Force
- Total Distance Traveled
- Yaw Angle
- Yaw Velocity
- Longitudinal Acceleration
- Lateral Acceleration

Table 3. Instrumentation Package Used in Tests

Parameter	Instrument
Yaw Angle, Yaw Rate, Long/Lat Acceleration	Humphrey Instrument Package, Model CF18-0905-1
Speed, Distance	Labeco Performance Monitor, Model 625
Steer Angle	Spectro Model 830
Brake Pedal Force	GSE Load Cell, Model 3100

Figure 3 - Test tire fitted with electronic detonation device (top). After blow-out, the tire sidewall sustained a hole approximately 1 inch in diameter (bottom).

In performing the simulations, the vehicle was accelerated in high gear to its measured velocity and the blow-out was initiated. Time histories for simulated steering and braking inputs were found that yielded an acceptable match between simulated and measured path distance, velocity and yaw angle. The results for each test are described below.

Experiment 7

In this test, the vehicle's speed was 63 mph at the time of the blow-out. The driver steered and braked as necessary to maintain vehicular control.

The steering inputs varied erratically between 0 and -45 (counter-clockwise) degrees, leveling off at about -30 degrees. Driver steering response began 0.5 seconds following blow-out. The braking input was a sustained, hard brake application beginning 2.4 seconds after blow-out.

Simulated vs measured path distance is shown in Figure 4(a). The agreement is excellent. Simulated vs measured velocity is shown in Figure 4(b). The agreement is good, although the simulated vehicle initially slows more quickly, possibly because of over-aggressive brakes on the 1976 Ford Granada simulation model. Figure 4(c) shows the graph of simulated vs test steering inputs. The simulated steering inputs were similar in character to the test inputs, although less steering was required. Steering compliance, not modeled in EDVSM, might be responsible for the difference. Differences between simulated tires and test tires might also be a factor.

Figure 4(d) shows the simulated vs test brake pedal inputs. The measured pedal force reached 65 lb; the simulated pedal force was 50 lb. It was noted that the vehicle model for this (and all other) tests appeared to use an excessively high wheel brake torque ratio, as evidenced by the lower pedal force required to achieve the required deceleration rates.

Simulated vs measured heading (yaw) angle is shown in Figure 4(e). Again, the agreement is excellent. The simulated vs measured yaw velocity is shown in Figure 4(f). The simulated data show a spike following blow-out. This spike would be expected based on the measured and simulated yaw angle change occurring soon after blow-out; refer to Figure 4(e). This phenomenon also seems like a reasonable vehicle response, and it shows up in most other tests. For unknown reasons, the spike does not appear in the measured data for this run.

Figures 4(g) and 4(h) show simulated longitudinal and lateral accelerations. Measured accelerations were not available for this test.

Experiment 8

In this test, the vehicle's speed was 63 mph at the time of blow-out. The driver steered hard to the left momentarily, then returned the wheel to the center position. Only light braking occurred.

Simulated vs measured path distance is shown in Figure 5(a). The agreement is very good, although the (over-braked) vehicle comes to rest about 50 feet earlier. Simulated vs measured velocity is shown in Figure 5(b). The agreement is quite good, although the simulated vehicle initially slows more quickly, possibly for reasons described earlier. The steering input was a single, heavy steering input, the beginning of which was coincident with blow-out, reaching a level of -70 degrees about 2 seconds after blow-out, and returning to 0 degrees about 3 seconds following blow-out. Figure 5(c) shows the graph of simulated vs test steering inputs. The simulated steering inputs match the measured values quite well. The simulated vs measured braking inputs are shown in Figure 5(d). The match is nearly perfect. Note that if the braking were reduced, the path positions would be improved.

Simulated vs measured heading (yaw) angle is shown in Figure 5(e). The total rotation for the simulated vehicle is -351 degrees (counter-clockwise), while the measured yaw angle is -370 degrees. This agreement for total angular rotation was quite good for a dynamic maneuver involving blow-out. The phasing of the maneuver did not match well; see Figure 5(e). The build-up was much slower for the test vehicle than the simulated one. The phasing error was possibly related to the initial slowing of the vehicle. Simulated yaw velocity is shown in Figure 5(f). No yaw velocity test data were available for this run.

The longitudinal and lateral accelerations are shown in Figure 5(g) and 5(h), respectively. The basic trends for simulated vs measured accelerations match reasonably well. The phase shift discussed above is quite evident in these graphs. This result is expected and consistent because the longitudinal and lateral tire forces are indirectly affected by yaw angle (tire forces are directly affected by tire slip angles, which, in turn, are affected by yaw angle).

Experiment 11

In this test, the vehicle's speed was 65 mph at the time of blow-out. The driver steered momentarily, then returned the wheel to the center position. Heavy braking occurred.

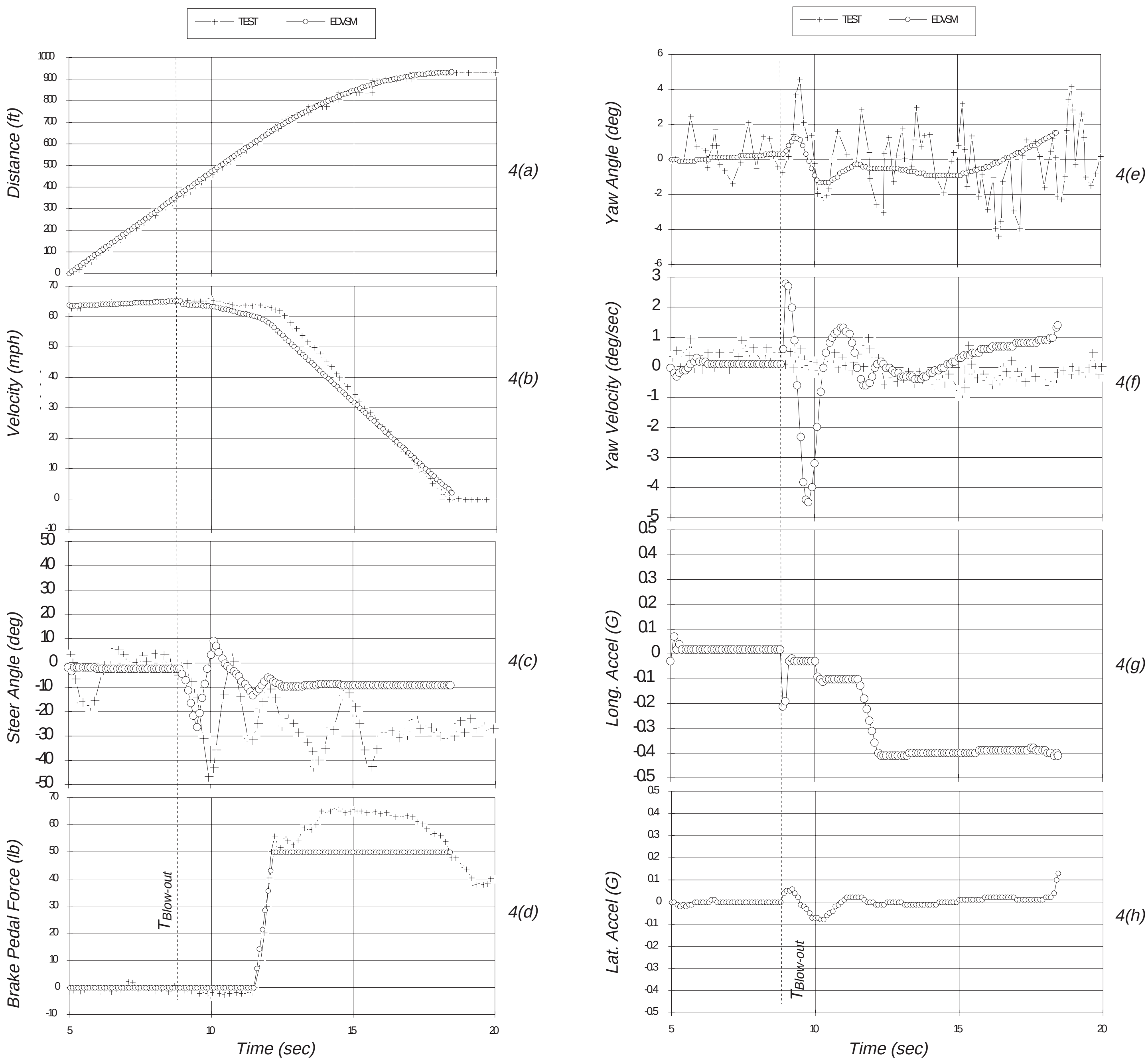

Figure 4 - Simulation vs Test Data for Experiment 7, Attempting to Maintain a Straight-ahead Path.

The steering input was a single moderate left steer beginning 0.5 seconds following blow-out, reaching a level of -50 degrees about 1 second after blow-out, steering back to the right slightly (about 10 degrees) about 4 seconds following blow-out, and finally returning to near 0 degrees about 5 seconds following blow-out.

Simulated vs measured path distance is shown in Figure 6(a). The agreement is very good, although the simulated vehicle comes to rest earlier than the test vehicle (again, aggressive brakes are suspected). Simulated vs measured velocity is shown in Figure 6(b). The agreement is quite good, although the simulated vehicle initially slows more quickly (for reasons described earlier). Figure 6(c) shows the graph of simulated vs test steering inputs. The trend of the simulated steering inputs match the measured values quite well. However, only 30 degrees of initial steering to the left, followed by 30 degrees of steering to the right were required, again possibly the result of missing steering system compliance. The simulated vs measured braking inputs are shown in Figure 6(d). The amount of braking, 95 pounds at the pedal, matches quite well. However, the simulated brakes must

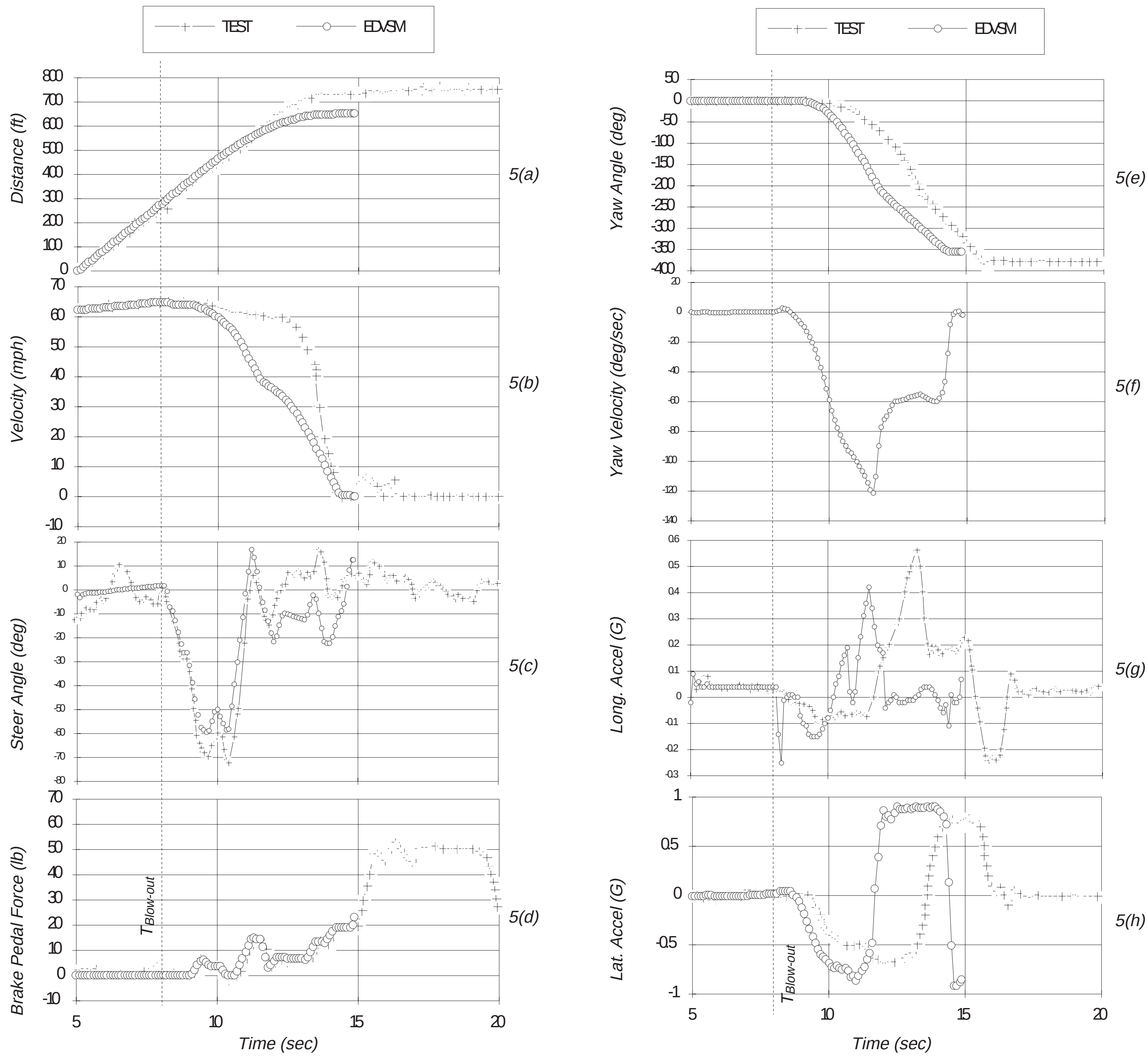

Figure 5 - Simulation vs Test Data for Experiment 8, Momentary 70 Degree Left Steer.

be released earlier, consistent with earlier observations about the simulated vehicle's overly aggressive brake system.

Simulated vs measured heading (yaw) angle is shown in Figure 6(e). The total rotation for the simulated vehicle is 180 degrees counter-clockwise, while the measured yaw angle is 185 degrees. This agreement for total angular rotation was excellent. The phasing of the maneuver also matched well. Simulated and actual yaw rates are shown in Figure 6(f). The trend is very good, however, the simulated peak yaw rate was twice that of the measured value. The reason for this difference was not identified.

The longitudinal and lateral accelerations are shown in Figures 6(g) and 6(h), respectively. The basic trends for simulated vs measured accelerations match well. The measured longitudinal acceleration prior to blow-out, 0.2 G, was significantly greater than that associated with the velocity vs time history (note that, according to the velocity history, the vehicle accelerates at a much lower rate, about 0.03 G, during the period before blow-out). Although the reason could not be identified, it is felt the instrument may not have been properly zeroed before the run. If true, the match between simulated and measured longitudinal accelerations is improved.

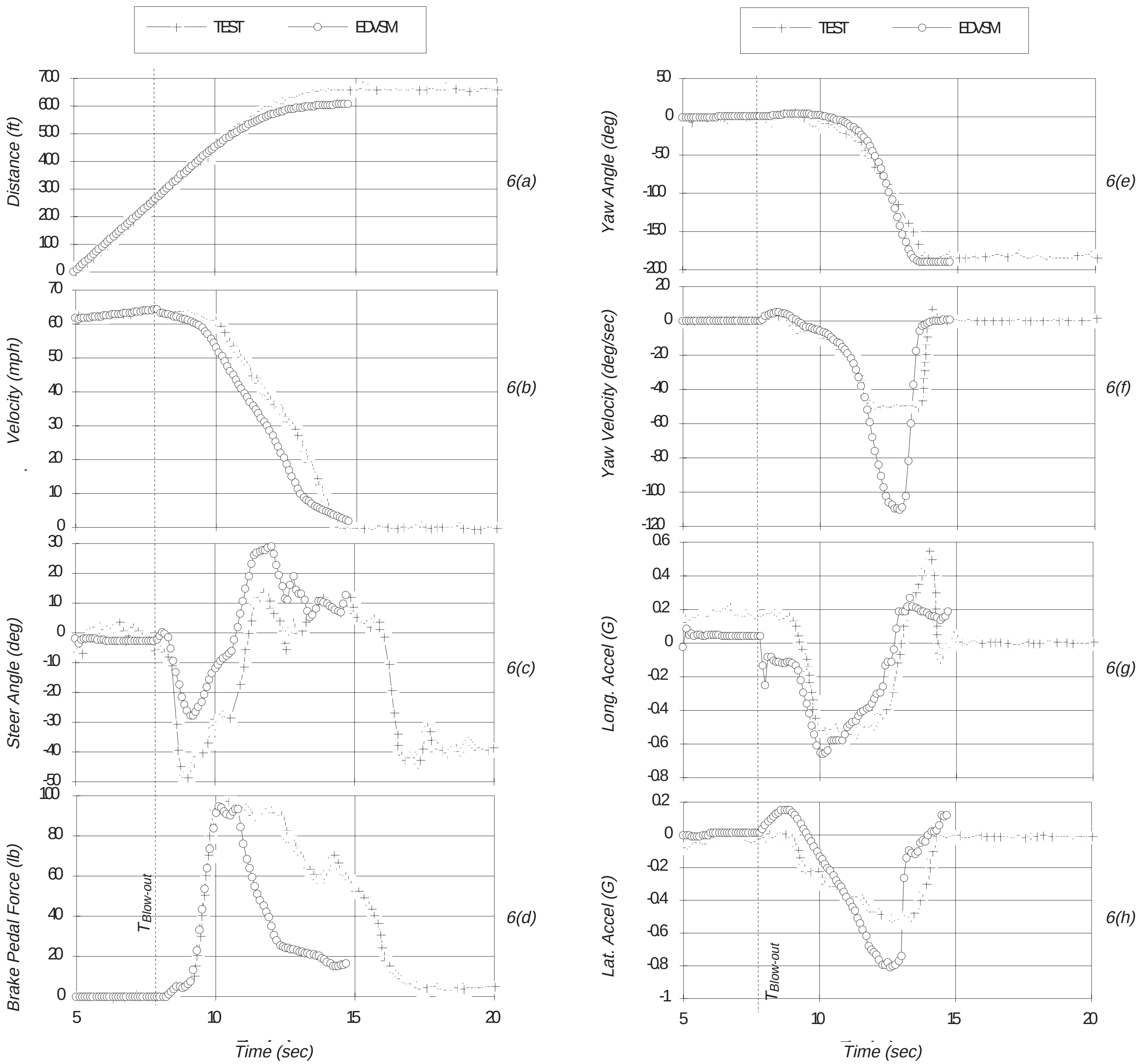

Figure 6 - Simulation vs Test Data for Experiment 11, Momentary 50 Degree Left Steer.

The match between simulated and measured lateral accelerations was probably affected adversely by higher total velocity late in the run (refer to the velocity vs time history, Figure 6(b), above).

Experiment 12

In this test, the vehicle's speed was 65 mph at the time of blow-out. The driver steered to the left, attempting to maintain a steady left-hand steer. Moderately heavy braking occurred. Like the steering input, the driver attempted to maintain steady braking.

The steering input was a single moderate steering input at blow-out, reaching a level of -35 degrees about 1.0 seconds after blow-out. The steering is reduced slightly to about -25 to -30 degrees, and maintained at that level.

Simulated vs measured path distance is shown in Figure 7(a). The agreement is excellent until the end of the run; again, the over-braked simulated vehicle comes to rest earlier than the test vehicle. Simulated vs measured velocity is shown in Figure 7(b). The agreement is quite good, although the simulated vehicle initially slows more quickly (for reasons described earlier). Simulated and measured steering inputs are

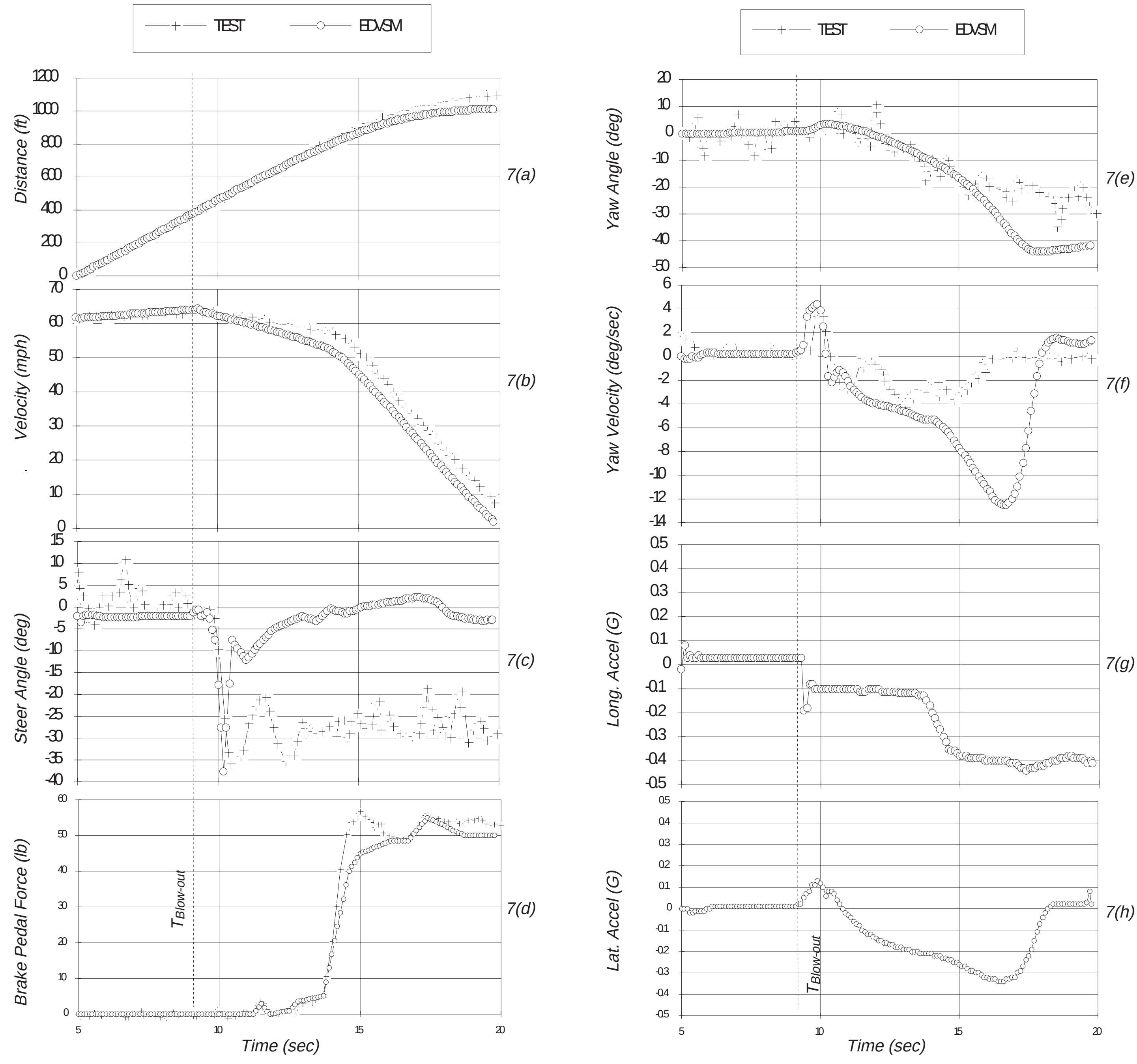

Figure 7 - Simulation vs Test Data for Experiment 12, Holding a 35 Degree Left Steer.

shown in Figure 7(c). The trend of the simulated steering inputs match the measured values quite well. However, the simulated steering returns to a much smaller value than the measured values. The simulated vs measured braking inputs are shown in Figure 7(d). The agreement is quite good, reaching and holding a pedal force of 50 to 55 pounds.

Simulated vs measured heading (yaw) angle is shown in Figure 7(e). This run showed the poorest agreement. The total rotation for the simulated vehicle is -45 degrees (counter-clockwise) while the measured yaw angle is -25 degrees. Again, the measured results contained a lot of noise.

Simulated and measured yaw rates are shown in Figure 7(f). The match between simulated and measured yaw rates was not as good as for other runs. Both simulated and experimental data show a yaw gain spike just after blow-out, and both show a reversal from a positive to negative yaw rate over the next 2 seconds, but the simulation shows a continuation of the negative yaw rate while the test vehicle's yaw rate returned to near-zero. The reason for this inconsistency is unknown. The simulated longitudinal and lateral acceleration histories are shown in Figures 7(g) and 7(h), respectively. Measured accelerations are not available for this run.

Parameter Studies

No test data were available for front tire blow-out. To address this issue, a simulation study was performed wherein a right front tire blow-out was simulated for a vehicle initially traveling straight ahead at a speed of 65 mph. The vehicle's response was recorded. Then, the event was re-executed to determine the amount of steering required to maintain a zero yaw angle (i.e., stay in its lane). Finally, large counter-clockwise steer angle was introduced to observe the vehicle's response.

No Steering - As a result of blow-out, the vehicle drifts to the right as shown in Figure 8. Careful review of the vehicle dynamic behavior reveals a momentary spike in roll and yaw velocity. The drifting is attributable to the momentary yaw velocity and a clockwise moment produced by the increased rolling resistance at the right front wheel.

Corrective Steering - The amount of steering required to keep the vehicle in its lane was simulated next. The maximum allowed lateral motion was 3 feet (corresponding to a 6-ft wide vehicle in a 12-ft wide lane). The steering began 0.5 seconds after blow-out. The maximum required amount of simulated steering was 37 degrees during the period from 0.5 to 1.0 seconds following the blow-out.

Too Much Steering - Finally, the amount of steering required to cause over-correction and loss of control was simulated. A sinusoidal steering input with a period of 2 seconds was used (this period was rather arbitrary; the authors felt this rate of steer input was easily achievable by a driver). For purposes of the test, 'loss of control' was defined as the amount of steering to the left required to cause the vehicle to leave its lane. Again, the steering began 0.5 seconds after blow-out. The required steering amplitude was +/-91 degrees.

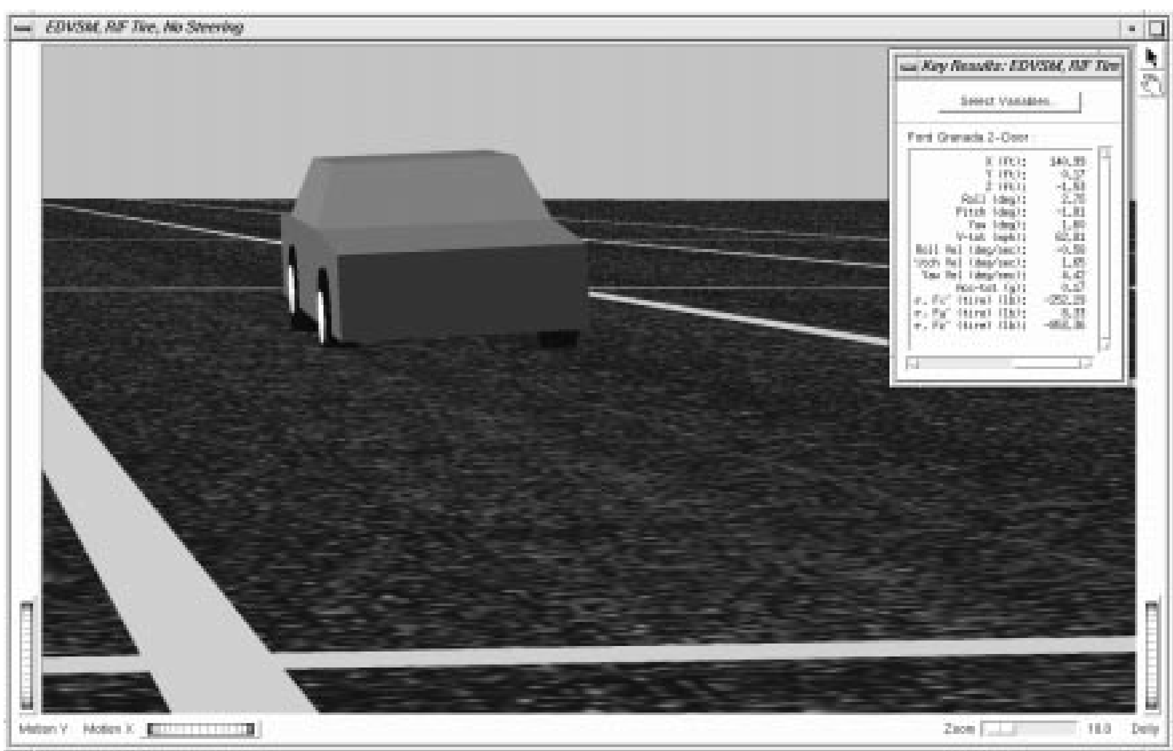

Figure 8 - Simulation of drifting vehicle 0.5 seconds following the commencement of the blow-out. Tire forces for right front tire are shown in Key Results window.

Vehicle Transient Behavior

While a vehicle is performing a steady-state, non-limit maneuver, the EDVSM tire blow-out model reveals the following information about how the transient tire forces and other vehicle parameters affect vehicle response for a right front tire blow-out:

- Initially, the vertical and shear forces at the tire-road interface are stable.
- When the right front tire deflates, its radial stiffness drops to about 10 percent of its original value, leading to a reduction in the tire's effective rolling radius.
- The vertical tire force, F_Z, for the blown tire drops to about 25 percent of its original value until the falling tire hits the ground and bottoms out on the (stiff) rim; then, a brief spike occurs.
- The vehicle begins to roll (positive) and pitch (negative) slightly, causing F_Z at left rear tire to drop, and F_Z at the left front and right rear tires to increase. The drop in F_Z at the right front tire also reduces the available cornering force at the right front, thus if steering is applied, the vehicle will tend to understeer.
- About 0.10 seconds following blow-out initiation, the blow-out is complete.
- Transient load transfer continues as the blown right front tire bottoms out on the rim. As the sprung mass continues to settle, F_Z at the left front tire and right rear tires then return back to near original values, while F_Z at the left rear continues to drop due to the vehicle's roll/pitch attitude, and F_Z at the right front begins to increase again as the tire bottoms out on the rim and the sprung mass drops on the tire.
- As a combined result of the air loss and increased F_Z at the right front tire, the blown tire's additional rolling resistance produces a clockwise moment on the vehicle. As a result, the vehicle begins to drift to the right.
- As the right front corner of the sprung mass continues to drop, a significant jounce condition occurs. Any suspension roll steer tendency causes steering of the right front wheel. Depending on suspension design parameters, the roll steer will either steer the wheel to the left, helping to offset the moment produced by the tire's increased rolling resistance, or to the right, exacerbating the condition.

Figure 9 shows a graph of the simulated F_x, F_y and F_z tire forces at the blown tire for this event.

For an air loss at a rear tire, the EDVSM tire blow-out model predicts the following details about the transient forces and moments acting on the vehicle that affect its behavior during and after the blow-out:

- Initially, the vertical and shear forces at the tire-road interface are stable.
- When the right rear tire blows, its radial stiffness drops to about 10 percent of its original value, leading to a reduction in the tire's effective rolling radius.
- The vertical tire force, F_Z, for the blown tire drops to about 25 percent of its original value until the falling tire hits the ground and bottoms out on the (stiff) rim; then, a brief spike occurs.
- The vehicle begins to roll (positive) and pitch (positive) slightly, causing F_Z at left front tire to drop, and

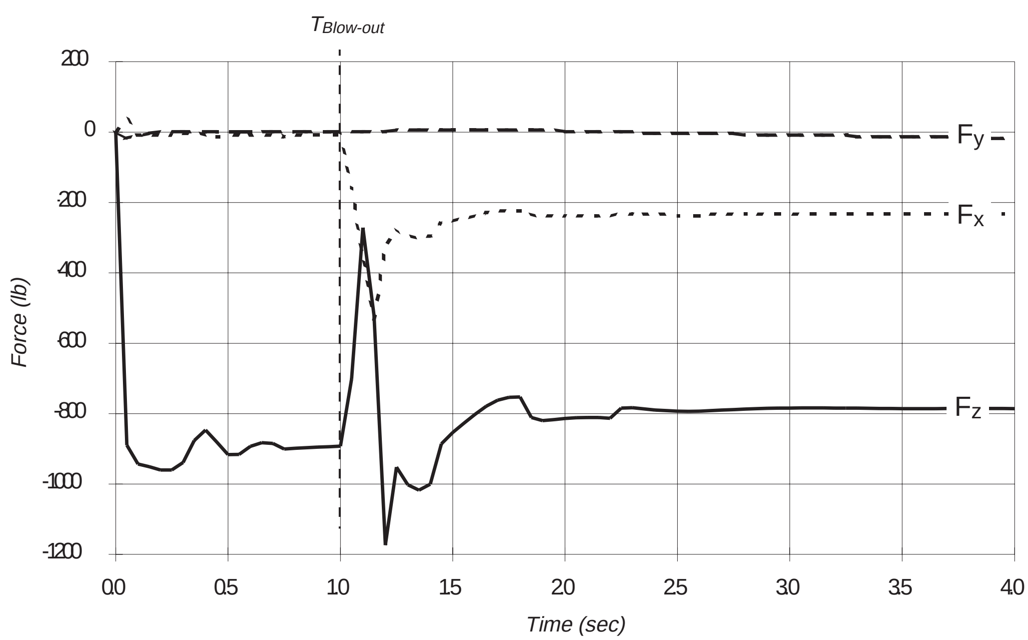

Figure 9 - Time history for F_X, F_y, F_z tire forces for a blown front tire during straight-ahead driving.

F_z at the right front and left rear tires to increase. The drop in F_z at the right rear tire also reduces the available cornering force at the right rear, thus, if steering is applied, the vehicle will tend to over-steer.

- About 0.10 seconds following blow-out initiation, the blow-out is complete.
- Transient load transfer continues as the blown right rear tire bottoms out on the rim. As the sprung mass continues to settle, F_z at the right front tire and left rear tires return back to near original values, while F_z at the left front continues to drop due to the vehicle's roll/pitch attitude, and F_z at the right rear begins to increase again as the tire bottoms out on the rim and the sprung mass drops on the tire.
- As a combined result of the air loss and increased F_z at the right rear tire, the blown tire's additional rolling resistance produces a clockwise moment on the vehicle. As a result, the vehicle begins to move to the right.
- As the right rear corner of the sprung mass continues to drop, a significant jounce condition occurs. The effect on handling is affected by the type of rear suspension: While the roll steer effect for most solid axle suspensions is quite small, the effect may be greater for independent suspensions (see Discussion).

Figure 10 shows a graph of the simulated F_x, F_y and F_z tire forces at the blown tire for this event.

While a vehicle is performing a high-G turn (near-limit maneuver), the EDVSM tire blow-out model reveals the following information about how the transient tire forces and other vehicle parameters affect vehicle response for a right rear tire blow-out:

- The maneuver begins at a speed of 65 mph with -50 degrees (counter-clockwise) of steering at the steering wheel (-2.1 degrees at the tires); no braking.
- The vehicle stabilizes at a lateral acceleration of about 0.6 G's. The vertical and shear forces at the tire-road interface are stable.
- The right rear tire blows at t=2.0 seconds.
- Loss of air at the right rear tire causes a reduction in radial tire stiffness, leading to a reduction in the tire's rolling radius. As a result, the vertical tire force, F_z, at the right rear tire drops to about 35 percent of its original value.
- The vehicle begins to roll (positive) and pitch (positive) slightly, causing F_z at the left front tire to drop, and F_z at the right front and left rear tires to increase. The drop in lateral (cornering and camber) stiffness combined with the drop in F_z at the right rear tire reduce by over 75 percent the cornering force at the right rear, producing a counter-clockwise moment on the vehicle, leading to an increase in sideslip.
- Transient load transfer continues as the blown right rear tire bottoms out on the (stiff) rim. As the sprung mass continues to settle, F_z at the right front tire and both rear tires return back to near-original values, while F_z at the left front tire continues to drop due to the combined effects of the vehicle's lateral acceleration and roll/pitch attitude.
- Loss of cornering force at the blown right rear tire causes the vehicle's sideslip angle to increase; the

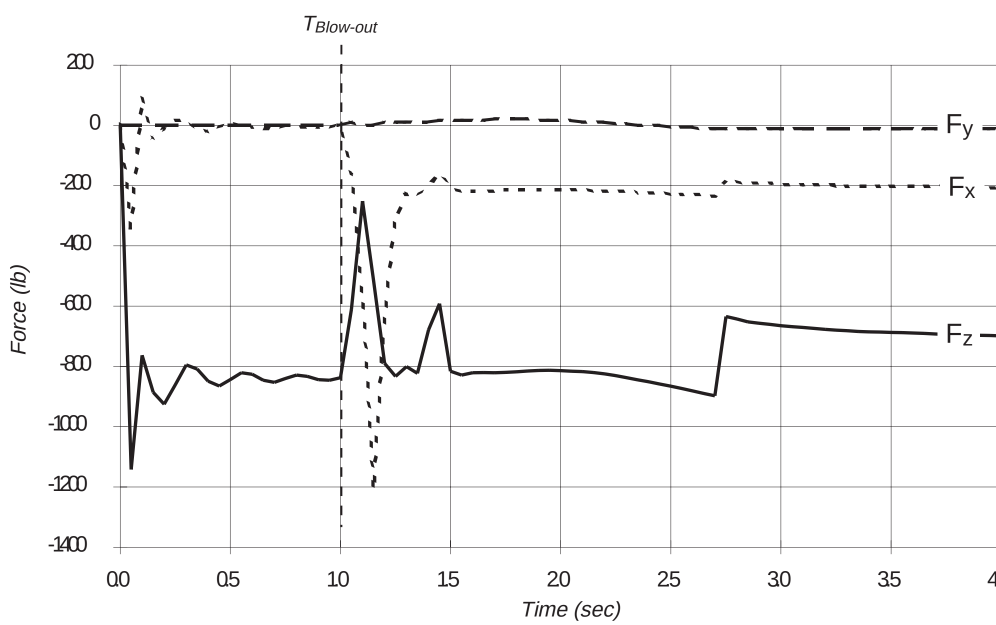

Figure 10 - Time history for F_X, F_Y, F_Z tire forces for a blown rear tire during straight-ahead driving.

vehicle begins to over-steer while attempting to reach force equilibrium at the four tires.

- The tire forces saturate at a level below that required to maintain yaw stability, and the vehicle spins out.

Figure 11 shows a graph of the simulated F_x, F_y and F_z tire forces at the blown tire while a vehicle is attempting a 0.6 G turn.

The above discussions apply to left-side blow-outs as well; vehicle behavior is bilaterally symmetrical except in unusual circumstances, such as asymmetrical loading or suspension failure.

Discussion

The ability to simulate vehicle behavior during and following a blow-out has led to many interesting and useful observations. Some of these observations are discussed below.

Blow-out Time Duration

The time duration for all blow-outs used in this study was 0.10 seconds. This value was estimated from analyzing slow-motion videos of blow-out experiments [14]. It should be noted that the blow-out model is general, in that it allows the user to program the time duration for the air loss. Thus, slow loss of air also may be simulated.

In-use and Driver Factors

Both experimental results and EDVSM simulation studies confirm that a tire blow-out alone does not lead to an inevitable loss of control. Additional factors must be present. Two of the most common factors are *in-use* and *driver* factors. Further EDVSM simulations could be performed to evaluate in-use factors, such as high lateral acceleration and low surface friction, and driver factors, such as various amounts of steering and braking.

Effect of Tire Location

For a given situation, the location of the blown tire is the predominant factor in determining how the vehicle initially responds. Front tire blow-out may potentially lead to under-steer, a stable vehicle response characteristic wherein the vehicle tends to maintain a relatively straight path. Rear tire blow-out may potentially lead to over-steer, an unstable vehicle response characteristic wherein the vehicle begins to sideslip and spin out. EDVSM simulations show this condition occurs in the presence of large pre-existing lateral forces, as from a high-G turn. In addition, post-blow-out driver steering and braking inputs are more critical in the case of rear tire blow-out, where relatively small corrective steering and braking inputs can lead to over-steer. These effects have been confirmed by both experiment and simulation.

Effect of Suspension Roll/Bump Steer

Tire blow-outs cause a momentary yaw velocity peak, the extent of which is primarily affected by suspension geometry. This effect may clearly be seen during front tire blow-out experiments involving full size passenger cars with relatively soft and poorly damped front suspensions [14]. This phenomenon is the result of suspension roll steer characteristics (more correctly, bump steer, since it occurs as a result of the momentary jounce and rebound at a single wheel). Thus, the vehicle roll steer characteristics are important for the accurate simulation of front tire blow-outs. The roll steer for a non-steerable,

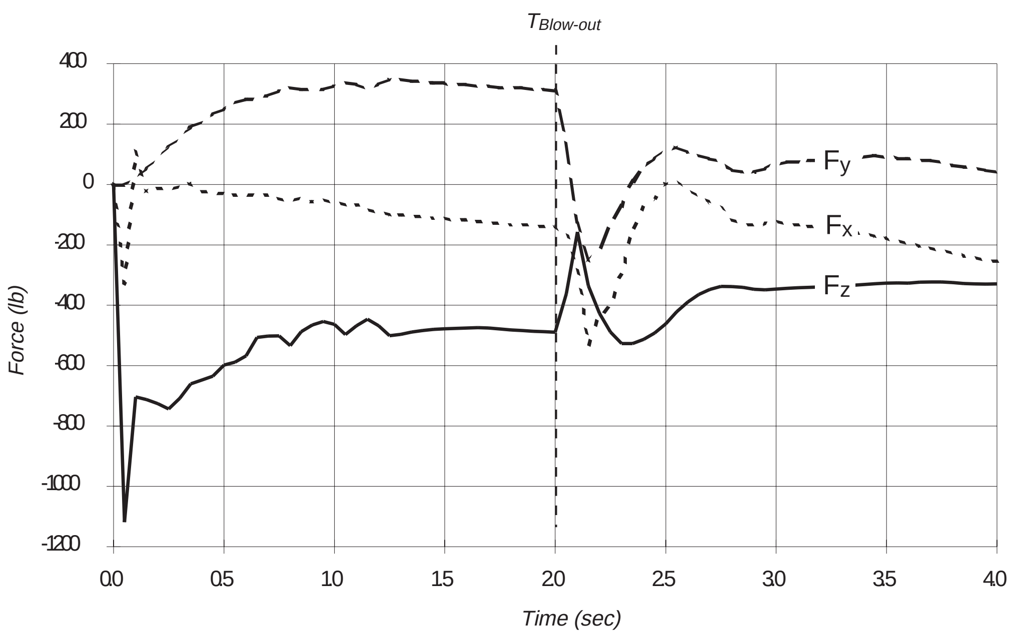

Figure 11 - Time history for F_X, F_Y, F_Z tire forces for a blown rear tire while negotiating a 0.6 G turn.

solid axle leaf-spring suspension, such as that found on the rear of the test vehicle, is normally very small. Newer passenger cars with independent rear suspensions may have a slightly greater tendency for rear suspension roll/bump steer.

Effect of Suspension Compliance

Compliance in suspension systems (mostly bushings) is widely known to affect vehicle handling, and is often included in suspension modeling for design purposes. Suspension compliance is not modeled by EDVSM; however, the contribution of suspension compliance to loss of control is normally small compared to other parameters.

Effect of Generic Tires

Tire lateral stiffness properties can vary greatly, even among tires of the same size. The use of generic tire properties on the simulated vehicle undoubtedly affected to a degree the match between simulated and measured vehicle paths. For example, the authors noticed that the simulated steering inputs were nearly always less than the measured values, suggesting the generic tires were slightly stiffer than the tires on the test vehicle. While the effect of lateral tire stiffness would affect non-limit maneuvers (such as attempting to maintain a straight path), the effect should be much less for limit maneuvers (and beyond) because the tire is operating well out of its normal operating range and behaves more like an isotropic material characterized more by its frictional properties than by its lateral stiffness.

Effect of Outriggers

The test vehicle was fitted with outriggers to prevent rollover. The inertial effect of these outriggers was not included in the vehicle model used for the simulations. Some of the phase shift in vehicle response may have been due to the inertial effect of the outriggers. The outriggers used were quite lightweight (see Figure 2); the authors felt they did not contribute significantly to any observed differences between simulated and measured results.

Effect of an Over-simplified Analysis

While simulating an outside rear tire blow-out in a curve, a researcher might run a simulation with normal characteristics, then reduce the cornering stiffness and repeat the simulation (with no other changes). The resulting simulation shows the vehicle over-steering and leaving the road on the inside of the curve. The logical conclusion is that the blown tire caused an inevitable loss of control. However, it can often be shown that by reducing the steering, the vehicle easily negotiates the curve. The blown tire at the rear of the vehicle reduces the cornering coefficient at the rear of the vehicle. Thus, to maintain lateral force equilibrium on the front and rear suspensions, *less* steering is required at the front. Before concluding a loss of control was the direct result of a blow-out, the researcher should rerun the simulation with *reduced* steering to determine if the vehicle can safely negotiate the curve.

Blow-out Model Parameters

All validations in this paper used a lateral/radial stiffness multiplier of 0.10 (i.e., the tire stiffnesses drop to 1/10th of their original values) and a rolling resistance multiplier of 30.0 (i.e., the tire rolling resistance increased to 30 times its original value). The authors felt it was important to find a single set of values that worked for all tests; we believe this goal was accomplished.

Application of Test Results

This paper includes a set of well-instrumented tests for a specific vehicle performing a series of specific maneuvers. Although the trends may be useful, caution should be exercised when attempting to extrapolate these test results to other vehicles performing different maneuvers.

Conclusions

1. Comparison between experimental blow-out studies and results using the EDVSM Tire Blow-out Model revealed a good to excellent match. The match between simulation and test data would probably be improved by revising the wheel brake torque ratios downward to reduce the over-braking observed in the simulations.

2. The EDVSM Tire Blow-out Model extends the current capability in vehicle handling simulation by allowing researchers to study how vehicle handling is affected by the sudden changes in tire properties associated with blow-out.

3. The EDVSM Tire Blow-out Model is a useful tool for studying crashes where tire blow-out was cited as a factor in the vehicle loss of control leading to the crash.

4. Experimental and simulated vehicle behavior following a right rear tire blow-out during straight-ahead driving revealed the following:

  a) At the time of the air loss, the individual tire rolling resistances are redistributed, resulting in a brief gain in yaw velocity and a subsequent drifting to the right.

  b) Little or no corrective action by the driver is necessary to maintain control. If required, proper corrective action would take the form of a minor steering input.

  c) If, for any reason, the driver supplies a large enough counter-clockwise steering input, the vehicle may over-steer and go out of control. Excessive braking may have a similar effect.

5. Simulated vehicle behavior following a front tire blow-out during straight-ahead driving revealed the following:

a) The vertical tire loads are redistributed and the tire cornering force at the rear is reduced. Both of these conditions reduce the lateral force at the rear, causing a loss of yaw equilibrium.

b) Minor corrective action by the driver may be necessary to create yaw equilibrium and maintain control. The corrective action would take the form of a minor steering input. The amount of the required input is dependent on the vehicle, tires and current lateral acceleration (i.e., speed and path radius).

c) If, for any reason, the driver supplies a large enough steering input, the vehicle may over-steer and go out of control. Excessive braking may have a similar effect.

6. Simulated vehicle behavior following an outside rear tire blow-out during a high-G cornering maneuver (typically above 0.5 G) revealed the following:

a) The vertical tire loads are redistributed and the tire cornering force at the rear is reduced. Both of these conditions significantly reduce the lateral force at the rear tires, causing a substantial loss of yaw equilibrium.

b) The vehicle re-orients itself by rotating in the yaw plane (without additional driver inputs) in an effort to reach yaw equilibrium. However, the tires saturate before equilibrium is reached and the vehicle spins out in an over-steer mode.

c) Typically, there is nothing the driver can do to prevent loss of control.

7. Suspension parameters, such as roll/bump steer characteristics, may be important for modeling front tire blow-out. These parameters are probably not important for modeling rear tire blow-out.

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The authors wish to thank Charles P. Compton, University of Michigan Transportation Research Institute, for providing the statistics used to evaluate the population of tire blow-outs.

Special thanks are due to Bradley R. Larson and H. Gregory Vitaich, of Sacramento, CA, for their interest in and support of the experimental work at TRC, to Paul Kayfetz, of Bolinas, CA, for his excellent recordation photography, and to Roman R. Beyer, of Los Altos Hills, CA, for locating reference materials used in the study.

Appendix A - Vehicle and Tire Data for 1976 Ford Granada 2-Dr

VEHICLE DATA

General Vehicle Information

Vehicle Name:	Ford Granada 2-Dr
Overall Length (in):	197.70
Overall Width (in):	74.00
CG to Front End (in):	90.80
CG to Rear End (in):	-106.90
Wheelbase (in):	109.90
Front Track Width (in):	58.60
Rear Track Width (in):	57.60
Front Overhang (in):	40.20
Rear Overhang (in):	-47.60
CG to Front Axle (in):	50.60
CG to Rear Axle (in):	-59.30
CG Height Above Ground (in):	20.60
Total Weight (lb):	3462.99
Air Drag Coef (in^2):	0.000069
Roll Resist Coef (lb-sec/in):	0.0000
Roll Resist Const (lb):	0.00

Sprung Mass Data

Mass (lb-sec^2/in):	8.15
Weight (lb):	3148.84
Rot Inertia (lb-sec^2-in),Ix:	3085.00
Iy:	20001.00
Iz:	23989.00

Suspension Data

	Front	Rear
Suspension Type:	Independ	Solid Ax
Wheel Location (in), x:	50.60	-59.30
y:	29.30	28.80
z:	7.53	7.53
Unsprung Weight (lb):	80.00	234.16
Axle Iy, Iz (lb-sec^2-in):		46.72
Axle Lat Spring Space (in):		43.50
Roll Center Height (in):		7.53
Sol Axle Roll Steer (deg/deg):		0.00
Roll Steer - Const (deg):	0.00	
Linear Rate (deg/in):	-0.19	
Quadratic Rate (deg/in^2):	0.00	
Cubic Rate (deg/in^3):	0.00	
Aux Roll Stiff (in-lb/deg):	540.48	0.00
Ride Rate @ Wheels (lb/in):	123.00	104.00
Damping @ Wheels (lb-sec/in):	7.72	6.56
Susp Friction Force (lb):	50.00	100.00
Min Vel for Friction (in/sec):	0.00	0.00
Jounce Stop (in):	-4.00	-4.00
Linear Rate (lb/in):	300.00	300.00
Cubic Rate (lb/in^3):	600.00	600.00
Rebound Stop (in):	4.00	4.00
Linear Rate (lb/in):	300.00	300.00
Cubic Rate (lb/in^3):	600.00	600.00
Energy Loss Ratio (%/100):	0.50	0.50

Camber and Half-track Tables

Front			Rear		
Susp Defl (in)	Camber (deg)	1/2-track Change (in)	Susp Defl (in)	Camber (deg)	1/2-track Change (in
-4.00	0.00	0.00	-4.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	4.00	0.00	0.00

Anti-pitch Table

Front		Rear	
Susp Defl (in)	Anti-Pitch (lb/ft-lb)	Susp Defl (in)	Anti-Pitch (lb/ft-lb)
-4.00	0.00	-4.00	0.00
0.00	0.00	0.00	0.00
4.00	0.00	4.00	0.00

Steering System Data

Steering Gear Ratio (deg/deg):	22.00

Brake System Data

	Front	Rear
Pedal Ratio (psi/lb):	1.75	
Torque Ratio (in-lb/psi):	43.58	43.58
Pushout Pressure (psi):	0.00	5.00
Proportioning?:	No	Yes
Proportioning, Pstart (psi):		200.00
P(wheel)/P(system) (%/100):		0.33

TIRE DATA
(All Tires Same)

Tire Location:	R/R
Tire Name:	Generic
Tire Type:	Passenger Car
Tire Manufacturer:	Generic
Tire Model:	Generic
Tire Size:	P205/75R14

Physical Data -

Unloaded Radius (in):	13.07
Initial Ride Rate (lb/in):	1197.80
2nd Ride Rate (lb/in):	11978.00
Defl @ 2nd Rate (in):	4.86
Maximum Tire Defl (in):	6.07
Pneumatic Trail (in):	1.07
Weight, Tire+Rim (lb):	39.99
Spin Inertia (lb-sec^2-in):	8.30
Rolling Resistance Const (lb/lb):	0.01
A0 Coefficient:	1665.91
A1 Coefficient:	9.38
A2 Coefficient:	3312.13
A3 Coefficient:	1.71
A4 Coefficient:	4200.00

Friction Data -

Location:	R/R		
Number of Loads:	3		
Number of Speeds:	2		
In-use Factor:	1		
Test Speed (in/sec):	528.00		
Test Load (lb):	774.00	1532.00	2294.00
Peak Longitudinal Mu:	0.92	0.86	0.85
Peak Lateral Mu:	0.92	0.89	0.89
Slide Mu:	0.74	0.64	0.62
Slip @ Peak Mu (%/100):	0.17	0.15	0.13
Long Stiffness (lb/slip):	15000.00	15000.00	15000.00
Test Speed (in/sec):	538.00		
Test Load (lb):	774.00	1532.00	2294.00
Peak Longitudinal Mu:	0.92	0.86	0.85
Peak Lateral Mu:	0.92	0.89	0.89
Slide Mu:	0.74	0.64	0.62
Slip @ Peak Mu (%/100):	0.17	0.15	0.13
Long Stiffness (lb/slip):	15000.00	15000.00	15000.00

Cornering Stiffness Data -

Location:	R/R		
Number of Loads:	3		
Number of Speeds:	1		
In-use Factor:	1		
Test Speed (in/sec):	528.00		
Test Load (lb):	762.60	1532.70	2297.70
Cornering Stfns (lb/deg):	125.19	163.90	144.30

Camber Stiffness Data -

Location:	R/R		
Number of Loads:	3		
Number of Speeds:	1		
In-use Factor:	1		
Test Speed (in/sec):	528.00		
Test Load (lb):	764.30	1531.00	2294.00
Camber Stfns (lb/deg):	4.21	11.29	21.50

Blown Tire Information -

Blown Tire Location:	R/R
Begin Blow-out (sec):	3.8000
Blow-out Duration (sec):	0.1000
Stiffness Multiplier:	0.10
RR Multiplier:	30.00

Reviewer's Discussion
By Michael S. Varat, KEVA Engineering
SAE #980370
3-D Simulation of Vehicle Response to Tire Blow-outs
William Blythe, Terry Day, Wesley Grimes, Authors

The authors have presented a new and valuable computer simulation tool that will assist in the analysis of dynamic vehicle response after a tire blow out. The principal benefit of the presented algorithm is that it encompasses transient effects that surround the blow out. It has been shown in the presented research that the transient effects are important and should be accounted for in a complete analysis.

While the test data and the presented simulations are well matched, minor differences did occur. As the authors stated, these differences may have been due to not simulating the outriggers, not accounting for compliance steer effects in the vehicle suspension model, the use of generic tire data, and a single value multiplier for the tire stiffness parameters affected by the blow-out. While these modeling issues may have caused minor differences between test and simulation, they are of minor significance in the presented analysis and do not invalidate the presented analysis of trends seen in the tire blow-out induced vehicle dynamics.

Further work with this useful simulation tool could involve an investigation into the determination of tire stiffness and rolling resistance multipliers for use in different tire blow out situations. Additionally, through a careful analysis of blow out induced tire properties, combined with in use and driver factors, perhaps countermeasures could be analyzed and developed in order to prevent future loss of control following a tire blow out.

Reviewer's Discussion
By Donald F. Rudny, P.E., Rudny & Sallmann Engineering
SAE #980370
3-D Simulation of Vehicle Response to Tire Blow-outs
William Blythe, Terry Day, Wesley Grimes, Authors

The authors have taken on a very complex and difficult task of simulating vehicle response to tire blow-outs. Prior studies have shown the EDVSM simulation model to be a good predictor of vehicle response to braking and steering inputs. This study extends the EDVSM model to include simulation of the transient effects of a tire blow-out. Although the model can handle a blow-out at any wheel, the model was only validated for a rear tire blow-out.

The validation study indicated generally good correlation between simulation and experimental test results. There does, however, appear to be some unexplained deviations. The lack of modeling steering compliance in EDVSM may explain some of the deviations experienced in the steer angle results. This is something the authors may want to evaluate in future studies. Both experimental and simulated studies support the generally accepted belief that, unless in-use conditions are a factor, driver overcorrection is required to lose control from a tire blow-out.

Although the EDVSM *tire blowout mode*l shows promise in predicting vehicle response to tire blow-outs, the user should be cautious in its application. The model still needs to be validated for front tire blow-outs and, as the authors indicated, characteristics such as vehicle roll/bump steer may be important for accurate front tire blow-out simulation. The simulation model clearly provides a tool which aids the engineer in understanding the mechanics of a tire blow-out and the effects that each parameter has on vehicle handling. It appears that the EDVSM *tire blow-out model* can also be an effective means of demonstrating driver reaction to various tire blow-out situations.